# 2

# Cold Plasma Generation

The cold plasmas are usually excited and sustained electrically by direct current (DC), radio frequency (RF), or microwave (MW) power applied to a gas. Plasma chemistry in cold plasmas is controlled mainly by electron energies and gas temperatures. Therefore, as far as identical energies and temperatures can be achieved, the type of discharge used to create the plasma is of little importance. The choice of a specific method and equipment to produce discharges is determined by requirements of flexibility, process uniformity, cost, and process rates. The different methods used for the generation of cold plasmas are described in the following sections, while Chapter 4 describes the reactors used in plasma processing.

## 2.1 DC GLOW DISCHARGES

A DC glow discharge is produced by applying a DC voltage between two conductive electrodes inserted into a gas at low pressure as illustrated in Fig. 2-1. A high-impedance power supply is used to provide the electrical field.

A small amount of free electrons is always present in the gas, as a result of ionization by naturally occurring radioactivity or cosmic rays. Free electrons can also be produced by photoionization or field emission. As the voltage applied to the gas in the discharge tube is gradually increased, the available free electrons are accelerated in the electric field, thereby gaining kinetic energy. Concomitantly, the electrons lose energy in collisions with the atoms or molecules of the gas. These atoms or molecules will be referred to also as collision targets.

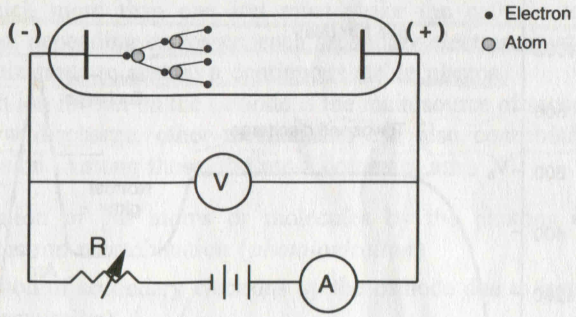


**Fig. 2-1** DC glow-discharge setup.

Initially, when the energy of the electron is too low to excite or ionize a target, the collisions will necessarily be elastic. The average fraction of the electron energy lost in an elastic collision with a gas atom or molecule is $-2m_e/M$, where $M$ is the mass of the target (Eq. 1.7 in Sec. 1.3). Thus only a very small fraction of the total kinetic energy of the electron, typically only $10^{-5}$, is lost per elastic collision. Meanwhile, the electron continues to gain energy between collisions until it attains sufficient energy to cause ionization of the targets through inelastic collisions. Large amounts of energy are transferred to the target in the inelastic collisions, making those collisions a more efficient mean of energy transfer. The new electrons produced in the ionization process are in turn accelerated by the electric field and produce further ionization by impact with the neutral atoms or molecules of the gas.

An *electron multiplication* process thus takes place. This process can be characterized by a macroscopic coefficient, $a_T$, which represents the mean number of ion-electron pairs formed by an electron along a path of 1 cm. The coefficient $a_T$ is called the *first Townsend coefficient* and is dependent on the electric field ($E$), *the pressure* ($p$), and the nature of the gas as well. Experimentally, it has been shown that for a given gas, $a_T/p$ depends on $E/p$ [1] only.

The changes that take place in the gas as a function of the applied voltage are described by the typical dependence of the discharge current, $I$, on the applied voltage, $V$, This dependence is called the *I-V characteristic* of the discharge. A representative typical characteristic of a DC glow discharge is shown in Fig. 2-2. When the applied voltage is low, the current through the tube is produced by the collection of the available free charges and is negligibly small. When the voltage increases and more charged particles are created by the ionization of the gas, the current increases steadily, while the voltage reaches a limit determined by the output impedance of the power supply. This region of the *I-V* characteristic is known as the *Townsend discharge* and indicated in Fig. 2-2.

When the applied voltage reaches a certain threshold value, marked $V_b$ in Fig. 2-2, an avalanche process occurs as a result of three simultaneous processes:

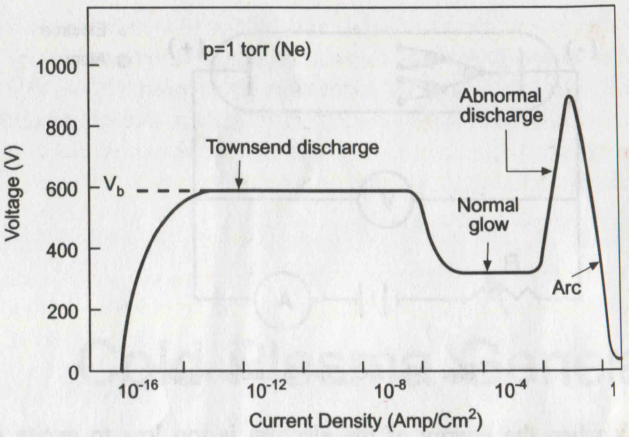


**Fig. 2-2** The I-V characteristic of a DC glow discharge.

1. Ions accelerated by the electric field strike the cathode with sufficient energy to cause the *emission of secondary electrons* from it; the secondary electrons in turn form more ions by collision with the neutral atoms of the gas.
2. The newly formed ions are accelerated to the cathode where collisions produce more electrons, which in turn produce more ions.
3. In parallel, electrons created in ionizing collisions and by secondary processes are removed from the plasma by drift and diffusion to the walls, by recombination with positive ions, and, in certain gases, by formation of negative ions. At pressures lower than a few mtorr, the recombination occurs mainly at the walls of the reactor.

When the number of electrons is sufficient to produce just enough ions to regenerate the number of lost electrons, a steady state is reached in which an equilibrium is established between the rate of formation of ions and the rate of their recombination with electrons. At this stage the discharge is self-sustaining. Extensive breakdown occurs in the gas and the *glow discharge* is thus established. The gas begins to glow, the voltage drops, and the current rises abruptly. The mode of the discharge at this point is called the *normal glow* (see Fig. 2-2). The energy decay of the electronically excited states of molecules and atoms account for much of the luminous glow of the gaseous discharge.

The minimal threshold voltage required to produce the glow discharge, $V_b$, is called the *breakdown voltage*.

The sustaining glow discharge is controlled by the emission of secondary electrons. That emission is characterized by the *electron emission coefficient*, defined as the ratio between the number of emitted secondary electrons and the number of impacting ions. This coefficient is often called the *yield of secondary electrons*. Because the electron emission coefficient is of the order of 0.1 for most

materials, much more than one ion must strike the cathode to produce one electron. Then, depending on losses, each secondary electron must be responsible for 10–20 ionizations to sustain a continuous stable plasma.

