

Plasma Reactors

4.1 PLASMA SYSTEMS

A block diagram of a cold plasma system used for material processing is presented in Fig. 4-1. Generally, it consists of several subsystems providing different necessary functions as following:

1. Gas handling system, which includes
 - a. *Precursor gas supply.* The source materials or precursors are in most cases gases in high-pressure cylinders or liquids with sufficiently high vapor pressures. Solids with reasonable vapor pressures are also used sometimes as precursors.
 - b. *Mass flow controllers.* These are used to measure and control the flow of the different gases fed to the reactor.

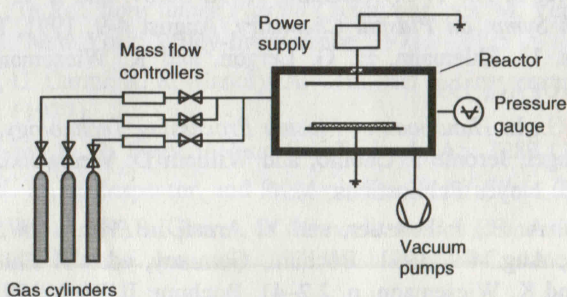


Fig. 4-1 General outline of a system for cold plasma processing.

- c. *Vacuum system comprising pumps and pressure controller.* The plasma reactors for materials processing operate at pressures between 10^{-4} and ~ 10 torr. However, lower background pressure is often required to ensure the cleanliness of the process. Therefore, the whole range of vacuum pumps, from mechanical to cryogenic, are used; the types and sizes of the pumps are determined by the required vacuum levels and gas flow rates.
2. *Plasma reactor.* The plasma reactors will be described in detail in later sections of this chapter.
3. *Powers supplies.* Different types of power supplies will be discussed together with the corresponding reactors. The role of power supplies is twofold: to sustain the plasma in the reactor and to provide a controlled external substrate bias when such is needed for the process.
4. *Safety devices* for handling hazardous gases. Most of the precursors used in plasma processing are hazardous, some even extremely so; these gases can be corrosive, highly toxic, flammable, or explosive. Some gases, such as the extensively used silane, are unpredictably pyrophoric. Germane, or doping gases, such as diborane, phosphine, or arsine, are extremely toxic. Some of the safety devices required when dealing with such hazardous materials are
- a. *Flow limiters*, mounted between the valve of the supply cylinder and the pressure regulator to prevent excessive flow of the gas in case of breakdown of the pressure regulator.
 - b. *Flashback arresters*, required when using flammable or explosive gases to prevent fire propagation to the gas in the cylinder; located in front of the pressure regulator.
 - c. *Cross-purge assemblies*, used to purge the regulators and prevent release of the hazardous gas to atmosphere when exchanging the gas cylinders; they are mounted between the cylinder and the pressure regulator.
 - d. *Scrubbers or diluters* of exhaust from the pumps.
 - e. *Detectors* for hazardous gases.

4.1.1 Process Parameters

For a given system, the outcome of the process is strongly dependent on its parameters. A comprehensive list of the process parameters that can affect the end result of plasma processing is given in Table 4-1 [1]. The classification of these parameters largely complies with the first three subsystems described before. The following list names the most important parameters among those in Table 4-1:

- Partial pressures of the feed gases, or flow rates of the different gases
- Total pressure in reactor
- Substrate temperature and bias

TABLE 4-1 Parameters Controlling Materials Processing by Cold Plasmas
(adapted after [2], reprinted with permission)

| Plasma Processing Parameters | | |
|------------------------------|-------------------------------|-------------------------------|
| Kinetic (gas system) | Electrical (plasma system) | Surface (substrate system) |
| Precursor gases | Frequency (DC to GHz) | Material |
| Carrier gases | Free fall | Conducting |
| Mass flow rates | Mobility | Insulating |
| Pressure | Diffusion | Temperature |
| Gas delivery location | Electrode geometry | Position |
| | Electrodeless | |
| | Electrode | |
| | Discharge power | |
| | Field strength | |
| | Current density | |
| | Particle energy | |
| | Active neutrals | |
| | VIS to UV radiation | |
| | Electrode material | |

- Reactor geometry and material
- Electrode material and distance between electrodes
- Electric power applied to the plasma

These parameters have to be carefully controlled to define the plasma chemistry and to achieve the desired results.

The complexity of the relationship between the macroscopic variables of a cold plasma processing system and the microscopic plasma parameters is illustrated in Fig. 4-2. Changes in macroscopic plasma variables such as composition of feed gas, flow rates, pumping speed, electrical discharge power, and frequency will generally change the basic plasma conditions, but the precise manner of these changes is in most cases unknown.

