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2000 Plasma Sources Sci. Technol. 9 441

(http://iopscience.iop.org/0963-0252/9/4/301)

Plasma Sources Sci. Technol. **9** (2000) 441–454. Printed in the UK PII: S0963-0252(00)17858-2

Plasma generation and plasma sources

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Received 1 October 1999, in final form 27 September 2000

Abstract. This paper reviews the most commonly used methods for the generation of plasmas with special emphasis on non-thermal, low-temperature plasmas for technological applications. We also discuss various technical realizations of plasma sources for selected applications. This paper is further limited to the discussion of plasma generation methods that employ electric fields. The various plasmas described include dc glow discharges, either operated continuously (CW) or pulsed, capacitively and inductively coupled rf discharges, helicon discharges, and microwave discharges. Various examples of technical realizations of plasmas in closed structures (cavities), in open structures (surfatron, planar plasma source), and in magnetic fields (electron cyclotron resonance sources) are discussed in detail. Finally, we mention dielectric barrier discharges as convenient sources of non-thermal plasmas at high pressures (up to atmospheric pressure) and beam-produced plasmas. It is the main objective of this paper to give an overview of the wide range of diverse plasma generation methods and plasma sources and highlight the broad spectrum of plasma properties which, in turn, lead to a wide range of diverse technological and technical applications.

Introduction

Plasmas are generated by supplying energy to a neutral gas causing the formation of charge carriers (figure 1) [1–3]. Electrons and ions are produced in the gas phase when electrons or photons with sufficient energy collide with the neutral atoms and molecules in the feed gas (electron-impact ionization or photoionization). There are various ways to supply the necessary energy for plasma generation to a neutral gas. One possibility is to supply thermal energy, for example in flames, where exothermic chemical reactions of the molecules are used as the prime energy source. Adiabatic compression of the gas is also capable of gas heating up to the point of plasma generation. Yet another way to supply energy to a gas reservoir is via energetic beams that moderate in a gas volume. Beams of neutral particles have the added advantage of being unperturbed by electric and magnetic fields. Neutral beams are primarily used for sustaining plasmas or for plasma heating in fusion devices. The generation of a plasma by using beams of charged particles, especially electrons, and by using beams of photons will be discussed towards the end of this paper.

The most commonly used method of generating and sustaining a low-temperature plasma for technological and technical application is by applying an electric field to a neutral gas. Any volume of a neutral gas always contains a few electrons and ions that are formed, for example, as the result of the interaction of cosmic rays or radioactive radiation with the gas. These free charge carriers are accelerated by the electric field and new charged particles may be created when these charge carriers collide with atoms and molecules in the gas or with the surfaces of the electrodes. This leads to an avalanche of charged particles that is eventually balanced by charge carrier losses, so that a steady-state plasma develops.

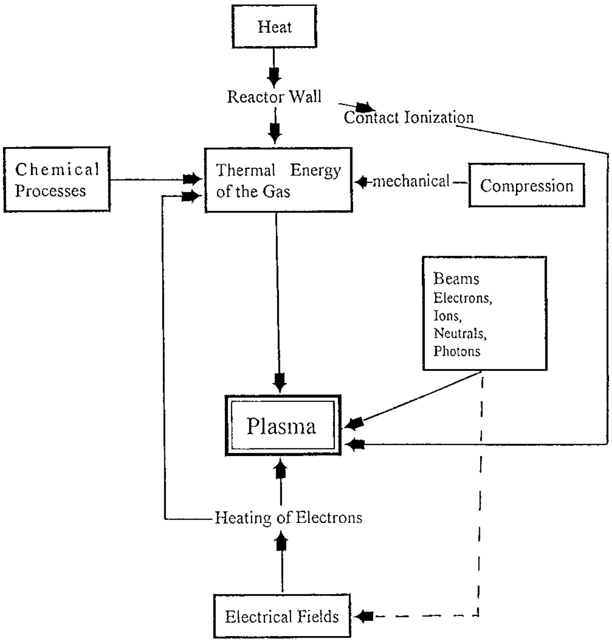

Figure 1. Principles of plasma generation.

The dimensions of a plasma source are determined largely by the particular applications for which the plasma is intended. Hence plasma sources for the production of integrated circuits or for coatings in the glass industry, on the one hand, and plasma sources for the remediation of exhaust gases and flue gases from power stations, on the other hand, require very different designs. There are distinct differences not only in the physical shape of various plasma sources, but also in the temporal behaviour of the plasmas that are generated in different sources. First, the time constants of the particular process determine the duration of the energy coupling to the plasma. These time constants cover a range of several orders of magnitude depending on the nature of the atoms and molecules used in the feed gas. Second, the characteristic features of the electric coupling, especially in electrode-less sources, determine the suitable frequency range of the exciting electric field. The technically suitable frequency ranges are further restricted by the need to comply with regulatory guidelines (which may vary from country to country) and in some cases also by design limitations for the required power sources. We mention that power amplification by squeezing more and more energy into shorter and shorter pulses has proved to be an effective way to increase the instantaneous power applied to a plasma without raising the operating costs significantly. In all technical applications, almost all of the above considerations are interrelated and not independent of one another. Another important aspect is the different state of technical maturity of the various plasma generation methods and plasma sources. Tables 1 and 2 summarize some selected plasma applications together with the required technical features, which are crucial for the appropriate choice of a plasma source for a given application.

Table 1. Applications of plasma sources.

- *Surface modification*
- Etching
  - structuring (microelectronics, micromechanics)
  - cleaning (assembly lines)
- Functionalization
  - hydrophilization
  - hydrophobization
  - graftability
  - adhesability
  - printability
- Interstitial modification
  - diffusion (bonding)
  - implantation (hardening)
- Deposition
  - change of properties
    - mechanical (tribology)
    - chemical (corrosion protection)
    - electrical (integrated circuits)
    - optical (antireflecting coating)
  - architecturing
    - crystallographics (lateral diamonds)
    - morphologic (scaffolds for cells)
- *Volume-related transformation*
- Energy conversion
  - electrical energy → electromagnetic radiation
    - particular populations of bounded electronic states
    - tailoring of the population of free electrons in phase space
      - luminiscent lamps
      - high-pressure metal vapour lamps
      - gas lasers
      - excimer radiation sources
  - electrical energy → nuclear energy
    - fusion of DT
- Plasma chemistry
  - transforming into specific compounds
    - production of precursors
    - production of excimers
  - clean-up of gases
    - odours
    - flue gases, diesel exhaust
- *Carrier functions*
- Electrical current
  - circuit breakers
  - spark gap switches
- Heat
  - welding/cutting arcs
  - plasma spray
  - thermoelectric drivers
- *Particle sources*
- Electrons
- Ions
- Neutrals

Table 2. Technical features of plasma sources.

- Costs
- Reliability
- Size
- Coupling of energy
- Conditioning of energy
- Efficiency
- Spatial distribution of plasma parameters (homogeneity)
- Positioning of plasma
- Controlling boundary conditions
- Through-put
- Safety

In the following sections we review the underlying principles that govern the generation of a plasma using electric fields as well as beams of electrons and photons. Several examples of commercial plasma sources and reactors will be discussed in some detail with special emphasis on non-thermal, low-pressure plasmas and plasma sources.

1. Plasma production using electric fields

The most widely used method for plasma generation utilizes the electrical breakdown of a neutral gas in the presence of an external electric field. Charge carriers accelerated in the electric field couple their energy into the plasma via collisions with other particles. Electrons retain most of their energy in elastic collisions with atoms and molecules because of their small mass and transfer their energy primarily in inelastic collisions. Discharges are classified as dc discharges, ac discharges, or pulsed discharges on the basis of the temporal behaviour of the sustaining electric field. The spatial and temporal characteristics of a plasma depend to a large degree on the particular application for which the plasma will be used.

1.1. Dc discharges

Non-thermal plasmas in dc discharges are generally created in closed discharge vessels using interior electrodes. Different types of discharges and plasmas can be obtained depending on the applied voltage and the discharge current (figure 2) [1, 4]. The Townsend discharge is a self-sustained discharge characterized by a low discharge current. The transition to a sub-normal glow discharge and to a normal glow discharge is marked by a decrease in the voltage and an increase in the current. An abnormal glow discharge develops as the current

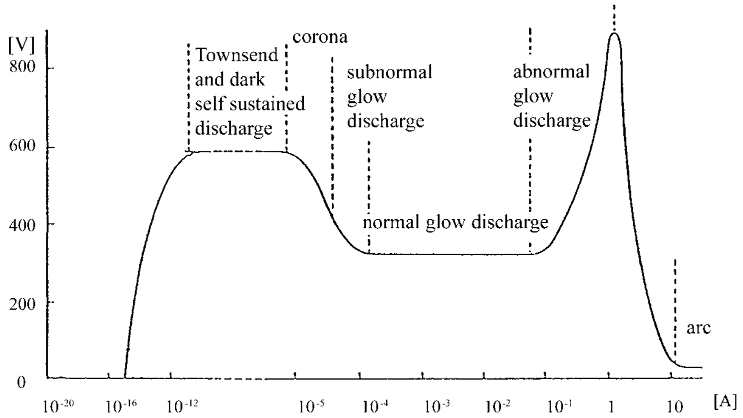

Figure 2. The dependence of voltage upon current for various kinds of dc discharges. (Ne, 1.3 mbar, flat copper electrodes 10 cm^2, electrode distance 50 cm), after [4].

is increased even further. Finally, at very high currents, the discharge undergoes an irreversible transition down into an arc (glow-to-arc transition). The operation of a glow discharge requires a resistor in series with the discharge to prevent the transition into an arc. Alternatively, the discharge can be interrupted for a short period of time before the glow-to-arc transition occurs and before it is re-ignited again.