Although ion impact on the cathode is the main source of secondary electrons in a DC glow discharge, other mechanisms can also contribute to secondary electron emission. Among those, the most dominant are:

1. Ionization of gas atoms or molecules by the photons emitted during ion-electron recombination (*photoionization*)
2. Emission of secondary electrons by the cathode due to impact of photons (*photoemission*)
3. Emission of secondary electrons by the cathode due to impact of excited atoms in a metastable state

The contribution of each of these effects to the emission of secondary electrons is strongly dependent on the nature of the gas and its pressure.

After the voltage reaches the breakdown value $V_b$ and the glow discharge is established, initially at low power, the discharge covers only the area near the rim of the cathode. When the power is raised, the current increases and the discharge spreads to cover the whole surface of the cathode. When the current of the discharge increases past the point of complete cathode coverage, the voltage begins to rise. This corresponds to the *abnormal discharge* region in Fig. 2-2, which is the mode used in glow discharge processing [2]. At this stage, the discharge current is limited by the surface area of the electrodes and by the resistance of the power supply and electrical circuit. A further increase in power will cause the heating of the cathode, which will, at a certain stage, result in thermionic emission. When this happens, the voltage decreases and the glow changes into an arc.

### 2.1.1 Paschen's Law

The breakdown voltage in a DC discharge is determined by the discharge gas, the gas pressure, and the tube dimension. The dependence of the breakdown voltage on gas pressure and inter-electrode distance can be expressed as [3]:

$$V_b = \frac{C_1 (pd)}{C_2 + \ln(pd)} \tag{2.1}$$

where $d$ = distance between electrodes

$C_1$ and $C_2$ = constants that change with the nature of the gas

According to Eq. (2.1), for large $pd$ values the breakdown voltage is proportional to $pd$. This dependence is called *Paschen's law*, which reflects in fact the dependence of the DC glow discharge on the secondary electrons.

If the distance between the electrodes is small or the pressure is small, the secondary electrons emitted from the cathode can reach the anode while undergoing only a very small number of collisions not creating a sufficient number of ions required for the regeneration of the secondary electrons. On the other hand,

if the pressure is too high, the electrons cannot acquire sufficient energy between collisions to produce enough ions. If the distance between electrodes is too large, only a small fraction of the produced ions will succeed in reaching the cathode and create secondary electrons.

At both extremes of the value of the *pd* product, the probability of ionization — and/or ion collection — is small and the breakdown voltage required to sustain the discharge is high. The breakdown voltage reaches a minimum between the two extremes. This behavior is described by Paschen's curves, which are shown for a few gases in Fig. 2-3 [4].

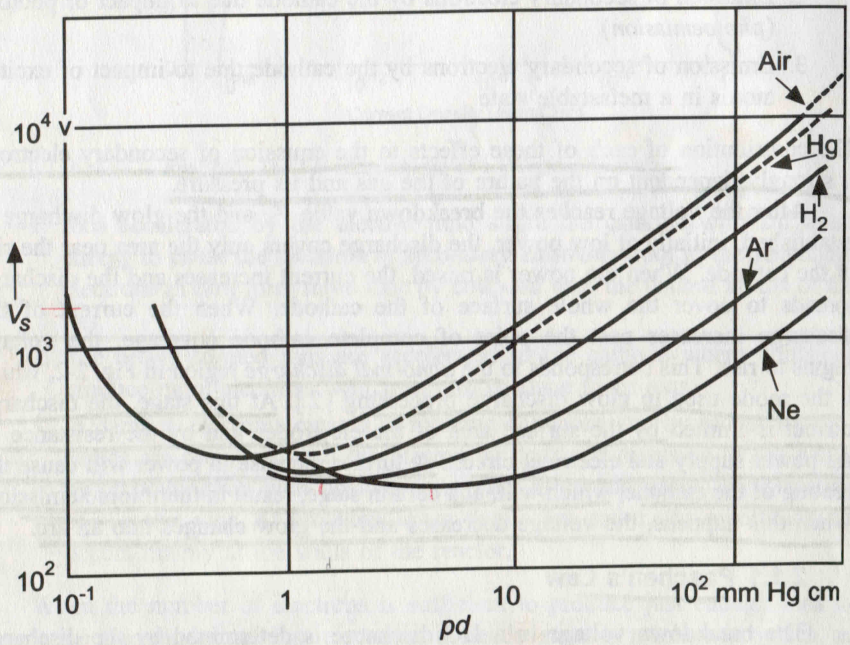


**Fig. 2-3** Paschen's curves for various gases (from [4], by permission of Oxford University Press).

For most gases the minimum breakdown voltage is between 100 and 500 V and occurs for *pd* in the range of $10^{-1}$–10 torr.cm. At 1 torr, typical values of the electric field are 10–100 $V.cm^{-1}$. Impurities in the gas can reduce the breakdown voltage, either through Penning ionization (see Sec. 3.3.1.2.) or when they have a low ionization potential.

### 2.1.2 Characteristics of DC Glow Discharge

Figure 2-4 shows a diagram of the regions of the discharge as they appear in the discharge tube together with the distribution of the potential and electric field along the tube. As can be seen in Fig. 2-4 (a), the discharge exhibits several

bright and dark regions along the discharge tube. The dark regions are called the *cathode* or *Crooke's dark space*, the *Faraday dark space*, and the *anode dark space*. The luminous regions are called the *cathode glow*, the *negative glow*, and the *positive column*.

The luminosity of the cathode glow results from the decay of the excitation energy of the positive ions during neutralization with electrons.

The cathode dark space is a positive space charge plasma sheath. At a given applied discharge voltage the product between the thickness of the cathode dark space, $d_{cd}$, and the pressure in the discharge, $p$, is approximately constant. For example, for a discharge in argon at 2000 V, $p \cdot d_{cd} = 50$ mtorr.cm. The secondary electrons produced at the cathode by positive ion bombardment gain energy through the cathode dark space.

Most of the glow discharge volume is occupied by the positive column.

The voltage drop occurs over three regions indicated in Fig. 2-4(b): the *cathode fall*, the *positive column*, and the *anode fall*. Most of the voltage drop occurs in the cathode fall region, whose dimension is a function of the material used for the cathode and the nature of the discharge gas. Values of the voltage drop in the cathode fall are presented in Table 2-1 for different combinations of cathode material and discharge gas. As can be seen from the table, the voltage values range from 59 V to about 500 V.

Since at constant voltage the product of the thickness of the dark space with pressure is fairly constant, the distance over which the cathode fall extends decreases with increasing pressure. The value of the product $p \cdot d_{cd}$ is presented in Table 2-2 for several combinations of cathode material and discharge gas. For the pressures normally used in DC glow discharges, these values correspond to dark space thicknesses, $d_{cd}$, of order of millimeters to centimeters.