The RF power determines the current and voltage between the electrodes. The composition of the gas mixture can affect the chemical reactions inside the plasma reactor and the properties of the final product, for example the composition of deposited film or the anisotropy and selectivity of etching. The composition of the gas feed, the total pressure in the reactor, and the electrical power will each affect the rates of the reactions. The reaction rates can be affected also by the distance between electrodes and by substrate bias or temperature. These last two plasma parameters can also affect the structure of a deposited film or the etching

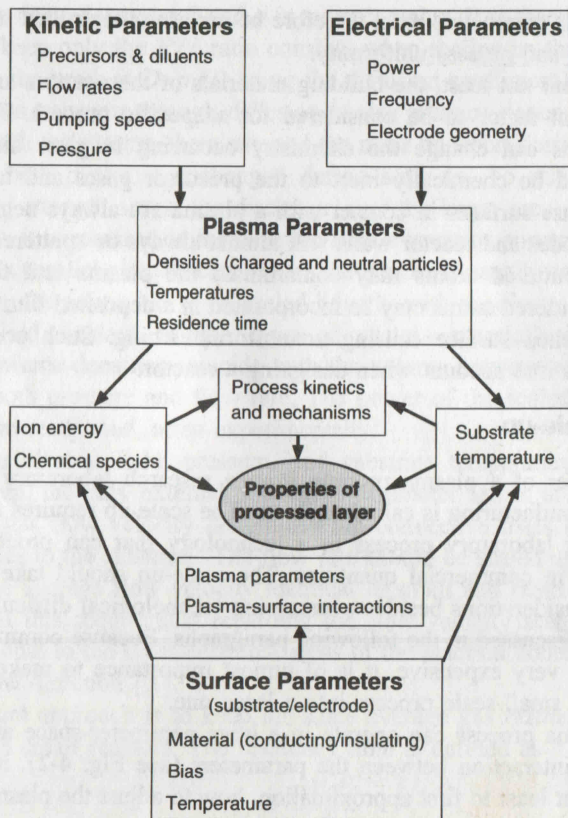


Fig. 4-2 Complexity of interaction between plasma variables (after [3], reprinted with permission). The arrows indicate the possible interactions between process parameters; they do not indicate that all the described interactions always take place.

anisotropy. The flow rates, total pressure, and reactor geometry can determine the uniformity of the process.

The gas flow rate, the pumping speed, and the pressure are interrelated. The pressure can be changed in two ways: by changing the flow rate at constant pumping speed or by changing the pumping speed at constant flow rate. While the two methods can provide the same pressure, they result in different residence times for the species in the reactor (see Sec. 4.1.2). The different residence times can cause changes in the chemistry of the process [4].

The frequency of the electric field is also a system parameter that can affect the plasma process or the properties of the product. A variation of the frequency can affect the number and energy of ions that can follow the alternating field, thus changing the flux and energy of the particles bombarding the plasma treated surface.

The process parameters must therefore be precisely controlled to achieve the required results and process uniformity.

And last, but not least, the building materials of the reactors and electrodes are an important factor to be considered for a specific process. Electrode and reactor materials can change the chemistry occurring in glow discharge. The materials should be chemically inert to the precursor gases and to the plasma products. Because surfaces in contact with a plasma are always negative relative to it, the electrodes and reactor walls will almost always be sputtered to a certain degree. The sputtered atoms may contaminate the plasma and the processed sample. The sputtered atoms may be incorporated in a deposited film or may mask areas of an etched surface causing nonuniform etching. Such possible effects should be taken into account when designing a reactor.

4.1.2 Scale-up

The transfer of a plasma process from a research laboratory apparatus to commercial manufacturing is called *scale-up*. The scale-up requires the upgrading of the working laboratory process to a technology that can process uniformly larger samples in commercial quantities. The scale-up should take into account economical considerations besides overcoming technological difficulties, some of which will be discussed in the following paragraphs. Because commercial scaled-up reactors are very expensive, it is of utmost importance to make a successful transfer from a small-scale process into a large one.

As a plasma process can operate in a large parameter-space and due to the complexity of interaction between the parameters (see Fig. 4-2), it is important to understand, at least to first approximation, how to adjust the plasma parameters according to changes in the size of the reactor.

The substrate temperature will normally be kept unchanged during the transfer of the process from a small to a large reactor. The main question is how to adjust gas flow rates, pressure, and electrical power in such a way that the scale-up of the reactor will not significantly affect the plasma chemistry. For this purpose, plasma processing can be conceptualized as being constituted of two subsequent processes [5]:

1. Formation of reactive species
2. Mass transport of the reactive species to the processed surface by convective diffusion

For the first process, it has been shown theoretically that, if the dissociation of the precursor molecules takes place through single collisions, the rate coefficients for the reactions caused by electrons depend only on the value of the ratio E/p , because the electron temperature in the plasma is determined mainly by E/p (E is electric field strength). One may therefore consider as a first approximation the fact that molecular dissociation rates caused by electron impact are dependent only on the E/p ratio. However, if dissociation is produced through multiple

collisions, the dependency on E and p is more complex. It is therefore usually not sufficient to keep only the E/p ratio constant when scaling-up the process.