Low-pressure, normal glow discharges between planar electrodes in a cylindrical glass tube exhibit characteristic luminous structures (figure 3) [4]. The brightest part of the discharge is the negative glow, which is separated from the cathode by the cathode dark space ('Crookes' or 'Hittorf dark space'). The cathode dark space is a region of the discharge where the electrical potential drops drastically (cathode fall). The negative glow is separated from the cathode dark space by a well defined boundary and it is followed by a diffuse region in the direction towards the anode. The negative glow, where the electric field is close to zero, and the positive column are separated by the 'Faraday dark space'. The homogenous or striated (standing or moving striations) positive column stretches all the way to the anode, which may be covered by a characteristic anode glow.

The variations of plasma parameters along the length of the discharge tube are shown schematically in figure 3. The microscopic processes in such a discharge can be described as follows. A positive ion from the negative glow is accelerated by the electric field in the cathode fall and directed towards the cathode surface. The collision of the energetic ion with the surface produces secondary electrons, which are subsequently accelerated in the cathode fall to comparatively high energies. These energetic electrons transfer most of their energy to heavy particles (atoms, molecules) in inelastic collisions (excitation, dissociation, and ionization, which also creates additional charge carriers), which occur primarily in the cathode fall and in the negative glow region. The cathode regions of the discharge play a crucial role in sustaining the glow discharge. The positive column is formed only in the presence of a long, narrow discharge gap with charge carrier losses to the wall. In the homogenous positive column, a constant longitudinal electrical field is maintained. The electrons gain energy in this field and form an electron energy distribution with an appreciable number of energetic electrons for the formation of a sufficiently large number of ions and electrons to balance the charge carrier losses to the wall.

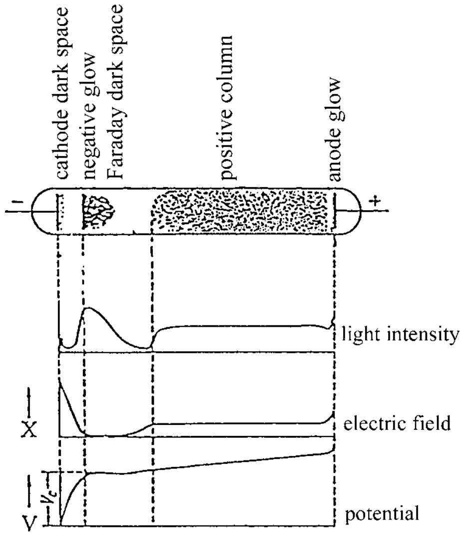

Figure 3. Variation of light intensity, electric field and electric potential along the length of a dc low-pressure glow discharge with plane electrodes, after [4].

An important process with technological applications, that occurs in the cathode region of the dc discharge, is the etching of the cathode material and the deposition of a thin film on a separate substrate by cathode sputtering [1]. This process is usually carried out at low pressure (10^{-1}–10 Pa) in order to avoid the re-deposition of the sputtered material on the cathode. If additional magnetic fields are present (magnetron), the efficiency of this process can be increased significantly. The Lorentz force causes a circular motion of the electrons e and ions i with the cyclotron frequency [1, 2]

$$\omega_{ce/i} = \frac{eB}{m_{e/i}} \tag{1}$$

where e, m_e, and m_i denote the charge and masses of the electrons and ions, and B refers to the magnetic field B. The radius of this motion is given by

$$r_c = \frac{m_e v}{eB} \tag{2}$$

where v is the velocity component perpendicular to B.

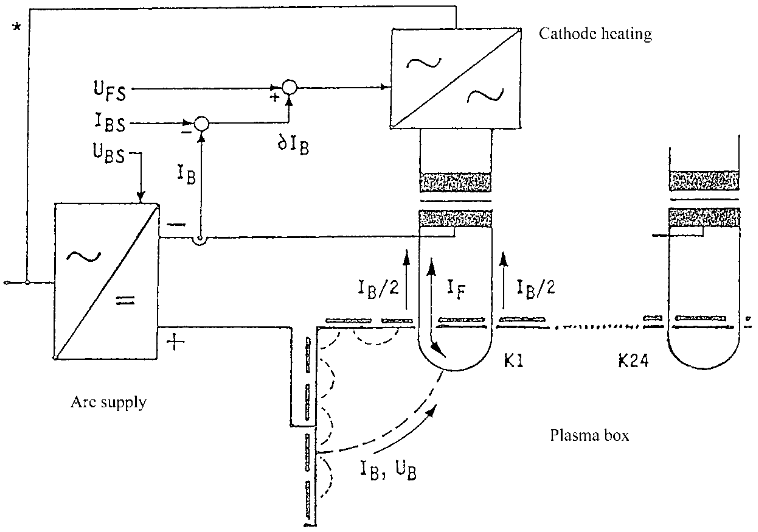

Figure 4. The bucket plasma source: K_n cathodes, I_B arc current, U_B arc voltage and I_F heating current of the cathode [5]. The magnetic field of the permanent magnets increases the pathway and hence the ionization efficiency of the electrons. A sketch of the plasma box and principal electric scheme.

A magnetic field perpendicular to the electric field increases the pathlength of the electrons and ensures a sufficiently high ionization rate [2]. The confinement of the secondary electrons by the magnetic field to a region near the cathode results in a high plasma density and an increased discharge current at relatively low discharge voltages.

If the planar cathode is replaced by a hollow cylinder with a diameter of nearly the length of the negative glow, the negative glow is observed inside the cathode cylinder. This results in a significant increase in the discharge current. The high efficiency of the so-called hollow cathode is due (i) to the 'pendulum electrons', which are trapped in the negative glow between the retarding cathode sheaths, and (ii) to additional electron emission caused by the impact of photons and metastables on the cathode surface. The cathode temperature increases with increasing discharge current. If this temperature is sufficiently high for thermionic electron emission, the glow discharge changes to an arc discharge characterized by a high current and a comparatively low voltage. Similar conditions are observed in discharges that use cathode materials with low work functions, such as oxide cathodes, or discharges with externally heated cathodes. Oxide cathodes are used, for example, in luminescent lamps.

The 'bucket source' [5] (figure 4) is an example of a plasma source with heated cathodes. A dense plasma is generated by using an array of low-voltage arcs with heated cathodes in conjunction with additional external magnetic fields. Such a source has been jointly developed by JET, ASDEX, and TEXTOR as an ion donor for an ion accelerator (100 A, 60 kV) in fusion research. The 'bucket source' is a large plasma source with cross-sectional area of 0.2×0.4 m^2 and consists of a 'bucket' made of copper, 24 insulated heated tungsten filaments, and a 'checker-board' of permanent magnets on the outside. The gas pressure is about 10^{-2} mbar. A voltage U_B is applied between the filaments and the bucket forcing a high dc arc current I_B to flow between the cathode filament and the bucket which acts as the anode. The ionization is sustained by the high current in conjunction with magnetic cusp-fields in the vicinity of the bucket walls produced by the checker-board magnets, which increases the pathlength of the electrons before they impinge on the wall. The result is a plasma that is characterized by a spatially very flat ion distribution up to the walls of the bucket. Electron temperatures and densities reach values that are typical for arcs: $T \sim 5$ eV and $N \sim 10^{12}$ particles per cm^3. In the most recent variant of this source, the arc filaments are replaced by rf antennae feeding 13 MHz power to the bucket in order to sustain the arc current. The plasma parameters are close to those of 'filament sources'. Although this kind of source has only been used in nuclear fusion devices up to now, such sources have the potential to be used in the etching of large lateral structures because of the abundance of low-energy ions in such a source.

1.2. Pulsed dc discharges

In addition to the continuous dc discharge, pulsed dc discharges are also used in plasma-technological applications. Pulsed sources have the following advantages:

- operation at higher power;
- additional performance control by a variable duty cycle of active plasma regime and plasma afterglow;
- while variations in the neutral gas composition between the plasma boundary and the plasma centre (due to plasma chemical reactions) may cause, for example, inhomogeneous thin film deposition in a continuous dc plasma, pulsed operation in conjunction with rapid gas exchange between pulses can prevent or minimize such effects.