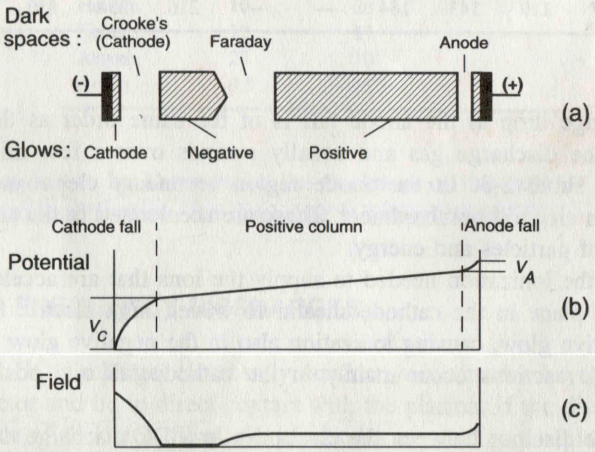


**Fig. 2-4** Regions and characteristics of a DC glow discharge: (a) discharge regions; (b) potential distribution in discharge tube; (c) distribution of electric field in discharge tube.

**TABLE 2-1** Values of Cathode Fall (in volts) (from [5], reprinted with permission from S. C. Brown, *Basic Data of Plasma Physics*, MIT Press, 1959)

| Cathode | Air | A | He | $H_2$ | Hg | Ne | $N_2$ | $O_2$ | CO | $CO_2$ | Cl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Al | 229 | 100 | 140 | 170 | 245 | 120 | 180 | 311 | — | — | — |
| Ag | 280 | 130 | 162 | 216 | 318 | 150 | 233 | — | — | — | — |
| Au | 285 | 130 | 165 | 247 | — | 158 | 233 | — | — | — | — |
| Ba | — | 93 | 86 | — | — | — | 157 | — | — | — | — |
| Bi | 272 | 136 | 137 | 240 | — | — | 210 | — | — | — | — |
| C | — | — | — | 240 | 475 | — | — | — | 525 | — | — |
| Ca | — | 93 | 86 | — | — | 86 | 157 | — | — | — | — |
| Cd | 266 | 119 | 167 | 200 | — | 160 | 213 | — | — | — | — |
| Co | 380 | — | — | — | — | — | — | — | — | — | — |
| Cu | 370 | 130 | 177 | 214 | 447 | 220 | 208 | — | 484 | 460 | — |
| Fe | 269 | 165 | 150 | 250 | 298 | 150 | 215 | 290 | — | — | — |
| Hg | — | — | 142 | — | 340 | — | 226 | — | — | — | — |
| Ir | 380 | — | — | — | — | — | — | — | — | — | — |
| K | 180 | 64 | 59 | 94 | — | 68 | 170 | — | 484 | 460 | — |
| Mo | — | — | — | — | 353 | 115 | — | — | — | — | — |
| Mg | 224 | 119 | 125 | 153 | — | 94 | 188 | 310 | — | — | — |
| Na | 200 | — | 80 | 185 | — | 75 | 178 | — | — | — | — |
| Ni | 226 | 131 | 158 | 211 | 275 | 140 | 197 | — | — | — | — |
| Pb | 207 | 124 | 177 | 223 | — | 172 | 210 | — | — | — | — |
| Pd | 421 | — | — | — | — | — | — | — | — | — | — |
| Pt | 277 | 131 | 165 | 276 | 340 | 152 | 216 | 364 | 490 | 475 | 275 |
| Sb | 269 | 136 | — | 252 | — | — | 225 | — | — | — | — |
| Sn | 266 | 124 | — | 226 | — | — | 216 | — | — | — | — |
| Sr | — | 93 | 86 | — | — | — | 157 | — | — | — | — |
| Th | — | — | — | — | — | 125 | — | — | — | — | — |
| W | — | — | — | — | 305 | 125 | — | — | — | — | — |
| Zn | 277 | 119 | 143 | 184 | — | — | 216 | 354 | 430 | 410 | — |

The voltage drop at the anode fall is of the same order as the ionization potential of the discharge gas and usually extends over a few millimeters, as illustrated in Table 2-3. In the anode region secondary electrons are created primarily from electron bombardment. These are accelerated in the anode fall and are a source of particles and energy.

Most of the ionization needed to supply the ions that are accelerated to the cathode takes place in the cathode sheath. However, high electric fields extend into the negative glow, causing ionization also in the negative glow region.

Chemical reactions occur mainly in the cathode fall and positive column zones.

When the distance between the electrodes in a DC discharge decreases, the Faraday dark space and positive column shrink and finally disappear, leaving only the negative glow and cathode dark space. This is generally the situation encountered in most glow-discharge processing reactors. The minimum distance between

**TABLE 2-2** Values of the Product Cathode Dark Space × Pressure (in torr.cm) (from [5], reprinted with permission from S. C. Brown, *Basic Data of Plasma Physics*, MIT Press, 1959)

| Cathode | Air | A | $H_2$ | He | Hg | $N_2$ | Ne | $O_2$ |
|---|---|---|---|---|---|---|---|---|
| Al | 0.25 | 0.29 | 0.72 | 1.32 | 0.33 | 0.31 | 0.64 | 0.24 |
| C | — | — | 0.9 | — | 0.69 | — | — | — |
| Cd | — | — | 0.87 | — | — | — | — | — |
| Cu | 0.23 | — | 0.8 | — | 0.6 | — | — | — |
| Fe | 0.52 | 0.33 | 0.9 | 1.30 | 0.34 | 0.42 | 0.72 | 0.31 |
| Mg | — | — | 0.61 | 1.45 | — | 0.35 | — | 0.25 |
| Hg | — | — | 0.9 | — | — | — | — | — |
| Ni | — | — | 0.9 | — | 0.4 | — | — | — |
| Pb | — | — | 0.84 | — | — | — | — | — |
| Pt | — | — | 1.0 | — | — | — | — | — |
| Zn | — | — | 0.8 | — | — | — | — | — |

**TABLE 2-3** Anode Fall Voltage, $V_A$, and Anode Fall Thickness, $d_A$ (after [5], reprinted with permission from S. C. Brown, *Basic Data of Plasma Physics*, MIT Press, 1959)

| Gas | Pressure (torr) | $V_A$ (V) | $d_A$ (cm) |
|---|---|---|---|
| Hydrogen | 1–5 | 17–19 | 0.5–0.7 |
| Nitrogen | 0.8 | 16.5 | |
| Nitrogen | 0.5 | 15.7 | |
| Oxygen | 1 | 14.2 | |
| Oxygen | ~0.1 | | >0.12 |
| Helium | 10 | 26 | |
| Neon | 10 | 17 | |
| Argon | 20 | 10 | |
| Argon | 0.5 | 15.3 | |

the electrodes has to be about twice the thickness of the cathode dark space; at smaller electrode separation, the discharge is extinguished [6].