Because the product $D \cdot p$ (D being the diffusion coefficient) is constant for a gas, the mass transport through diffusion is also pressure dependent. Therefore, to preserve both the plasma chemistry and the mass transport during scale-up, one has to keep both p and E unchanged during scale-up. To maintain the same electrical field strength across the discharge over the larger area of the manufacturing reactor, it is required to increase the total current or power supplied to the discharge. In a parallel plate reactor, where the plasma is usually confined between the electrodes, the power has to be scaled linearly with the electrode area to keep the electric field constant. In other types of reactors, especially in tubular ones, the plasma volume does not coincide with the volume between electrodes and is affected by both pressure and flow rate. The power of the scaled-up reactor has to be therefore readjusted, often experimentally.

With the electric field, pressure, and substrate temperature kept constant during scale-up, the only external adjustable parameter left is the gas flow rate. The average gas flow velocity determines the convective mass transport of the reactive species to the substrate. The flow rate should be scaled up in such a way as to keep the average flow velocity identical in small and large reactors. It can be shown that this requirement regarding the flow velocity scales the gas flow rates proportional to the cross-sectional areas of the reaction zones, perpendicular to the gas flow direction [5].

A different approach is to keep the same average gas *residency time*, τ_r , in both large and small reactors. The residency time is defined as

$$\tau_r = \frac{p \text{ Vol}_r}{Q} \quad (4.1)$$

where Vol_r = volume of reaction zone

Q = total mass flow rate

The gas residency time is a measure of the average distance over which the reactive species diffuse in the reaction zone, and thus determines the diffusional mass transport. According to Eq. (4.1), if the pressure is kept constant, the requirement of constant residence time scales the gas flow rates proportional to the volumes of the reaction zone. If the interelectrode distances are the same in the large and small parallel plate reactors, the requirements for the same gas velocity and same gas residency time are equivalent. In other types of reactors, the volume of the reaction zone can be dependent on the gas flow rate, and this approach cannot be used.

In summary, the main process parameters have to be adjusted during scale-up to a first approximation as following:

| | |
|---------------------------|---|
| <i>sample temperature</i> | unchanged |
| <i>pressure</i> | unchanged |
| <i>electric power</i> | proportional to area of electrodes in parallel plate reactors |

gas flow rates

proportional to electrode area normal to the flow direction, or proportional to volume of reaction zone.

It thus appears that the main changes in plasma parameters during scale-up are the linear extrapolations of electric power and gas flow rates. However, these changes alone may not be sufficient. In practice, a change in reactor geometry may affect other important intrinsic plasma parameters, especially if the reactors are not of the parallel plate type.

The foregoing description of scale-up principles did not take into consideration how the active species are formed along the flow path of the gas from the gas inlet to the treated substrate and their interaction before reaching the substrate. The formation and transport of the reactive species that form the final product are dependent on the flow patterns and on the time spent along the path to the substrate. The diffusion of the precursor molecules takes place along most of the distance from the gas inlet to the substrate, while diffusion of reactive species takes place mainly from the boundary of the plasma zone to the substrate. The reactor geometry and the geometry of the electrodes (size, distance between them) can change the gas flow patterns, the relative volume of the plasma region, the transport of the reactive species, and the rate and uniformity of the process.

Electric field patterns, especially at the edges, are also influenced by the reactor geometry and may affect the uniformity of the process at the edges of the substrate. This is especially true for tubular reactors or for bell jar reactors, often used in plasma polymerization [6]. In such reactors the volume of the plasma is not defined by the electrodes and is dependent on the interaction between different plasma parameters. Finally, the wall temperature of the scaled-up reactor is generally different from that in the smaller one, causing different gas retention or memory effects.

Because of these effects, the approximated parameters of the scaled-up reactor have to be generally readjusted either empirically or using theoretical modelling of the process and reactor. The last approach would generally still need empirical fine-tuning of the process parameters.

The ease with which a reactor can be cleaned has to be given careful consideration during its design. This is especially important for deposition reactors. Film material that deposits and accumulates on the surroundings of the deposition zone and on the walls of the reactor has to be regularly removed from any deposition system to avoid flaking and powder formation that may have adverse effects on the quality of the film deposited on the substrates.