The plasma focus [6] is a special type of a high-power pulsed plasma. Figure 5 shows a schematic diagram of such a device. The device consists of two coaxial electrodes separated by a hat-shaped insulator at one end, while the other end is open. The space between the electrodes is filled with the feed gas. A capacitor bank C is charged via the resistor R_1 when the switch S is open. The resistor R_2

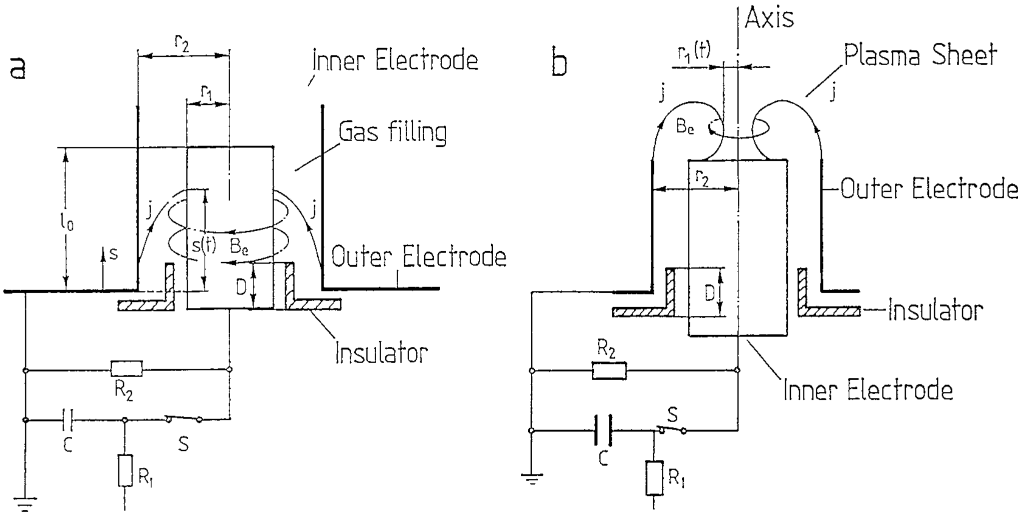

Figure 5. Schematic drawing of the plasma focus formation during run down (a) and the pinching period (b). Shown are a cross section of the cylindrical inner and outer electrodes, the hat shaped insulator, the plasma sheath j with the magnetic field lines B_e and the principle electric scheme [6].

facilitates easy ignition of the plasma when the switch S is closed. An umbrella-like plasma is formed as shown in figure 5(a). In the early stage of the formation of the plasma focus, a plasma sheath is formed as shown in figure 5(b). The dense plasma focus is a result of an $m = 0$ plasma instability, which is driven by an azimuthal magnetic field. This field increases as the current is forced to flow through an increasingly smaller annular plasma structure. There is a one-to-one correspondence between the maximum current that can be achieved and the power density in the final plasma state. This final state is called the plasma focus. A coaxial line is used as an inductive storage device for the capacitor bank which is discharged in order to deliver the required high current. During the early stage, the plasma acts as a short circuit between the conductors. Subsequently, it is pushed to the open end of the line by the magnetic field of the discharge current. The travel time of the plasma has to equal one quarter of the time it takes to discharge the capacitor. Thus, the $m = 0$ plasma instability can start at the maximum value of the current for a given circuit configuration. The high power density in the plasma focus causes the resistivity to increase by more than a factor of 100 due to electrostatic fluctuations. The inductively stored energy is coupled to the plasma very effectively. Ion and electron beams are generated by the plasma focus which exceed power densities of TW cm^{-2}. The nuclei of light ions fuse and a rich spectrum of electromagnetic radiation is emitted. Applications of the plasma focus range from pulsed neutron sources for on-line analysis of volatile components in coal to radiation sources for lithography and microscopy in the range of soft x-rays.

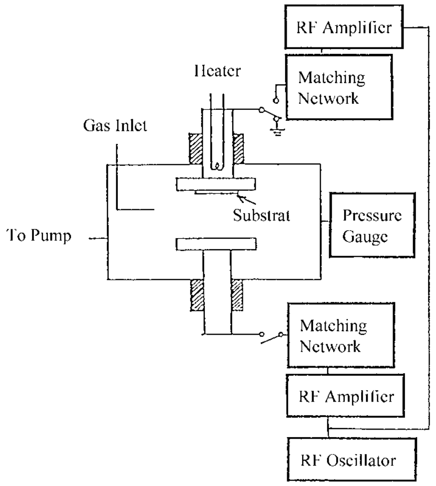

Figure 6. Schematic drawing of a deposition apparatus with a capacitively coupled rf discharge. The rf power is transmitted to the electrodes by a matching network. The substrat can be on the powered or grounded electrode, after [11].

1.3. Rf and microwave discharges

Discharges excited and sustained by high-frequency electromagnetic fields are of increasing interest for technical and industrial applications. The power absorption [1, 2, 7] P_{abs} per volume V by a plasma in a high-frequency field is given by

$$\frac{P_{abs}}{V} = \frac{1}{2} n_e \frac{e^2}{m_e \nu} \frac{\nu^2}{\nu^2 + \omega^2} E_0^2 \tag{3}$$

where n_e is the electron density, e and m_e are the electron charge and mass, ν is the electron–neutral collision frequency, and ω refers to the angular frequency of the electromagnetic field whose amplitude is E_0. In the presence of a magnetic field B perpendicular to the electric field, the power absorption changes to

$$\frac{P_{abs}}{V} = \frac{1}{4} \frac{e^2}{m\nu} \left(\frac{\nu^2}{\nu^2 + (\omega - \omega_c)^2} + \frac{\nu^2}{\nu^2 + (\omega + \omega_c)^2} \right) E_0^2 \tag{4}$$

where ω_c denotes the electron cyclotron frequency. Electromagnetic waves with frequencies below the electron

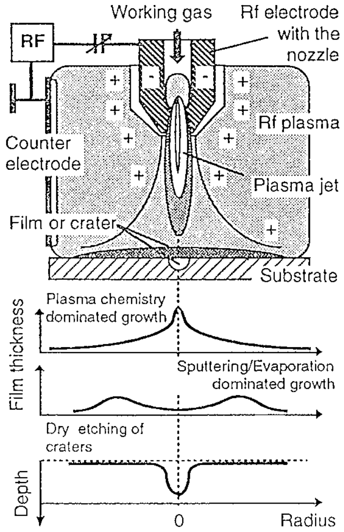

Figure 7. Schematic representation of the rf plasma jet system for plasma processing. The actual process depends on the working gas mixture and system parameters. The powered rf electrode with the nozzle is negatively charged because of the self-bias. In the lower part of the figure are presented examples of deposition and etch profiles. Plasma chemistry dominated deposition and etching is maximum in the centre because of the highest concentration of radicals in this part of the plasma. The source of the sputtered/evaporated material is the nozzle [15].

plasma frequency

$$\omega_e = \left(\frac{e_0^2 n_e}{\varepsilon_0 m_e}\right)^{1/2} \tag{5}$$

(here ε_0 denotes the permittivity of vacuum) will be reflected. Therefore, the electron density corresponding to the electron plasma frequency is called the cut-off density. However, the skin effect enables the penetration of the wave into the plasma to some extent. The power absorption is limited to the dimension of the skin sheath of thickness δ_s. For $\nu \gg \omega$ the skin depth is given by [8]

$$\delta_s = \sqrt{2}c\left(\frac{\varepsilon_0 m_e \nu}{e^2 n_e \omega}\right)^{1/2}. \tag{6}$$

In a non-thermal plasma with $n_e = 10^{10}$ cm^{-3} and $\nu = 10^9$ s^{-1} the above relation yields a skin depth of 0.25 m and 0.02 m, respectively, for frequencies of 13.56 MHz and 2.45 GHz.

Rf discharges usually operate in the frequency range $f = \omega/2\pi \simeq 1$–100 MHz. The corresponding wavelengths ($\lambda = 300$–3 m) are large compared to the dimensions of the plasma reactor. For microwaves the most commonly used wavelength is 12.24 cm, corresponding to a frequency of 2.45 GHz. This wavelength is roughly comparable to the dimensions of a typical microwave reactor. For lower frequencies, the ions accelerated in the field move towards the electrodes and produce secondary electrons, similar to what happens in a dc discharge. As the frequency increases, the ions and subsequently also the electrons can no longer reach the electrode surface during the acceleration phase of the exciting external field.

The power coupling in rf discharges can be accomplished in different ways, as:

- capacitively coupled discharges, 'E' discharges;
- inductively coupled discharges, 'H' discharges [9].