## 2.2 RADIO FREQUENCY DISCHARGES

To sustain a DC discharge, electrically conductive electrodes have to be inserted inside a reactor and be in direct contact with the plasma. If the discharge is used for deposition of dielectric films, the electrodes exposed to the plasma gradually become covered with an insulator. Therefore, although a DC discharge may be initiated, it will quickly extinguish as the electrons accumulate on the insulator and recombine with the available ions. In some cases it is preferred to have the

electrodes outside the reactor, to avoid or minimize contamination of the process by material removed from the electrodes. Such problems can be solved by alternating the polarity of the discharge.

When an alternating electric field of low frequency ($< 100$ Hz) is applied between the two electrodes of the discharge tube, each electrode acts alternately as cathode or anode. Once the breakdown potential is surpassed on each half cycle, a temporary DC glow discharge is obtained. When the voltage drops during the cycle below the breakdown value, the discharge is extinguished, and for sufficiently low frequencies, the space charge decays before the discharge is reinitiated with inverse polarity [7].

When the frequency of the electric field increases above a *critical ion frequency*, $f_{ci}$, defined by Eq. (2.2), the time taken by the positive ions to move between electrodes becomes larger than half the period of the electric field. Ions created near a momentary anode cannot reach the cathode before the field is reversed. In this situation, the distance traveled by the ions in the electric field becomes smaller than the thickness of the plasma sheath. At such frequencies the positive space charge is partly retained between the two half cycles of the alternating electric field and facilitates the reinitiation of the discharge. The critical ion frequency, also called the *ion transition frequency* [8], is defined by [9]:

$$f_{ci} = \frac{< v >_{di}}{2L} \tag{2.2}$$

where $< v >_{di}$ = average drift velocity of the ion
$L$ = the distance between the two electrodes

Ion transition frequencies range from 500 kHz to several MHz.

A similar critical frequency can be defined for electrons:

$$f_{ce} = \frac{< v >_{de}}{2L} \tag{2.3}$$

where $< v >_{de}$ is the average drift velocity of the electrons.

Due to the much larger mobility of the electrons as compared to that of the ions, $f_{ce}$ is much higher than $f_{ci}$. For frequencies higher than $f_{ce}$, both positive and negative space charges are retained between cycles, and, as a result, the voltages required to initiate and maintain the alternating current discharge decrease strongly in comparison to a DC glow discharge [5, 9].

The frequencies used in the high-frequency discharges are in the range of radio transmission giving the high-frequency discharges the name of *radio frequency*, or shortly, *RF discharges*.

The elastic collision frequency, $\nu$, in gases at glow discharge conditions is normally between $10^9$ and $10^{11}$ collisions/sec [10]. Thus the collision frequency is much higher than the applied radio frequency even for 13.56 MHz discharges and electrons will experience many collisions during each applied field cycle. They will be lost by diffusion to the reactor walls and will be regenerated by impact ionization in the body of the plasma. Therefore, the loss of electrical

carriers from the RF discharge is controlled by ambipolar diffusion and homogeneous recombination (recombination in the gas phase) and not by the electric field. New charged particles are produced mainly through electron impact ionization of neutral gas atoms and molecules.

The *power absorption* by the RF discharge can be either collisional or collisionless. The collisional absorption of high-frequency power in the plasma is due to collisions of electrons with ions, at a frequency $\nu_{ei}$, and with neutral particles, at a frequency $\nu_{en}$. In plasmas at pressures above $10^3$ Pa (7.5 torr), the degree of ionization is usually very low ($< 10^{-4}$), the density of neutrals is much higher than that of ions, and the electron-neutral collisions are predominant. At pressures below 1 Pa (7.5 mtorr), the degree of ionization can reach values higher than $10^{-2}$ (see Table 1-1 in Sec. 1.3.1), and the electron-ion collisions are predominant. At intermediate pressures, both $\nu_{ei}$ and $\nu_{en}$ determine the power absorption [11]. At even lower pressures, when the collision frequency decreases and $\nu/\omega \ll 1$, collisionless absorption becomes dominant in the plasma.

In a collisionless situation, an electron would oscillate in the RF field and would reach maximal velocity $\dot{x}$, amplitude $x$, and energy $W$, given by [6]

$$\dot{x} = \frac{eE_o}{m_e\omega} \tag{2.4a}$$

$$x = \frac{eE_o}{m_e\omega^2} \tag{2.4b}$$

$$W = \frac{m_e\dot{x}^2}{2} \tag{2.4c}$$

where $E_o$ is the amplitude of the electric field.

At a typical RF frequency of 13.56 MHz and a field strength of 10 V/cm, this corresponds to

$$\text{amplitude} = 2.42 \text{ cm}; \quad \text{velocity} = 2.1 \times 10^8 \text{ cm.sec}^{-1};$$

$$\text{energy} = 11.3 \text{ eV}$$

This indicates that, for an electron to reach the ionization energy of argon (15.7 eV) in a collisionless plasma, a field somewhat higher than 10 V/cm is required. However, the collisions with the atoms of the gas cause a random motion of the electrons and the electrons acquire additional energy from the external field during each collision with the atoms. If an electron makes an elastic collision with an atom, reversing its motion at the time the electric field changes direction, it will continue to gain speed and energy [12]. Electrons in a RF discharge could thus accumulate enough energy to cause ionization even at low electric fields. As a result of this behavior, the RF discharge is more efficient than the DC discharge in promoting ionization and sustaining the discharge.

The *mean power absorbed* by an electron, $\bar{P}$, is given by [1]

$$\bar{P} = \frac{e^2E_o^2}{2m_e} \cdot \frac{\nu_{ea}}{\nu_{ea}^2 + \omega^2} \tag{2.5}$$

where $\nu_{ea}$ is the elastic collision frequency of an electron with the atoms or molecules of the gas. The dependence of $\overline{P}$ on $E_0^2$ indicates that the absorbed power is independent of the sign of the electric field and the electron gains energy both when it moves with the field or against it. The quantity

$$E_{eff} = \frac{E_o}{\sqrt{2}} \left( \frac{\nu_{ea}^2}{\nu_{ea}^2 + \omega^2} \right)^{1/2} \tag{2.6}$$

is called the *effective electric field strength.*

The *average RF power* transferred from the outside electric field to the *unit volume of gas*, $\overline{P}_v$, is

$$\overline{P}_v = \frac{n_e e^2 E_o^2}{2m_e} \left( \frac{\nu}{\nu^2 + \omega^2} \right) \tag{2.7}$$

For RF frequencies of $\omega \approx 10^7$ Hz, and with $\nu > 10^9$ sec$^{-1}$, the collision frequency is much higher than the frequency of the field $\nu \gg \omega$. In this case the transferred power, $\overline{P}_v$, is practically not affected by the driving frequency, $\omega$.