Another important aspect to be considered when scaling up a laboratory system to a commercial manufacturing unit is the efficiency of precursor utilization, or the *material efficiency* of the process. In a deposition process, the material efficiency can be defined as the ratio between the weight of the deposited film and the weight of the film components in the feed gas. The material efficiency can be defined similarly for an etching process, in this case taking into account the removed instead of the deposited material. The highest material

efficiency is generally obtained at high plasma density and low flow rates and, at a first approximation, is independent of pressure for the processes described in this book (based on gaseous precursors). The pressure, however, affects the process efficiency in sputtering processes, where the sputtering yield is pressure dependent. Because of the condition of low flow rate, high material efficiency is usually associated with lower process rates in deposition and etching. As a result, high material efficiency does not always imply maximum process efficiency, which demands high process rates [5].

The optimum trade-off between reactor design, material efficiency, and process rate is determined by each individual manufacturing process. The development of a manufacturing process is finally to a large extent empirical in defining the optimal conditions for achieving either film deposition or etching rate uniformity.

Due to the diversity of plasma reactor designs and plasma parameters, it is not within the scope of this chapter to describe in detail all designs and experimental approaches used. Only the general principles of the most common used reactor designs for producing the plasmas, based on the methods discussed in Chapter 2, are described in the following.

4.2 DC REACTORS

DC plasma reactors operate as described in Sec. 2.1. The plasma is sustained between two parallel plate electrodes as illustrated in Fig. 2-1, and the electric power is supplied to excite the plasma in the abnormal discharge mode. The distance between the electrodes and the pressure in the reactor have to satisfy Paschen's law for the used gas mixture (see Sec. 2.1.1).

The power supplies used to sustain DC plasmas can generally be used at constant voltage, constant current, or constant power mode. The power supplies should be able to control the preset value in each mode. The excitation and sustainment of a DC plasma require the use of electrically conductive electrodes and samples. However, electrically insulating films may deposit locally on the surface of the electrodes or samples due to contaminants formed in the plasma. In such cases, local dielectric breakdown normally occurs, causing arcing that results in spikes of high currents.

The power supply must be able to withstand these spikes and return to normal operation without shutting off. However, it must also be able to distinguish between the transient arcing currents and shorts that may occur between the electrodes and grounded surfaces. This feature, called *arc suppression*, must be a characteristic of a DC power supply of a plasma reactor.

4.3 RF REACTORS

The power supplies used to sustain commercial RF plasma systems are operated at specific frequencies established by international agreements [7]. The most used

frequency is 13.56 MHz, but sometimes the higher harmonics of 27.12 MHz and 40.68 MHz are also used. The RF generators are designed to operate at constant output impedance of 50 Ω . The impedance of the glow discharge is, however, much higher and varies with the process parameters. An impedance matching network or matching unit is thus required between the RF power supply and the reactor. Otherwise, most of the power will reflect to the power supply instead of being absorbed into the plasma.

The matching unit is placed physically as close as possible to the powered electrode. In parallel plate reactors the matching unit is usually mounted on the flange supporting the powered electrode. Normally, variable automatic matching units are used, and these adjust themselves to keep the output impedance of the RF power supply constant at 50 Ω , independent from the changing plasma conditions.

4.3.1 Electrodeless Discharges

When using high-frequency power supplies, it is possible to transfer the energy to the plasma without inserting the electrodes inside the reactor, if a suitable coupling between the power supply and the reactor is used. For such a design, the reactor has to be built from dielectric materials such as quartz or Pyrex, which are generally used for this purpose. Since the electrodes are not in direct contact with the discharge, the plasma formed is called an *electrodeless discharge*.

Electrode designs for transferring the power to the plasma in electrodeless discharges are illustrated in Fig. 4-3. These electrodes correspond to two types of coupling the RF power to the electrodeless plasmas:

1. *Inductive coupling*, in which a coil connected to the power supply through a matching unit is wound around a tubular reactor, as shown in Fig. 4-3 (a).
2. *Capacitive coupling*, in which the RF power is transferred between two separated electrodes mounted outside the reactor. The electrodes can be in the shape of two rings mounted around the reactor as shown in Fig. 4-3 (b) or two plates placed along the reactor as shown in Fig. 4-3 (c).

Although the terms of inductive and capacitive coupling are often used as just defined, the inductive coupling is not purely inductive, and it always has a capacitive component too, through the wall of the reactor. Thus, when an inductive coupling is used, deposition on the walls is often observed to follow a pattern matching the shape of the coil. This is an indication of localized stronger electric fields on the walls, showing that the coupling is at least partly capacitive through the walls of the reactor [2].