1.3.1. Capacitively coupled discharge. The vessel of a capacitively coupled discharge [8–13] may have interior circular disc-shaped parallel electrodes which are separated by a distance of a few centimetres. They may be in contact with the discharge or they be insulated from it by a dielectric. In the case of insulating chamber walls, outer electrodes, i.e. electrodes on the outside of the vessel, are sometimes used. Gas pressures are typically in the range 1–10^3 Pa. A conventional rf system for sustaining a discharge consists of a generator, usually combined with an impedance matching network, and the reactor with the electrodes. The generator type has to be licensed in terms of the frequency band for commercial use. A matching network is necessary to match the impedance of the generator to that of the discharge. In this case, the power transfer from the generator to the discharge is at peak efficiency and the reflected rf power is minimized (figure 6) [11]. The electrodes in the rf discharge are covered by sheath regions, which are similar to the cathode dark space in a dc glow discharge. The space between the electrodes is filled with the bulk plasma. For moderate pressures, capacitively coupled rf discharges exist in two forms, the α and the γ mode [12, 13]. The α mode is characterized by lower currents and a positive voltage–current characteristic, whereas the γ mode corresponds to higher currents and a partially negative V–I characteristic. The sheath regions in front of the electrodes are quite different in the two modes. Electrical conductivity and charge carrier concentration in the α sheath are very small in contrast to the γ sheath. The α discharge shows a weak luminous region in the centre of the gap between the electrodes with maximum glow intensity near the electrodes. In the γ mode, the emission is generally much more intense. The 'positive column' at the gap centre is separated from the bright 'negative glows' by 'Faraday dark spaces'. Rf discharges at intermediate pressures are used, for example, in CO_2 lasers. The denotations α and γ modes are caused by the Townsend's first ionization coefficient α for the avalanching of charge carriers in the volume and the γ coefficient for the releasing of secondary electrons from a target surface by incident positive ions, respectively.

The so-called 'self-bias' is a characteristic feature of this type of plasma. The 'self-bias' is a negative dc potential that develops between the plasma and the powered electrode as a consequence of (i) the use of a coupling capacitor between the rf generator and the powered electrode and (ii) the use of appropriately shaped areas of the (smaller) powered electrode and the (larger) grounded electrode. This feature can assume that the currents from the plasma to both electrodes must be equal. The higher current density at the small electrode demands a higher voltage between the plasma and electrode. In other plasma devices, the application of an additional rf bias to the sample holder produces a self-bias with higher ion energies.

In a capacitively coupled rf discharge, the electron density is in the range $n_e = 10^9$–10^{10} cm^{-3} and densities of up to 10^{11} cm^{-3} are possible at higher frequencies [14]. The ion energy near the powered electrode can reach energies of a few hundred electron-volts due to the self-bias. Such

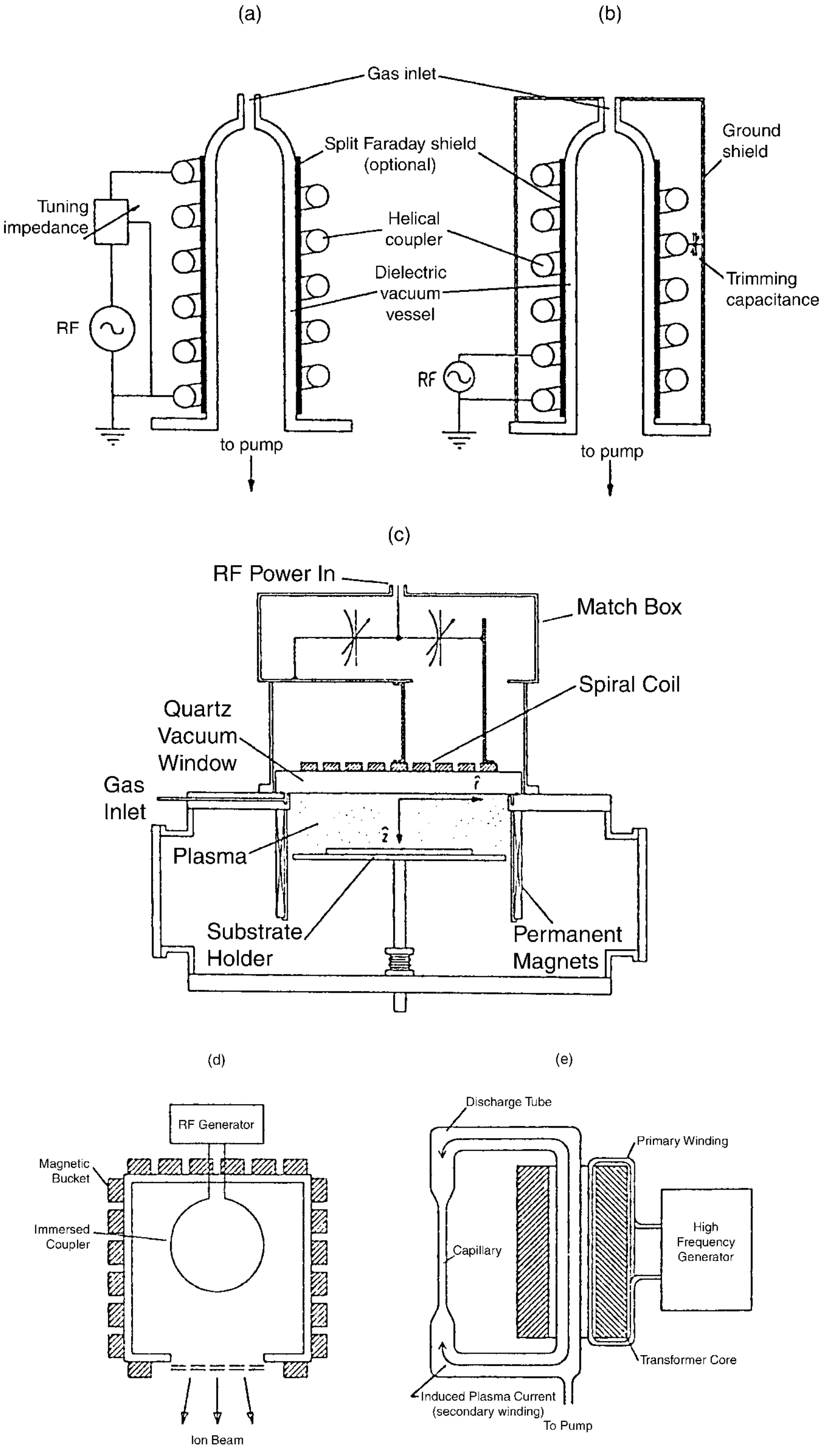

Figure 8. Diagrams of various ICP reactors: helical coupler (a), helical resonator (b), spiral coupler (c), immersed coupler (d), and transformer-coupled plasma (e). The Faraday shield in devices (a) and (b) avoids capacitively coupling from the coil to the plasma. The permanent magnets (c) and (d) confine the plasma, enhance the uniformity, and increase the plasma density [16].

discharges are successfully applied to thin-film deposition and plasma etching as well as to the sputtering of insulating materials.

A hollow cathode effect can also be observed for rf discharges and can be used for the design of plasma reactors. Such a scheme has been used in a supersonic rf plasma jet, which was successfully tested in thin-film deposition and etching experiments (figure 7) [15].

1.3.2. Inductively coupled discharge.

An inductively coupled plasma (ICP) [8, 9, 16] is excited by an electric field generated by a transformer from a rf current in a conductor. The changing magnetic field of this conductor induces an electric field in which the plasma electrons are accelerated. Various ICP reactors are shown in figure 8. The current-carrying coil or wire can either be outside or inside the plasma volume. The coil is formed as a helix (figures 8(a) and (b))

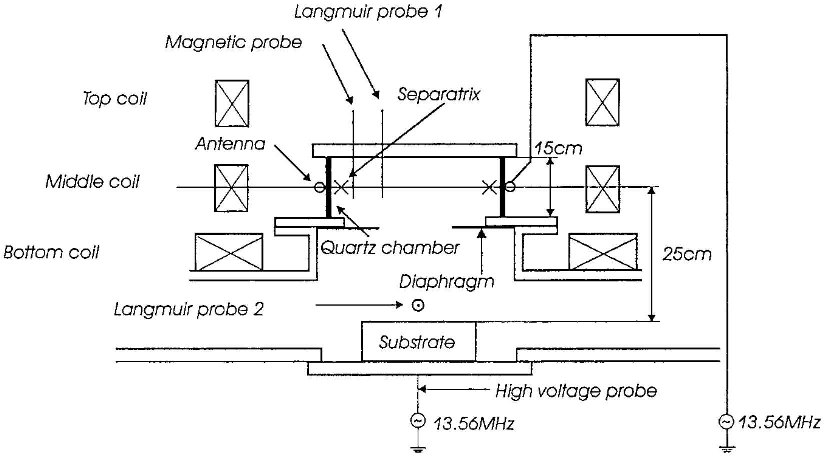

Figure 9. NLD plasma source, after [17]. The top and bottom coil generate a magnetic field configuration with the neutral loop (separatrix) with vanishing magnetic field. The middle coil determines the radius of the neutral loop. The rf power (13.56 MHz) is applied to a one-turn antenna coil for plasma excitation.