At frequencies higher than 50 kHz, the oscillating electrons acquire sufficient energy to cause ionizing collisions, thus reducing the dependence of the discharge on secondary electrons and lowering the breakdown voltage. The discharge can thus be sustained independent of the yield of secondary electrons from walls and electrodes. Because of the low mobility of the ions, their distribution is essentially stationary at high frequencies. In the same time, the electrons are swept between the electrodes by the electric field and their distribution is a function of position and time.

The secondary electrons emitted from the electrodes or walls of the reactor of an RF discharge are accelerated across the plasma sheath and add to the ionization process but are less important in sustaining the discharge. At a given pressure, the electrical impedance of the discharge decreases with increasing frequency, making it possible to drive more current through the discharge at the same voltage [6]. The yield of atoms and free radicals in a molecular discharge is also increased by the use of RF excitation as compared to a DC discharge of the same field strength and pressure.

Although the frequency of power supplies used for the excitation of RF plasmas can be as high as 100 MHz, lower frequencies are generally used. This is due to the fact that sophisticated arrangements have to be made to sustain a uniform plasma in large volumes when the wavelength becomes comparable to, or shorter than, the dimensions of the reactor.

The RF discharges can be operated at pressures as low as 1 mtorr because the efficiency of ionizing collisions is enhanced by the electron oscillations. This is useful in sputtering, where it is undesirable to have sputtered material reflected back to the etched surface as a result of collisions with gas molecules, or in etching or deposition, when directionality of the ions is required.

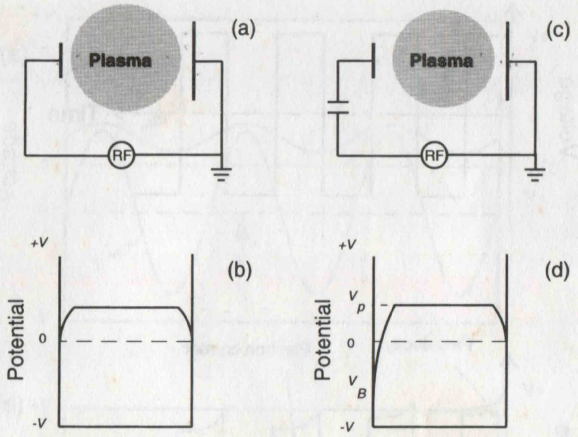


**Fig. 2-5** RF connection to parallel plate reactor with unequal electrodes and developed self-bias: (a) direct RF connection to electrodes; (b) potential distribution between electrodes for arrangement (a); (c) RF connection through blocking capacitor; (d) potential distribution between electrodes for arrangement (b).

### 2.2.1 Self-bias in RF Plasmas

Let's consider a RF plasma generated between two parallel electrodes, as shown in Fig. 2-5, and assume that one electrode has an area much larger than the other. The electrodes will be at negative potentials, $V_1$ and $V_2$, relative to the plasma and the sheaths of thickness $d_{s1}$ and $d_{s2}$ will develop near the two electrodes of areas $A_1$ and $A_2$. If the RF field is connected directly to the electrodes, as illustrated in Fig. 2-5(a), the two electrodes will be at the same potential relative to the plasma (Fig. 2-5(b)), because the plasma is equipotential:

$$V_1 = V_2 \tag{2.8}$$

$$d_{s1} = d_{s2} \tag{2.9}$$

The situation changes, however, if a blocking capacitor is inserted, as often happens, between the RF supply and the electrodes, as shown in Fig. 2-5(c). In this case, the potential distribution between the electrodes is as illustrated in Fig. 2-5(d) and this nonsymmetric potential develops as explained next.

If a square-wave potential of amplitude $V$, as illustrated in Fig. 2-6(a), is applied to the electrodes through the capacitor, the voltage across the plasma will follow the curve shown in Fig. 2-6(b) [3]. Initially the voltage across the plasma will be equal to the applied voltage $V$. The capacitor will charge up rapidly by electron current, and the potential will drop as shown in Fig. 2-6(a). When the applied voltage changes sign, the voltage across the plasma drops by $-2\,V$, after which the voltage decays at a slower rate because the capacitor charges this time by the current of less mobile ions. This process continues until the time-averaged ion and electron currents become equal.

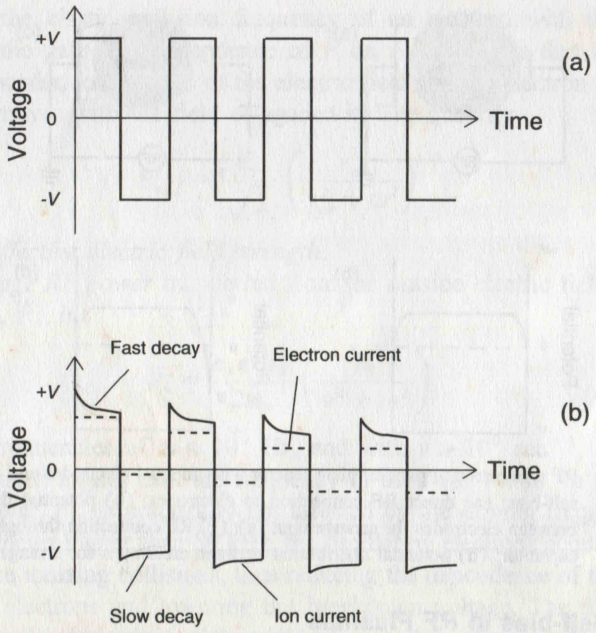


**Fig. 2-6** Development of a self-bias in a parallel plate discharge: (a) applied voltage; (b) voltage across the discharge versus time.

This steady state results in a *time-averaged negative bias* on the small electrode. The time-averaged potential distribution between the electrodes is therefore as illustrated in Fig. 2-5(d). The same will happen if a sinusoidal voltage is applied to the electrodes, as illustrated in Fig. 2-7(a). This figure also illustrates the time variation of the plasma potential (curves 2) for the symmetric and nonsymmetric cases. If the electrodes have the same area, the system remains symmetric, as shown in Fig. 2-7(b).

In all cases, the plasma is at a higher potential than each electrode.