In a tubular reactor of one of the types shown in Fig. 4-3, and especially in Fig. 4-3(a), the strength of the electric field is not uniform along the reactor. Therefore the substrate position inside the reactor becomes a parameter that can

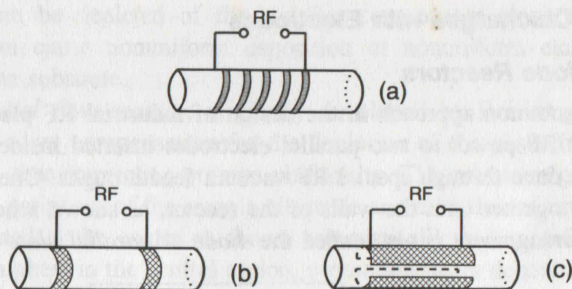


Fig. 4-3 RF coupling methods to electrodeless reactors.

affect the result of the process and can be controlled to achieve desirable properties [8, 9]. In tubular reactors the substrates are usually positioned with their surfaces perpendicular to the axis of the reactor.

The types of RF reactors just described, also called *barrel reactors*, are used sometimes for industrial applications, although they are more popular in research laboratories, being relatively inexpensive and easy to set up. In industrial applications, the tubular reactors are normally used for ashing of photoresist or etching in microelectronic fabrications and for noncritical deposition processes where uniformity is of no great concern.

A barrel reactor used for etching often includes an *etch tunnel*. The metallic perforated cylindrical etch tunnel, illustrated in Fig. 4-4, is inserted in the reactor

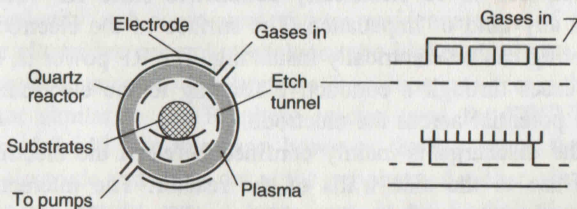


Fig. 4-4 Diagram of a barrel reactor.

to improve temperature uniformity along the length of the sample holder and to minimize particle bombardment of the substrates. This metallic cylinder acts as a Faraday cage and confines the glow region to the annulus between the etch tunnel and the wall of the reactor. Substrates are thereby shielded from direct contact with the plasma and are subject to little, if any, ion or electron bombardment. Neutral species diffuse, nevertheless, through the perforations and reach the surface of the processed substrates.

4.3.2 RF Discharges with Electrodes

4.3.2.1 Diode Reactors

The most common approach in the design of industrial RF plasma reactors is to couple the RF power to two parallel electrodes inserted inside the reactor. The coupling is done through special RF vacuum feedthroughs. One electrode is often grounded together with the walls of the reactor, as shown schematically in Fig. 4-5. This arrangement is also called the *diode* or *parallel plate reactor*.

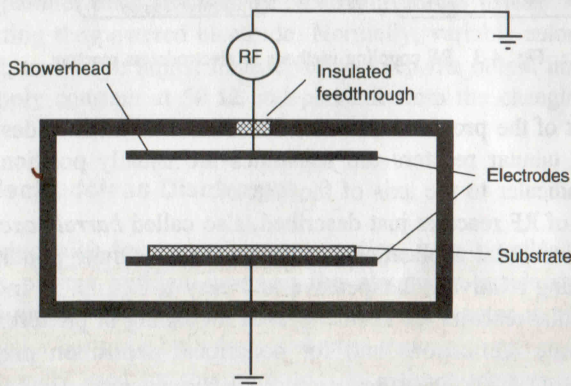


Fig. 4-5 Power coupling to a planar diode reactor.

For RF discharges, the surface of the electrodes in contact with the plasma are no longer required to be electrically conductive since RF voltages can be coupled through any kind of impedance. The surface of the electrode, substrate, or deposited coating can be electrically insulating. The RF power is, nevertheless, supplied in all cases through a conductive backing to the electrodes, to ensure uniform electric potential across the electrode.

Although the discharge is mainly confined between the electrodes, plasma species also diffuse to the side walls of the reactor. The interaction between plasma and electrodes can result in contamination of the plasma with atoms, which are either physically sputtered or chemically etched from the electrodes. The same is true, though to a lesser extent, for contamination with atoms from the walls. The right choice of materials for electrodes and reactor is therefore of utmost importance, especially in microelectronic processing, for which prevention of contamination is imperative. The electrodes are usually made of stainless steel and the reactors are built from stainless steel, aluminum, or quartz.

Capacitive coupling to parallel electrodes inside the reactor enables the creation of uniform electric fields, making it possible to achieve high process uniformity over large areas, determined by the size of the electrodes. However, the uniformity of the electric field alone is not sufficient to guarantee the uniformity of the results of PECVD processing when reactive gases are involved. Depending on their concentration and consumption and on their flow pattern in the reactor,

the gases can be depleted of the reactive components along their path. This depletion can cause nonuniform deposition or nonuniform etching across the surface of the substrate.

The *radial flow reactor*, originally developed by Reinberg [10, 11], was designed to allow compensation for the depletion of the gases from the reactive components, thus improving process uniformity. The precursor gases were introduced at the periphery of the sample electrode and then flowed inward where they were exhausted at the center as shown schematically in Fig. 4-6. The discharge intensity is highest in the central region, promoting faster depositions in that area.