or as a spiral (figure 8(c)). It is also possible to use a ring-shaped plasma volume as a single-turn secondary winding of a transformer (figure 8(e)). The effect of the electric field of the wire can be shielded resulting in a suppression of capacitive coupling. The neutral loop discharge (NLD) source, which was developed for plasma processing of large wafers for the production of microelectronics [17], is an interesting variant of the ICP source technology for low processing pressures (~0.1 Pa). A neutral magnetic loop is generated by a set of coils as indicated in figure 9. If the upper coil and the lower coil had a balanced current and the same windings, the neutral loop would be positioned exactly at the location of the middle coil. The magnetic field of the middle coil, however, squeezes the neutral line inward. As the current increases, the diameter of the neutral loop gets smaller (separatrix). Free electrons undergo a periodic oscillation in the electric field, when the magnetic field is turned off. An additional force is added in the presence of the magnetic separatrix

$$m_e \frac{\mathrm{d}^2 s}{\mathrm{d}t} = e\left[E + \left(\frac{\mathrm{d}s}{\mathrm{d}t}\right) \times B\right] \qquad (7)$$

and becomes significant when $\nabla B \neq 0$. The periodically oscillating trajectory of the free electrons in the rf field starts to meander. This results in a significant energy gain in the vicinity of the separatrix, which has the largest magnetic field gradient in all directions except for the direction tangential to the separatrix circle. The gain in energy is substantial. It was reported [17] that the etch rate of a NLD source can be three times higher than that of a conventional ICP source under otherwise identical conditions in the low-pressure regime. The gain in electron energy by the NLD source enables the production of species that are three times more etch active. As the dimensions of the etched structures become smaller, fast electrons and associated VUV radiation are becoming increasingly undesirable. Since the radius of the separatrix can be varied by the current in the centre coil, the line-of-sight between the separatrix and the substrate can be blocked by a diaphragm, if the radius of the vacuum vessel is not too small. Such a diaphragm is shown schematically in figure 9.

ICPs can achieve high electron densities ($n_e = 10^{12}$ cm^{-3}) at low ion energies. Several applications are reported such as thin-film deposition, plasma etching, and ion sources in mass spectrometric analysis [18].

The helicon discharge is a special type of the inductively coupled discharge [14, 19]. The plasma is usually generated in a cylindrical vacuum vessel in a longitudinal homogeneous magnetic field at 100–300 G [14] or higher [20]. The electromagnetic energy is transferred to the plasma source with frequencies between 1 and 50 MHz, usually with 13.56 MHz for processing plasmas [8]. Helicon waves are generated in the plasma column by specially-shaped antennas. The damping of this wave can be explained by collisional theory alone [20], but collisionless (Landau) damping of helicon waves has also been discussed [8]. This type of discharge achieves electron densities of up to 10^{12}–10^{13} cm^{-3} in the 0.1 Pa pressure range. A schematic diagram of an experimental apparatus is shown in figure 10 together with experimental results for the plasma density and the electron temperature [20]. The high efficiency of the helicon discharge ($B = 800$ G, figure 10(a)) in comparison with the ICP source ($B = 0$, figure 10(b)) is obvious. Several antenna constructions [21] and a schematic diagram of a technical reactor [22] are presented in figures 11 and 12.

1.4. Microwave discharges

Plasma generation using microwaves is widely employed in many applications [7, 23–28]. Characteristic features of microwaves are the wavelength, which is comparable to the dimensions of the plasma apparatus (2.45 GHz: $\lambda = 12.24$ cm), and the short period of the exciting microwave field. The amplitude of the oscillations of the electrons in the microwave field is very small. For an excitation frequency $f = 2.45$ GHz and an amplitude $E_0 = 500$ V cm^{-1} it is 3.5×10^{-3} cm. The power absorption (equation (3)) depends on the electron–neutral collision frequency, i.e. on the gas pressure and the gas composition. The absorption efficiency in a 2.45 GHz discharge is high for He in the region between 10^3 and 10^4 Pa, whereas the maximum efficiency for Ar is reached for 200 Pa. However, microwave discharges can

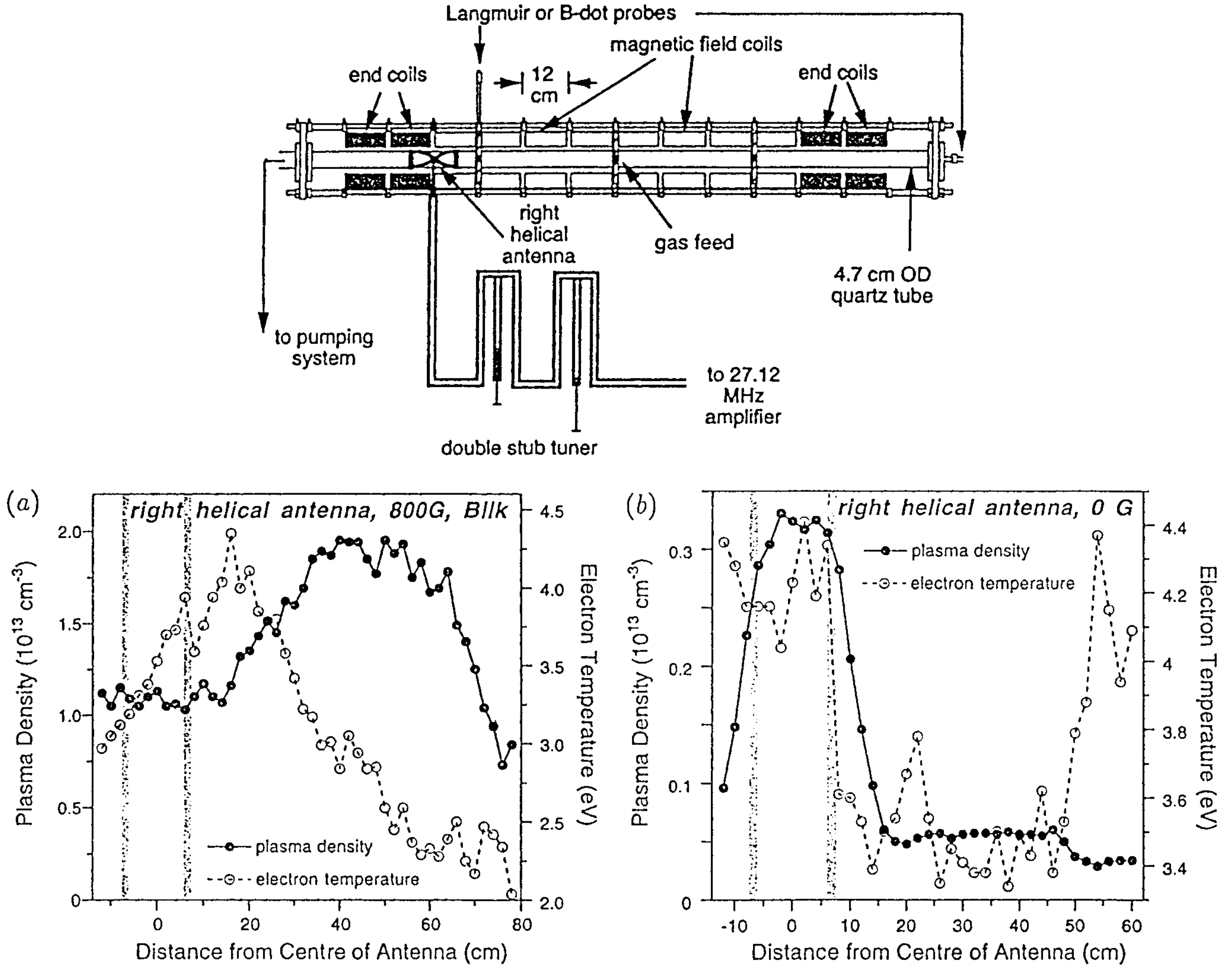

Figure 10. Helicon discharge apparatus with right-hand helical antenna and a quartz tube (length 1.6 m, diameter 5 cm) with the magnetic coils. Experimental results of electron temperature and plasma density as a function of distance from the antenna (shaded lines) for a 800 G helicon discharge (a) and a 0 G inductively coupled (ICP) discharge (b) in Ar, 15 mTorr. The electron density in the helicon discharge is considerably higher than in the ICP discharge [20].

be operated at higher pressures as well, even at atmospheric pressure. The corresponding cut-off density of the electrons (equation (5)) at 2.45 GHz is about 10^{11} cm^{-3}. Waves of this frequency can penetrate into plasmas with higher densities only up to the thickness of the skin sheath (equation (6)), which equals a few centimetres under these conditions. The microwave power absorption inside the skin sheath transfers energy into the plasma via waves with a frequency below the cut-off frequency. A microwave plasma reactor consists in principle of a microwave power supply, a circulator, the applicator, and the plasma load. The transmission lines are rectangular waveguides or, at lower powers, coaxial cables. The applicator should optimize the energy transfer into the plasma and minimize the power reflection. The circulator protects the power supply from reflected power.