When a blocking capacitor is used with two electrodes of different areas, the negative self-bias of the electrodes relative to the plasma is dependent on the relative areas of the two electrodes. According to Koenig and Maissel [13], the following relation exists,

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^4 \tag{2.10}$$

$$\frac{d_{s1}}{d_{s2}} = \left(\frac{V_1}{V_2}\right)^{3/4} \tag{2.11}$$

where $V_1$, $V_2$ = negative biases on the two electrodes
$A_1$, $A_2$ = areas of the electrodes

Often, one of the electrodes is grounded together with the walls of the reactor and

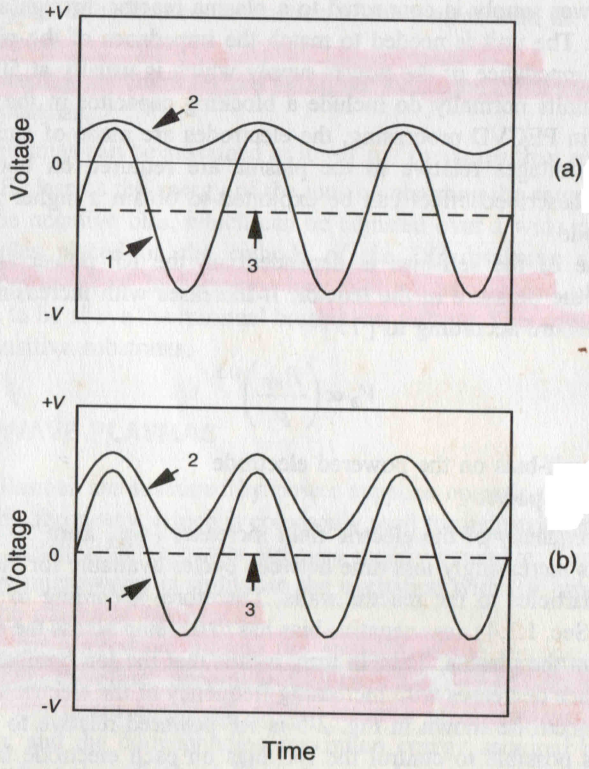


**Fig. 2-7** Development of a self-bias with a sinusoidal wave: (a) unequal electrodes; (b) electrodes of equal area.
1, voltage on powered electrode; 2, plasma potential; 3, time-averaged voltage on powered electrode.

its effective area becomes very large, causing the other electrode to become much more negative.

Equation (2.10) was obtained assuming that the ions pass through the sheath without collisions and that the current density of the ions is equal at the two electrodes. The first assumption is correct only at pressures of a few mtorr, and the second assumption is questionable. Equation (2.10) takes into consideration the total areas of the electrodes, which includes the area of the reactor for the electrode that is electrically connected to it. However, the plasma is often mostly confined between the electrodes while the walls are practically not exposed to it.

The experimental evidence indicates that the voltage ratio $V_1 / V_2$ depends also on the gas used in the discharge, the peak-to-peak applied voltage, as well as the area ratio $(A_2/A_1)^n$. For area ratios between 0.6 and 0.1 the fourth power relationship is approximately obeyed. However, it is not obeyed for smaller area ratios. For an Ar discharge with an electrode area ratio of 0.3, the value of $n$ can range from 1.2 to 2.5 [14].

A RF power supply is connected to a plasma reactor through an *impedance matching unit*. The unit is needed to match the impedance of the plasma reactor to the output impedance of the power supply which is usually at 50 Ω. Because the matching units normally do include a blocking capacitor in the planar diode reactors used in PECVD processing, the electrodes are made of equivalent areas when similar voltages relative to the plasma are required on both electrodes. However, the described effect can be exploited to obtain a higher negative bias on one electrode.

The value of the self-bias is dependent on the RF power applied to the electrode and the pressure in the reactor. It increases with increasing power and decreasing pressure according to [15]

$$V_B \propto \left(\frac{P_{RF}}{p}\right)^{1/2} \tag{2.12}$$

where $V_B$ = self-bias on the powered electrode
$P_{RF}$ = RF power

As the frequency of the electric field increases (e.g., from 50 kHz to 13.56 MHz), there is increasingly less time between cycles available for the diffusion of the charged particles to the reactor walls. Therefore, according to Bohm sheath criterion (see Sec. 1.3.4), less negative bias has to develop across the sheath to keep the electrons in the plasma. This, in turn, means that the ion bombardment of the electrode surface decreases with increasing frequency of the electric field [14].

If each electrode shown in Fig. 2-5 is RF powered relative to the grounded chamber, it is possible to control the DC bias on each electrode independently. Thus the plasma can be generated by powering one electrode and the degree of ion bombardment on the other electrode can be regulated independently by a second power supply.

Magnetic fields parallel to the electrode are sometimes superposed on the RF plasma. The magnetic field confines the electrons next to the electrodes and increases the ionization efficiency. This increase in ionization lowers the sheath potential and the energy of the bombarding ions.

### 2.2.2 RF Versus DC Plasmas

The advantages of RF discharges over the DC discharges, as summarized next, explain the wider use of RF plasmas as compared to DC plasmas:

1. RF plasmas can be excited and sustained using either conductive or nonconductive electrodes, while DC discharges require the electrodes to be conductive throughout the process.
2. RF plasmas can be sustained with internal as well as external electrodes, while DC discharges require the electrodes to be inserted inside the reactor and be in direct contact with the plasma. Use of external electrodes is sometimes required when the gases of the discharge are corrosive or when

one wants to reduce contamination of the plasma with the material of the electrodes.

3. RF plasmas are characterized by higher ionization efficiencies than are the DC plasmas.
4. RF plasmas can be sustained at lower gas pressures than are DC plasmas.
5. In RF plasmas the energy of the ions bombarding the sample is controlled by the negative bias, which can be adjusted over a wide range of values. Samples placed on the cathode of the DC discharge are exposed to bombardment of high-energy ions that are accelerated at voltages that have to be above the minimal breakdown voltage. This can cause damages to sensitive substrates.

## 2.3 MICROWAVE PLASMAS

Microwave plasmas are sustained by power supplies operating at a frequency of 2.45 GHz. This frequency, which is commonly used for industrial or home heating applications, makes suitable power supplies readily available. The excitation of the plasma by microwaves is similar to the excitation with RF, while differences result from the ranges of frequencies.

In a typical microwave plasma the strength of the electric field is about $E_o \approx 30$ V/cm; therefore, according to Eqs. (2.4a)–(2.4c), in a collisionless situation, the maximum amplitude of the electron at microwave frequencies is $x < 10^{-3}$ cm, and the corresponding maximum energy acquired by an electron during one cycle is about 0.03 eV. This energy is far too small to sustain a plasma. Therefore microwave discharges are more difficult to sustain at low pressures (< 1 torr) than DC or RF discharges.