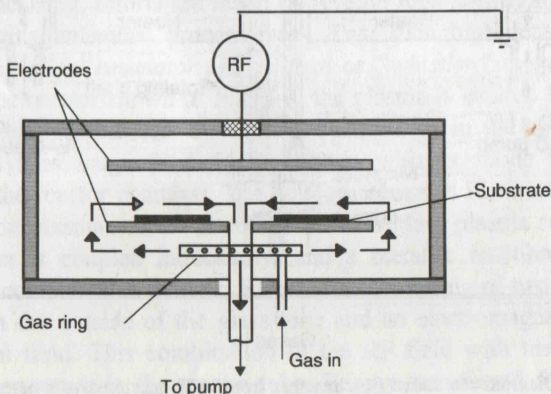


Fig. 4-6 Diagram of a Reinberg reactor.

The higher velocity and consequent shorter residence time of the gases at the center of the electrodes can counterbalance the higher discharge intensity in the center, leading in many cases to a uniform deposition rate across the whole radius.

A reactor similar to the Reinberg reactor used for PECVD processing is shown in Fig. 4-7 [12]. In this case, however, the gas enters through the center of the lower electrode and flows out at the periphery. Another often-used approach for achieving uniformity over a large area is by feeding the gas through a showerhead that forms one of the electrodes in the parallel plate reactors. The sample electrode can sometimes be heated or rotated to smooth out nonuniformity in processing.

4.3.2.2 Triode Reactors

If both electrodes in a parallel plate RF reactor are insulated from the walls, the reactor is called a *triode-type reactor*. In the triode reactor, each electrode and the reactor walls can be powered independently, and each can be biased, floating, or grounded. A diagram of a triode reactor is shown in Fig. 4-8.

Another version of the triode reactor is the one in which the discharge is sustained between two electrodes and the substrate is supported on a third elec-

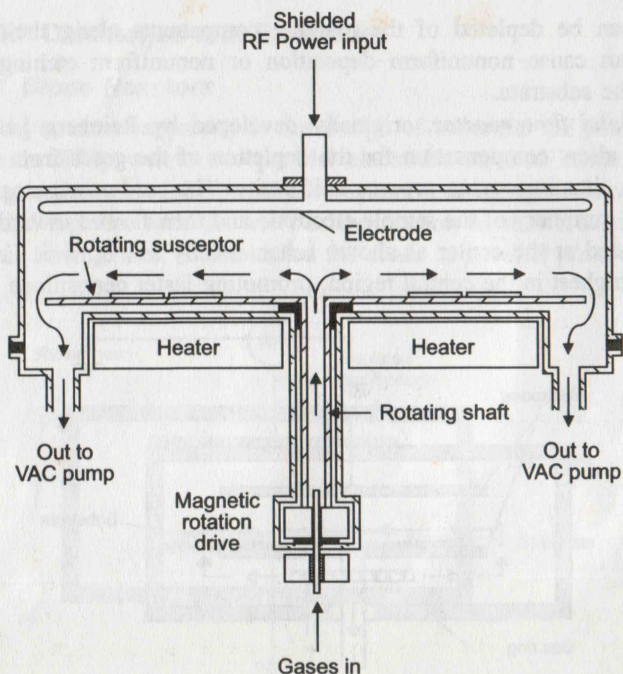


Fig. 4-7 Diagram of a radial flow reactor (from [12], reprinted with permission from *Thin Solid Films*, vol. 113, p. 135, 1984).

trode, which can be biased separately [13]. The electrodes in a triode reactor can be powered by combinations of power supplies, such as RF and microwave, RF and DC, RF and AC (< 50 kHz). While in the diode reactors, the RF power density may be limited by the maximal bias allowable on the substrate electrode, this limitation is eliminated in the triode reactors. The plasma density is controlled

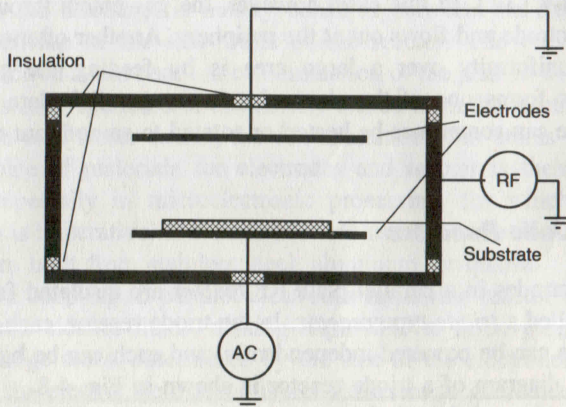


Fig. 4-8 Power coupling to a planar triode reactor.

by the power sustaining the plasma, while the substrate bias and thereby the energy of the ions bombarding it is controlled directly by the generator supplying the power to the substrate electrode.