Various types of microwave reactors have been described. Marec and Leprince [24] distinguished three types: discharges produced in closed structures, in open structures, and in resonance structures with a magnetic field. In closed structures, the plasma chamber is surrounded by metallic walls. Resonant cavities of high quality with their high electric field allow an easy ignition of discharges, even at higher pressures. Examples for discharges in open structures are microwave torches, slow wave structures, and surfatrons. Electron cyclotron resonance (ECR) plasmas are a typical example of a microwave plasma in magnetic fields. Methods for the coupling of waveguides to discharge tubes are presented in figure 13 [25]. Figure 13(a) presents a closed configuration. The discharge tube is located at the point of maximum electric field, the distance between tube and stubs is $\lambda/4$. The slow wave structure is an open-type configuration which is shown in figure 13(b). This principle can also be used for the excitation of rf plasmas. The excitation of surface waves [24] is another way of generating plasmas by microwaves. The essential elements of a surface-wave plasma source are shown in figure 14. The surface wave propagates along the boundary between the plasma column and the dielectric vessel. The wave energy is absorbed by the plasma. A technical application of this type of plasma excitation is realized in a surfatron.

The slot antenna (SLAN) plasma source [7] transfers the microwave energy from a ring cavity through equidistantly positioned resonant coupling slots into the plasma chamber which is made of quartz (figure 15). As a plasma of

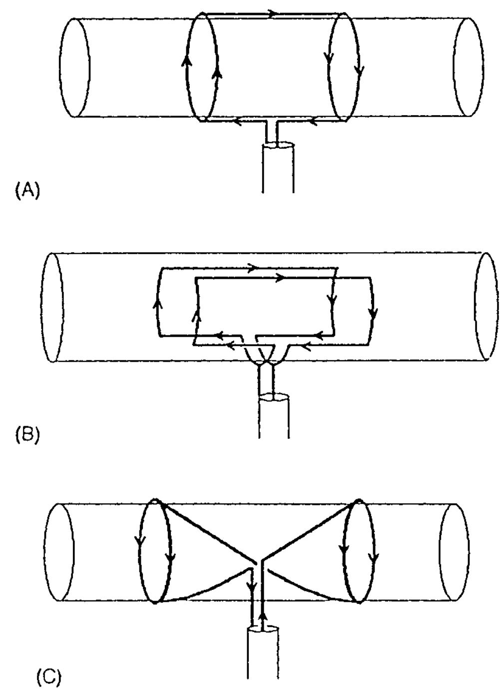

Figure 11. Antennae for helicon discharges. Half-wavelength, $m = 1$ antenna configurations: Nagoya type III (A), Boswell type (B), Shoji (helical) type (C) [21].

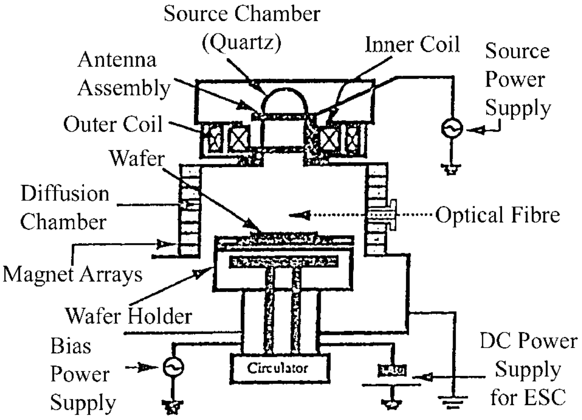

Figure 12. Schematic diagram of $m = 0$ helicon plasma experimental apparatus for SiO_2 etching. The magnetic coils generate the magnetic field for the helicon wave to propagate in the plasma. The magnet arrays on the wall of the diffusion chamber prevent plasma losses at the wall, after [22].

high conductivity, this configuration can be treated as a coaxial waveguide with standing waves. For lower conductivity (caused by lower power), travelling wave modes can be observed. Large volume plasmas with electron concentrations of up to 10^{12} cm^{-3} in broad pressure ranges can be created based on this principle.

Large-area planar microwave plasmas can be generated by coupling the microwave field from a rectangular waveguide into the plasma volume [26, 27]. This scheme and a sketch of the microwave applicator are presented in figure 16. It consists of two waveguides. The first one is connected to the microwave power source and closed by a matched load. The second one is connected to matched loads on both ends. Travelling waves exist in this interface waveguide only. Microwave energy is coupled from one waveguide to the other using discrete, adjustable coupling elements distributed along the waveguides. The plasma which is separated from the second waveguide by a quartz window acts as the fourth wall for this waveguide. An adjustment of the coupling elements creates a homogeneous planar plasma. Plasmas with a length of 1.2 m have been produced. The generation of a planar plasma of 30 × 30 cm^2 was possible by using an array of such waveguide arrangements. Substrate surfaces are modified either in the active plasma zone or in the remote plasma outside of the active zone depending on the position of the sample holder.

The ignition of microwave discharges in the low-pressure regime with a low collision frequency and thus low power absorption can be aided by a magnetic field B where the electrons rotate with the electron cyclotron frequency ω_c in a magnetic field (equation (1)). If the cyclotron frequency equals the microwave frequency, the power absorption reaches a maximum (equation (4)). For a magnetic field of

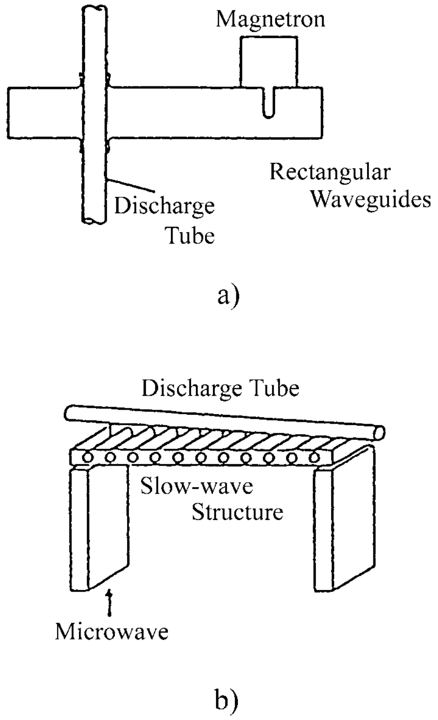

Figure 13. Methods of coupling of microwaves to discharge tubes for generation of microwave discharges: coupling with a rectangular waveguide (a) and by a slow wave structure (b), after [25].

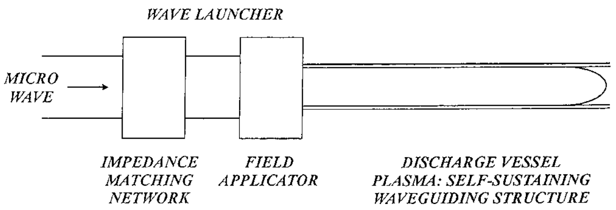

Figure 14. Elements of a surface-wave plasma source, after [24]. The surface wave propagates on the plasma surface in the dielectric discharge tube.

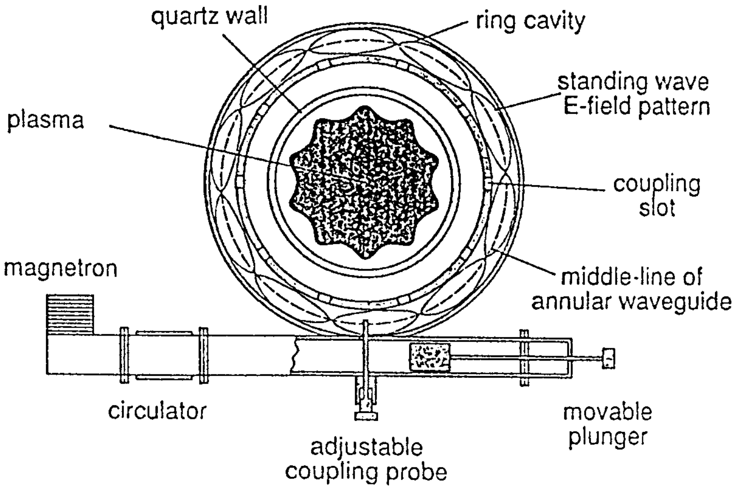

Figure 15. Microwave applicator of the SLAN plasma source. The resonant annular cavity enables a homogenous microwave power distribution, the microwave power is radiated by slot antennas into the application space with the plasma [7].

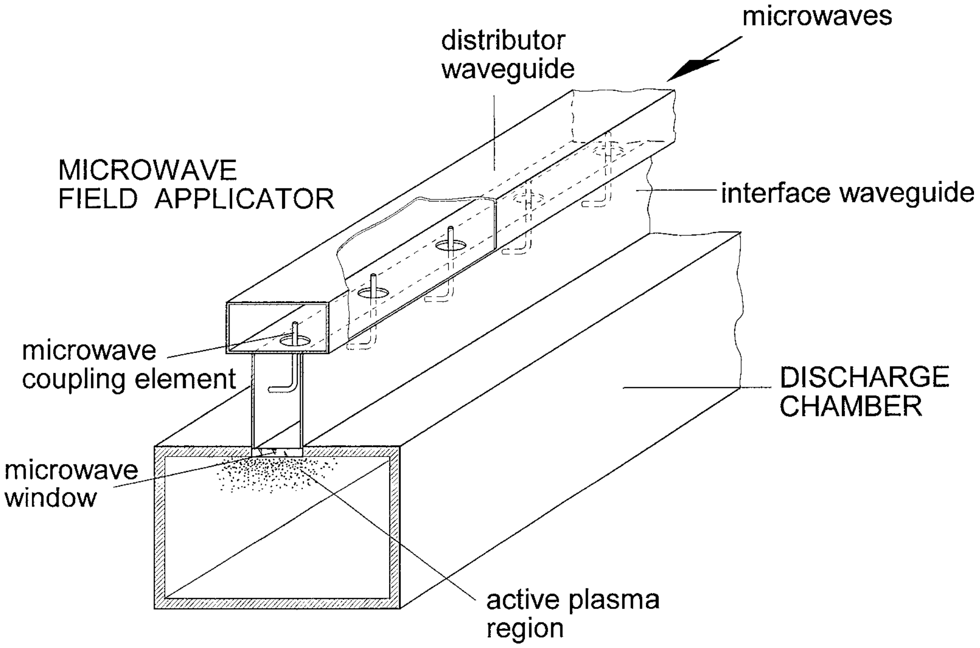

Figure 16. Scheme of a planar microwave plasma source with a modified slotted waveguide microwave field applicator consisting of two rectangular waveguides in a T-shaped configuration, after [26].