In a collisional discharge, at constant electric field and power density, Eq. (2.7) has a maximum when $\nu = \omega$. The absorption of microwave power is thus a function of the collision frequency of the electrons with the heavy species and is therefore dependent on the pressure in the discharge. For a microwave frequency of 2.45 GHz, efficient microwave absorption in helium occurs at 5–10 torr [16]. For other gases, the optimum pressure for microwave discharges is in the range 0.5–10 torr.

While the RF glow discharge can be made to extend virtually throughout the entire reactor, whose dimensions are much smaller than the wavelength of the RF field ($\approx 22$ m at 13.56 MHz), the microwave plasma has its greatest glow intensity at the coupling microwave cavity and diminishes rapidly outside it, because of the much smaller wavelength of the microwave ($\lambda = 12.24$ cm for a frequency of 2.45 GHz). In a microwave plasma, the magnitude of the electric field can vary within the reactor, which now has dimensions of the same order of magnitude as the wavelength. One can thus find active species from the discharge still persisting into a region free of the glow of the plasma, that is, in the afterglow.

The transfer of the microwave power to the plasma is achieved with the help of *microwave applicators* such as waveguides, resonance cavities, or coaxial applicators. With the exemption of coaxial applicators, the applicator has to be separated from the plasma reactor by a dielectric wall, characterized by low absorption of microwaves. A window made of quartz or alumina separates the microwave from the plasma. Any absorbing material inserted in the path of the microwave will cause both absorption and reflection of the microwaves, reducing the efficiency of the power transfer and impeding the tuning of the microwave system.

The microwave applicators will be further discussed in detail in Sec. 4.4.

## 2.4 ELECTRON CYCLOTRON RESONANCE PLASMAS

Electron cyclotron resonance (ECR) plasmas have the capability to operate at lower pressures than RF plasmas and to create higher plasma densities, with corresponding higher degrees of ionization ($a > 10\%$ in some cases [17]).

According to Eq. (2.5), which describes the relation between the absorbed power and the frequency of the electric field, the power absorbed by plasma approaches zero for conditions of rare collisions, when $\nu \ll \omega$, or frequent collisions, when $\nu \gg \omega$. Very high values of electric field, $E_o$, are therefore required to sustain microwave discharges at very low pressures of less than 1 Pa (7.5 mtorr), for which $\nu \approx 10^8$ sec$^{-1}$.

If a magnetic field $B$ is applied to a plasma system, the charged particles are subjected to a gyromotion around the magnetic field lines with a radius $r_L$ and an angular frequency $\omega_c$. The radius $r_L$ is called the *Larmor radius* and is given by [8]

$$r_L = \frac{mv_\perp}{eB} = \frac{1}{eB}\sqrt{2\frac{W_\perp}{m}} \tag{2.13}$$

where $m$ = mass of charged particle
$v_\perp$ = velocity component of particle, normal to the magnetic field line
$W_\perp$ = energy component corresponding to the normal component of the velocity

The frequency $\omega_c$ is called the *cyclotron angular frequency* and is given by

$$\omega_c = \frac{eB}{m} \tag{2.14}$$

As can be seen from Eq. (2.14), the cyclotron or *Larmor frequency* is independent of the velocity of the individual charged particle. The cyclotron frequency of the electron is therefore a characteristic parameter of the system.

For a magnetic field of 875 gauss, the cyclotron frequency of the electrons defined by Eq. (2.14) with $m = m_e$, becomes 2.45 GHz, and if microwaves of frequency $\omega = 2.45$ GHz are used to excite and sustain the plasma, the gyromotion of the electrons is in resonance with the microwaves. This is called the

*electron cyclotron resonance* condition, and a plasma excited in the presence of a magnetic field, which satisfies the resonance condition, is called an *ECR plasma.*

At the ECR condition, the component of the electron velocity normal to the magnetic field increases continuously and the electrons follow a spiralling gyrating path along the magnetic field line. The radius of the electron path is limited by collisions with other particles or with the walls or by the electron moving out of the ECR zone.

The plasma is extracted from the ECR chamber toward the sample by a divergent magnetic field, the intensity of which decreases from the ECR chamber toward the sample. The charged particles are accelerated toward lower magnetic field values, and electrons will stream out of the plasma along the magnetic field lines much faster than ions. This causes the formation of an electric field that accelerates the ions in the plasma toward the substrate holder. Because of the ambipolar diffusion that keeps the plasma neutral, the ions are extracted from the plasma with the same diffusion coefficient as the electrons. The electrical potential is a function of the gradient of the magnetic field and increases with increasing gradient. The energy of the bombarding ions is about 20 eV [18].

An electric field, propagating parallel to the magnetic field lines and rotating in the plan of the gyromotion of the electron, is called a circularly polarized field. If the field is rotating in the same direction as the gyromotion of the electrons, it is a right-hand circularly polarized field. In a right-hand polarized field, the electrons are in fact exposed to a reduced frequency $(\omega - \omega_c)$ and in this case Eq. (2.7) changes to

$$\overline{P}_v = \frac{n_e e^2 E_o^2}{2m_e}\left[\frac{\nu}{\nu^2 + (\omega - \omega_c)^2}\right] \tag{2.15}$$

In the resonance case, when $\Delta\omega = \omega - \omega_c = 0$, the electrons are continuously accelerated by the magnetic field, and according to Eq. (2.15), the average power absorbed by the electrons is maximal. A drastic gain of power transfer to the plasma is therefore obtained at near-resonance conditions, especially for low-collision frequencies. This is illustrated in Fig. 2-8 which shows the absorbed power as a function of the normalized collision frequency, $\nu/\omega$.

For a microwave frequency of 2.45 GHz and a near-resonance condition corresponding to $\Delta\omega/\omega = 0.1$, the maximum power absorption is obtained at 10 Pa (0.075 torr), as indicated in Fig. 2-8. At lower pressures, the absorbed power is much higher than at nonresonant conditions [19].

It has been shown [20, 21] that the energy absorption in an ECR plasma is greater than 70 to 75% even in the $10^{-4}$ torr pressure range. Asmussen [22] has shown that when gas pressure is increased, there is a transition from ECR heating to collisional heating of the electron gas. This means that the ECR coupling technique is especially useful for low-pressure discharges, approximately below 3 torr.