Sometimes the discharge in a planar reactor may be assisted by thermionic electrons emitted from a hot filament; this type of reactor is also called a triode reactor.

4.3.3 High-Density RF Reactors

While different variations of the RF reactors described previously are widely used in manufacturing, efforts are made to develop *high-density RF plasma reactors* for achieving enhanced process rates. Two such high-density RF plasma sources are the *helical resonator* and *helicon* or “*whistler*” source [14]. In the helical resonator reactor shown in Fig. 4-9, the plasma is excited by a slow wave structure that achieves quarter- or half-wave resonance in the source [14]. The helicon source uses magnetic fields to obtain whistler mode waves that are launched into the reactor chamber. The helicon reactor is illustrated in Fig. 4-10.

The helicon plasma reactor is composed of a glass plasma source, to which electrical power is coupled inductively, and a metallic reaction chamber. The helicon source comprises an external RF antenna consisting of two loops diametrically placed on the outside of the glass tube and an electromagnet that produces a constant axial field. This combination of the RF field with the magnetic field excites a helicon wave in the source tube. Energy transferred from the helicon wave sustains the plasma. The axial magnetic field restricts the radial motion of the electrons and confines their movement along the magnetic field lines. If the

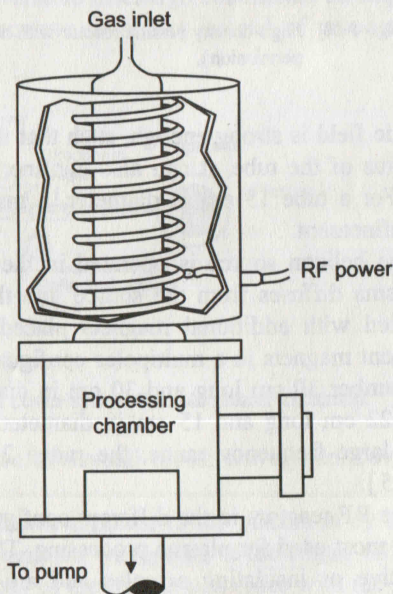


Fig. 4-9 Diagram of plasma reactor with helical source (from [14], reprinted with permission).

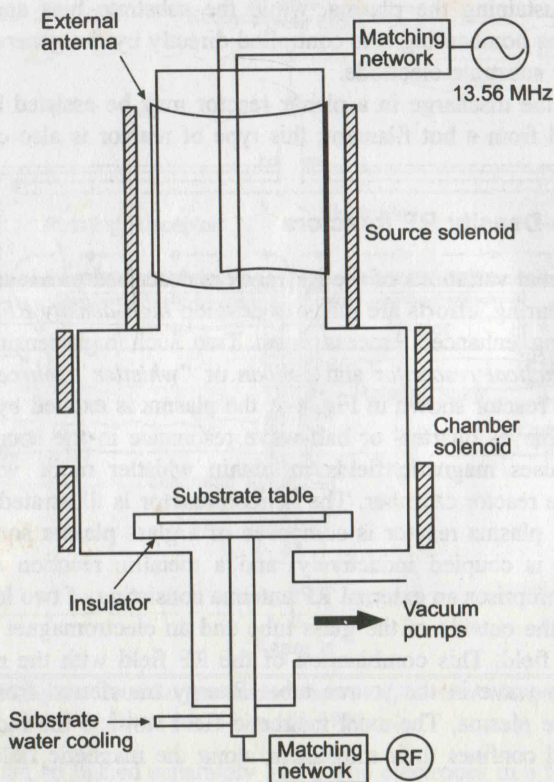


Fig. 4-10 High-density plasma reactor with helicon source (from [15], reprinted with permission).

magnetic field is strong enough, such that the ion cyclotron radius is smaller than the radius of the tube, it can also confine the ions by reducing their loss to the walls. For a tube 15 cm in diameter, a magnetic field of ~ 100 G can achieve the confinement.

The helicon source is operated in the pressure range 10^{-4} – 10^{-2} torr, and the plasma diffuses from the source into the reaction chamber. The diffusion is controlled with additional magnets placed around the chamber. These can be permanent magnets in a multipolar configuration or electromagnets [15]. A reaction chamber 30 cm long and 30 cm in diameter can be operated with a helicon source 22 cm long and 15 cm in diameter. The helicon source can be operated over a large frequency range, the range 2–70 MHz appearing to be most suitable [15].

The RF reactors in the different configurations are the most versatile reactors and are most used for plasma processing. The RF reactors can process electrically conductive or insulating samples and are used for deposition of inorganic or

polymeric films, for surface treatment of organic or inorganic solids, and for plasma and reactive ion etching.