875 G, the electron cyclotron frequency becomes 2.45 GHz and the rotational movement of the electrons is in resonance with the microwaves of 2.45 GHz. The mean free path of the electrons between collisions should be larger than the radius r_c (equation (2)).

Figure 17 [28] shows an example of an ECR plasma source. The plasma is excited in the upper part of the apparatus and the magnetic field is generated by the magnetic coils. The remote plasma generated in this device can be used for thin-film deposition applications. ECR plasma sources work in the pressure range 1 to 10^{-3} Pa [2]. Typical values of electron temperatures and ion energies at the substrate are near 5 eV and between 10 and 25 eV, respectively [1]. In such plasmas, collisions between the atoms, molecules, and ions are reduced and the generation of particles in the plasma volume (dusty plasmas) is avoided.

1.5. Dielectric barrier discharges

The silent or dielectric barrier discharge [29, 30] which operates at higher pressures (0.1–10 bar) is a special type of ac or rf discharge. In 1857, Siemens [31] used this type of discharge for the generation of ozone from air or oxygen. Today, these silent discharge ozonizers are effective tools and a large number of ozone installations are being used worldwide for water treatment. The silent discharge is generated between two electrodes with a dielectric barrier in between (figure 18). The gas-filled gap is small (typically a few millinetres). A voltage of 1–100 kV with frequencies of 50 Hz–1 MHz is necessary to sustain these discharges. The streamer breakdown mechanism leads to the formation of a large number of filaments (diameter $\sim$0.1 mm). The current is limited by the dielectric materials between the

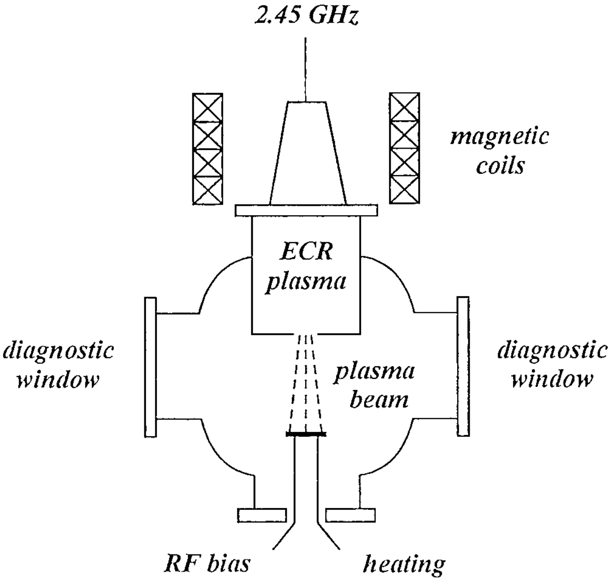

Figure 17. Scheme of a ECR plasma source for thin-film deposition [28].

electrodes. The charge carriers streaming from the plasma to the dielectric remain on the surface of the dielectric and compensate the external electric field. Therefore, the lifetime of the filaments is very short (1–10 ns). The current density in the filaments is 100–1000 A cm^{-2}, the electron density is 10^{14}–10^{15} cm^{-3}, and typical electron energies are in the range 1–10 eV. This non-thermal plasma is also used to pump CO_2 lasers and to generate excimer radiation in the UV and VUV spectral regions. Other applications include the production of methanol from methane/oxygen mixtures, various thin-film deposition processes [32, 33], and the remediation of exhaust gases. These discharges are also being used for plasma displays. The advantage of the dielectric barrier discharge over other discharges is the option to work with a non-thermal plasma at atmospheric pressure and the comparatively straightforward scale-up to larger dimensions.

2. Plasma production using beams

Plasma generation using beams is most frequently accomplished by the use of electron beams and laser beams. A beam-produced plasma discharge [34] is sustained, for example, by the interaction of an electron beam with a gaseous medium. Collective effects produce turbulent plasma oscillations with high amplitudes. The heating of the plasma electrons in this turbulent field is sufficient to sustain the beam-produced discharge plasma. The energy transfer is very effective as up to 70% of the beam energy can be transferred to the plasma. It is possible to create plasmas with high degrees of ionization in low-pressure environments. The plasma properties may be controlled by the electron beam current, the acceleration voltage, the gas pressure, and by the shape of the beam. Electron-beam generated plasmas are being used for large-area material processing [35]. A spatially flat plasma with a processing area of about 1 m^2 and a thickness of about 1 cm is sustained by an electron beam confined by a magnetic field of 100–200 G. The beam source is a hollow cathode discharge. For process gas pressures between 1 and 100 Pa, plasmas with electron densities up to 10^{12} cm^{-3} and electron temperatures of about 1 eV can be obtained.

The interaction of laser beams with matter has many facets that cannot be discussed in detail here. As the electric field near a given surface or in a given gas exceeds a particular value, molecules and atoms begin to lose electrons and a plasma can be generated. The required power and duration of the laser irradiation strongly depends on the specific application. Two examples are discussed further. The cutting of Al or Cu by dc plasmas results in unwanted seams, because too much energy is deposited in the liquid phase of the material. A short, intensive laser pulse ignites a plasma in air. Hence the power transfer from the laser to the metal is hindered. Only special conditions regarding the wavelength, the power, and the pulse shape achieve adequate power coupling to the metal and a sufficiently high power density in the cutting groove to vaporize the molten material [36].

The remote chemical analysis of solids requires a first laser pulse to vaporize the material and a second laser pulse of different wavelength and power to excite a particular atomic or molecular states in the resulting cloud for the actual analysis. Examples for the application of such an analysis procedure are rapidly moving goods, hazardous materials, or melts at high temperatures.

3. Comparison of various plasma excitation mechanisms

Each of the various plasma sources discussed above has its own peculiarities, advantages, and disadvantages. The choice of the proper source for the specific task requires the study of the characteristics of the various plasmas. We can only give a brief summary of the various plasma sources. The dc discharge has the advantage that the microscopic processes are rather well known and understood and that such plasmas can be diagnosed in great detail. Interior electrodes are required and the possibility of reactions with reactive and corrosive gases must be considered in certain applications. The ion energy at the cathode is usually comparatively high. Power sources are well developed and widely available. By contrast, rf discharges can operate with insulated or external electrodes, i.e. they are electrode-less. Therefore, reactive processes with metal electrodes can be avoided. The lifetime of devices with electrode-less rf discharges is long. Rf sources can be operated over a wide range of pressures. Low gas pressure is possible in discharges using magnetic fields (helicon discharges). The ion energy can be controlled over a wide range. The microscopic processes in rf discharges are rather complex. Diagnostics tools are well developed, but sometimes difficult to use due to interference by the rf sustaining voltage. Microwave discharges also operate without electrodes. Plasmas of high density can be generated in the pressure range from 10 Pa up to atmospheric pressures. The plasma excitation at very low pressures (less 1 Pa) is effective in microwave-excited and magnetic-field-supported ECR discharges. The ion energy in the microwave plasma is generally low and can be controlled by additional dc fields or

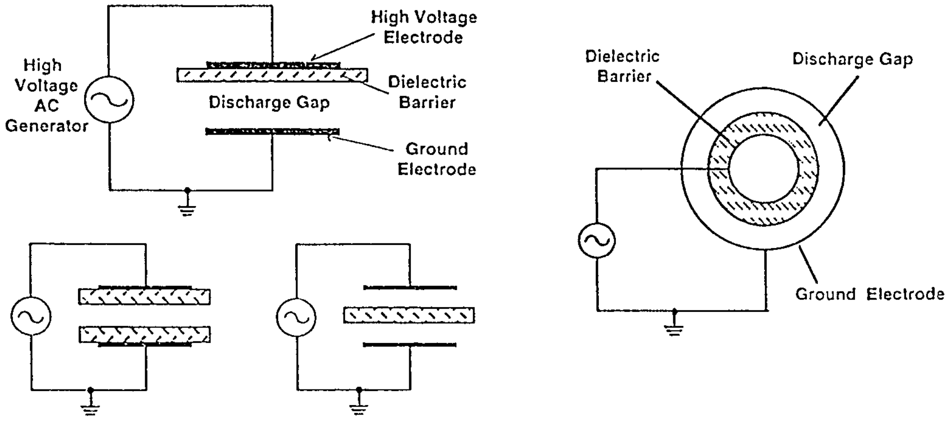

Figure 18. Common dielectric barrier discharge configurations with one or two dielectric barriers [30].