Propagation of an electric field into a plasma, in the absence of an externally applied magnetic field, requires the fulfillment of the condition

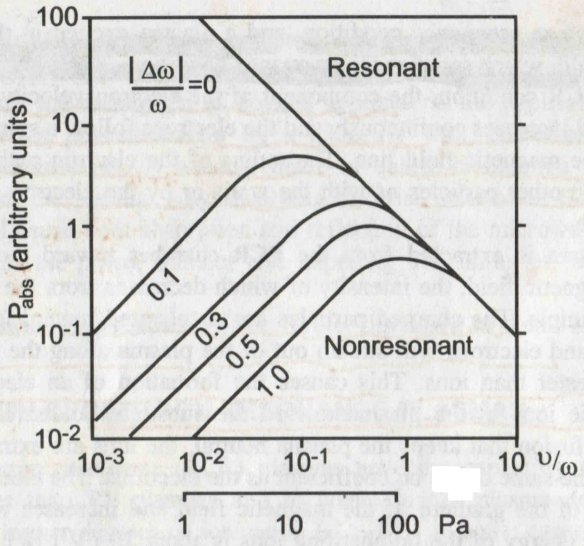


**Fig. 2-8** Absorbed microwave power versus normalized collision frequency; the curves correspond to different values of $|\Delta\omega|/\omega$ (from [19], reprinted with permission from *Journal of Vacuum Science and Technology*, vol. A8, p. 908, 1990).

$$\omega \geq \omega_p \tag{2.16}$$

where $\omega_p$ is the frequency of the plasma given by Eq. (1.33) from Sec. 1.3.5:

$$\omega_p = \left(\frac{n_e e^2}{m_e \varepsilon_o}\right)^{1/2} \tag{2.17}$$

Eq. (2.16) and Eq. (2.17) can be solved for $n_e$:

$$n_e \leq \frac{\omega^2 \varepsilon_o m_e}{e^2} = n_c \tag{2.18}$$

Equation (2.18) shows that, for a given frequency $\omega$ of the electric field, there is an upper limit $n_c$ for the maximum attainable electron density.

If the electron density, $n_e$, is too big ($n_e > n_c$) or the field frequency, $\omega$, too small, an electromagnetic wave cannot pass through the plasma. An increase in the plasma density above the critical value will prevent further absorption of the microwave power in a nonmagnetic plasma. The critical density, also called the plasma *cut-off density*, is the highest plasma density achievable in the bulk of nonmagnetic plasmas. For the frequency of 2.45 GHz, the corresponding cut-off density is

$$n_c = 7.1 \times 10^{10} \text{ cm}^{-3} \tag{2.19}$$

However, when a magnetic field, $B$, is superposed to the plasma, right-hand polarized waves propagate along magnetic field lines, as long as $B$ remains above the ECR value. Plasma densities as high as $n_e = 10^{12}$ cm$^{-3}$ have been obtained in ECR plasmas, when the wave was fed along the magnetic field line [17].

### 2.4.1 Advantages of ECR Plasmas

The magnetic confinement in the ECR plasmas enhances the degree of ionization, which enables operation at low pressures. ECR plasma sources are usually operated in the pressure range of $10^{-5}$ to $10^{-3}$ torr. The combination of low operating pressure with strong microwave coupling generates higher electron temperatures ($T_e \approx 5$ eV) in ECR plasmas as compared to nonmagnetic plasmas. The energy of the ions flowing out of the ECR source is in the range of 10–25 eV, typically three to five times the electron temperature. If necessary, this energy can be increased either by extracting grids at the plasma source or by biasing the processed substrate.

ECR plasmas are becoming a popular etching and deposition tool in microelectronics processing due to their ability to sustain highly dissociated and highly ionized plasmas at very low pressures. Anisotropic etching can be achieved in these plasmas without the damage induced to sensitive substrates by energetic ions in RF plasmas [23].

Some of the advantages of ECR plasmas over RF and DC plasmas are:

1. Lower, broad range of operating pressures
2. High ionization efficiency
3. Wide range of achievable ion energies:
   a. Intrinsic ion energies below values that can induce radiation damage
   b. Higher energies can be achieved easily with assistance of extraction grids, or substrate bias
4. Electrodeless coupling (attractive for use with corrosive gases) of the electric power to the plasma
5. Directionality of the ion and even neutral beam. The directionality of the neutral beam is a result of the large mean free path at low operating pressure and can be exploited for:
   a. Anisotropic etching
   b. Good filling of high-aspect ratio trenches in VLSI processing

## 2.5 QUESTIONS

1. What are the differences between the plasma regimes corresponding to the Townsend discharge and normal discharge regions of the I-V characteristic of a DC discharge?
2. a. What is the breakdown voltage and what determines its value?
   b. What is the value of the breakdown voltage for a discharge in argon at a pressure of 10 torr if the electrodes are 10 cm apart?
   c. At what pressure will the breakdown voltage be minimal in an argon plasma sustained in the reactor of question 2.(b)?
3. What causes the luminosity of the plasma?

4. What are the advantages of RF plasma excitation as compared to DC excitation? Why can an RF plasma be sustained at lower voltages than required by a DC discharge?
5. a. Assuming an elastic collision frequency of $10^{10}$ $sec^{-1}$ and a RF field of an amplitude of 10 $V.cm^{-1}$ at 13.56 MHz, calculate the mean power absorbed by an electron in the plasma.

   b. If the plasma density is $10^{10}$ $cm^{-3}$, what is the average power transmitted to 1 $cm^3$ of this plasma?
6. a. Calculate the bias on the electrode of a RF discharge in a cylindrical reactor described in Fig. 2-9 assuming that
   plasma potential = 30 V
   electrode diameter, $D_e = 5$ in.
   reactor diameter, $D_R = 8$ in.
   reactor height, $h_R = 6$ in.

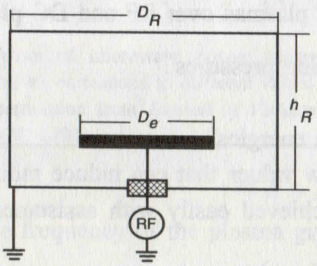


**Fig. 2-9** Cylindrical RF reactor for question 6.

   b. What change in RF power is required to double the self-bias on the electrode?
7. a. Calculate the Larmor radius of an electron that has an energy component of 5 eV normal to a magnetic field of 100 gauss.

   b. Calculate the Larmor radius of an argon ion for the same conditions.
8. Calculate the Larmor radius of an argon ion having an energy component of 3 eV normal to the magnetic field at resonance condition in an ECR plasma sustained at 2.45 GHz. How does the Larmor radius determine the dimensions of the reactor and plasma uniformity?
9. What is the maximum electron energy attainable in a microwave plasma sustained at 2.45 GHz? Compare this value to that attainable in a RF plasma at 13.56 MHz.

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