Table 3. Plasma sources and their parameters.

Physics	Pressure (mbar)	n_e (cm^{-3})	T_e (eV)	Bias	Application
Dc glow	10^{-3}–100				
cathode region			100	Yes	Sputtering, deposition, surface elementary
negative glow		10^{12}	0.1	No	Chemistry, radiation
positive column		10^{11}	1–10	No	Radiation
hollow cathode	10^{-2}–800	10^{12}	0.1	No	Radiation, chemistry
magnetron	10^{-3}			Yes	Sputtering
Arc, hot cathode					
external heating low voltage	1	10^{11}	0.1	No	Radiation
internal heating	1000	10^{13}	0.1	No	Radiation welding
Focus	10		keV		Radiation
Rf capacitive					
low pressure	10^{-3}–10^{-1}	10^{11}	1–10	Yes	Processing, sputtering
moderate pressure	10^{-1}–10	10^{11}	1–10	No	Processing, deposition
hollow cathode	1	10^{12}	0.1	No	Processing, radiation
magnetron	10^{-3}			Yes	Sputtering
Rf inductive	10^{-3}–10	10^{12}	1	No	Processing, etching
helicon	10^{-4}–10^{-2}	10^{13}	1	No	Processing
MW					
closed structure	1000	10^{12}	3	No	Chemistry
SLAN	1000	10^{11}	5	No	Processing
open structure					
surfatron	1000	10^{12}	5	No	Processing
planar	100	10^{11}	2	No	Processing
ECR	10^{-3}	10^{12}	5	No	Processing
Electron beam					
BPD	10^{-2}–1	10^{12}	1	No	Processing
Dielectric barrier discharge	1000	10^{14}	5	No	Ozone, processing chemisry

an rf bias voltage. Suitable power supplies are readily available. Plasma generation in the low-pressure range (<100 Pa) by electron beams involves more or less complicated beam sources. The shape of the plasma may by controlled by the shape of the exciting beam. The dielectric barrier discharge operates at or near atmospheric pressure. The plasma that is produced is highly non-thermal. Various applications in the area of surface treatment, cleaning, and modification are feasible, because no vacuum environment is required.

Plasma sources are usually operated with static electric or alternating electromagnetic fields. An additional static magnetic field performs two tasks. Firstly, the plasma confinement is enhanced by limiting the diffusion of charged particles perpendicular to the magnetic field. Secondly, the power absorption is enhanced by increasing the electron–neutral collision rate due to the longer trajectories of the electrons in the plasma at low pressures. The magnetic fields also open new absorption channels, caused by, for example, ECR resonances or helicon waves. The installation of static magnetic fields can be cheap, if permanent magnets are used.

4. Summary

The generation and maintenance of a plasma is one of the main challenges in plasma technology. Plasma parameters, such as densities, temperatures, potentials, chemical composition, flows, pulse shaping, the position relative to the target, and additional bias potentials, etc, have to be designed specifically for a given application. The choice of the plasma source and its particular design depend on the specific requirements of each application. In this paper, we discussed only a small selection of plasma sources. Table 3 lists some of the sources along with their parameters and their possible applications. These sources cover a wide range of plasma parameters and linear dimensions because most of the plasma sources are not scaleable over a large range of parameters, i.e. there are no simple, known formulae according to which power densities, homogeneity of the plasma parameters, or linear dimensions etc can be predicted for sources not yet built and diagnosed. Furthermore, the state of maturity of the various plasma sources discussed in this paper is quite different from source to source. Many opportunities remain for further research and development of plasma sources in order to meet the demands of the various diverse plasma technological applications.

Acknowledgments

Helpful discussions with K Becker, Stevens Institute of Technology, Hoboken, NJ, and our colleagues R Foest and L Mechold are gratefully acknowledged.

References

[1] Grill A 1994 *Cold Plasma in Material Fabrication, From Fundamental to Applications* (New York: IEEE Press)

[2] Rossnagel S M, Cuomo J J and Westwood W D (eds) 1990 *Handbook of Plasma Processing Technology* (Park Ridge: Noyes)

[3] Rutscher A and Deutsch H (eds) 1983 *Wissensspeicher Plasmatechnik* (Leipzig: Fachbuchverlag)

[4] Francis G 1956 The glow discharge at low pressure *Handbuch der Physik* vol VVII, ed S Flügge (Berlin: Springer)

[5] Conrads H, Euringer H and Schwarz U 1994 *Contributions to High Temperature Plasma Physics* ed K H Spatschek (Berlin: Akademie)

[6] Bernard A, Cloth P, Conrads H, Coudeville A, Gourlan G, Jolas A, Maisonnier C and Rager J P 1977 *Nucl. Instrum. Methods* **145** 191

[7] Korzec D, Werner F, Winter R and Engemann J 1996 *Plasma Sources Sci. Technol.* **5** 216

[8] Lieberman M and Lichtenberg A 1994 *Principles of Plasma Discharges and Materials Processing* (New York: Wiley)

[9] Lister G G 1992 *J. Phys. D: Appl. Phys.* **25** 1649

[10] Hollahan J R and Bell A T 1974 *Techniques and Applications of Plasma Chemistry* (New York: Wiley)

[11] Hirose M 1986 Plasma-deposited films: kinetics of formation, composition, and microstructure *Plasma Deposited Films* ed J Mort and F Jansen (Boca Raton, FL: Chemical Rubber Company)

[12] Raizer Yu P 1991 *Gas Discharge Physics* (Berlin: Springer)

[13] Raizer Yu P, Shneider M N and Yatsenko N A 1995 *Radio-Frequency Capacitive Discharges* (Boca Raton, FL: Chemical Rubber Company)

[14] Popov O (ed) 1995 *High Density Plasma Sources* (Park Ridge: Noyes)

[15] Bardos L 1993 *Proc. XXI. Int. Conf. Phen. Ion. Gases* vol 3, p 98

[16] Hopwood J 1992 *Plasma Sources Sci. Technol.* **1** 109

[17] Tsuboi H, Itoh M, Tanabe M, Hayashi T and Uchida T 1995 *Japan. J. Appl. Phys.* **34** 2476

[18] Holland G and Eaton A N (eds) 1991 *Applications of Plasma Source Mass Spectrometry* (Cambridge: Royal Society of Chemistry)

[19] Boswell R W 1993 *Proc. XXI. Int. Conf. Phen. Ion. Gases* vol 3, p 118

[20] Chen F F, Sudit I D and Light M 1996 *Plasma Sources Sci. Technol.* **5** 173

[21] Chen F F 1992 *J. Vac. Sci. Technol.* A **10** 1389

[22] Nogami H, Ogahara Y, Mashimo K, Nakagawa Y and Tsukada T 1996 *Plasma Sources Sci. Technol.* **5** 181

[23] Ferreira C M and Moisan M (eds) 1993 *Microwave Discharges, Fundamentals and Applications (NATO ASI Series, Series B: Physics vol 302)* (New York: Plenum)

[24] Marec J and Leprince P 1993 *Microwave Discharges, Fundamentals and Applications (NATO ASI Series, Series B: Physics vol 302)* ed C M Ferreira and M Moisan (New York: Plenum)

[25] Konuma M 1992 *Film Deposition by Plasma Techniques* (Berlin: Springer)

[26] Ohl A 1993 *Microwave Discharges: Fundamentals and Applications (NATO ASI Series, Series B: Physics vol 302)* ed C M Ferreira and M Moisan (New York: Plenum)

[27] Ohl A 1998 *J. Physique* IV **8** Pr7 83

[28] v Keudell A 1996 *Report IPP Garching* 9/110

[29] Eliasson B and Kogelschatz U 1991 *IEEE Trans. Plasma Sci.* **19** 309

[30] Kogelschatz U, Eliasson B and Ehli W 1995 *J. Physique* IV **7** C4 47

[31] Siemens W 1857 *Poggendorfs Ann. Phys. Chem.* **102** 66

[32] Kogelschatz U and Eliasson B 1996 *Phys. Blätter* **52** 360

[33] Salge J 1995 *J. Physique* IV **5** C5 583

[34] Schmidt M, Föste T, Michel P and Sapkin V V 1982 *Beitr. Plasma Phys.* **22** 436

[35] Meger R A, Fernsler R F, Lampe M, Leonhardt D, Manheimer W M, Murphy D P and Pechacek R E 1999 *Bull. Am. Phys. Soc.* **44** 38

[36] Bielesch U 1999 *Laserstrahlschneiden von Metallen mit Hochleistungs-*CO_2*-Laserplasmen hoher Repititionsfrequenz* (Aachen: Shaker)