4.4 MICROWAVE REACTORS

The microwave plasmas are sustained by coupling the microwave energy to the plasma gas through applicators of various designs. Microwaves are easily absorbed or reflected by most materials and cannot be transmitted via cables, like RF energy, without significant losses. Special coaxial cables can be used to transmit low-power (< 200 W) microwaves. The coax consists of two concentric conductors separated by a dielectric. For higher-power levels, specially designed waveguides have to be used. The waveguides are hollow rectangular tubes of high electrical conductivity. The cross sections of the conductors of the coax or the waveguide are determined by the wavelength of the microwave [16].

A microwave power supply system used for microwave or ECR plasma generation is illustrated in Fig. 4-11 and consists of

1. A filtered, low-ripple microwave power supply of constant frequency but variable power.
2. A circulator, whose role is to protect the power supply from large reflected power which may result from an impedance unmatched microwave applicator.
3. Meters for monitoring both the incident and reflected power.
4. A variable, manual or automatic, impedance matching of the applicator with plasma, at different and variable discharge conditions; an impedance mismatch will cause the microwave to reflect instead of propagate into the plasma.

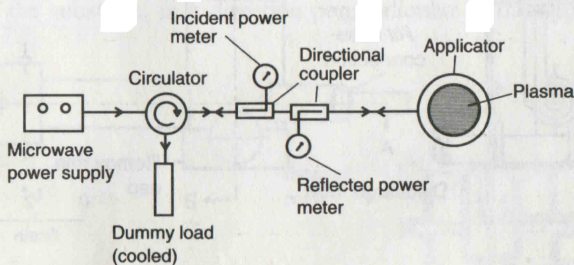
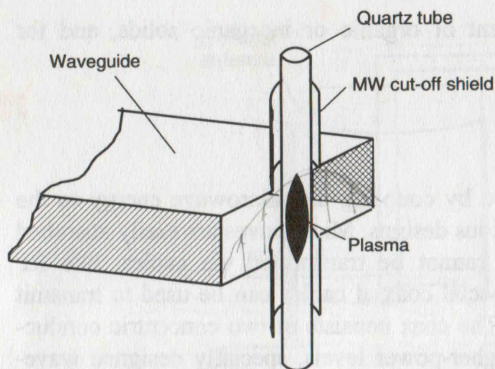


Fig. 4-11 Diagram of microwave power system for cold plasma excitation.

The microwave applicators can be of several types: waveguide, cavity, and coaxial.

The simplest way to transfer microwave power to the plasma is by inserting a dielectric tube reactor through a rectangular waveguide at the center of its wide face, as illustrated in Fig. 4-12. The axis of the reactor coincides with the position



✓ Fig. 4-12 Waveguide-tube microwave coupling.

of the highest electric field in the waveguide, facilitating the acceleration of the electrons by the microwave. To prevent leakage of microwave outside the reactor, the discharge region is enclosed on both sides by metallic tubes with diameters smaller than the cut-off diameter corresponding to the wavelength of the used microwave [16].

The diameter of the reactor is limited in this case by the size of the waveguide, whose width for a frequency of 2.45 GHz is 7.21 cm.

Fig. 4-13 illustrates a different way of microwave coupling to the plasma by a quarter-wave microwave cavity or an Emerson antenna. It is essentially a resonance cavity that is fed by a coaxial cable and is suitable for low powers (< 200 W). The cavity has a removable cap that allows easy disconnection of the

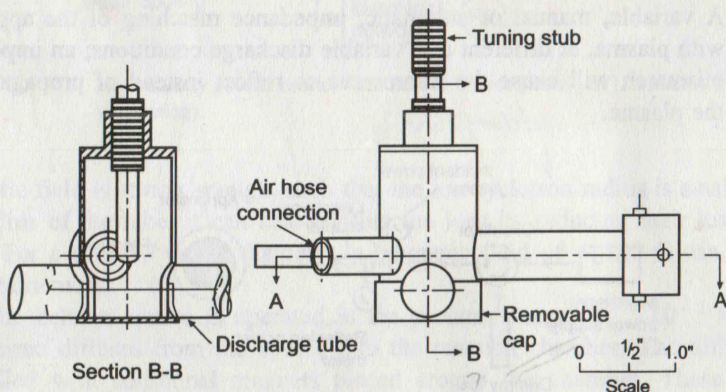


Fig. 4-13 Coaxial $\lambda/4$ cavity (from [17], reprinted with permission from *Plasma Chemistry in Electrical Discharges*, p. 65, 1967).

reactor from the cavity. For microwaves of a frequency of 2.45 GHz, the diameter of the reactor is generally limited to less than 2 cm.

Microwave plasmas of larger volumes than those attainable by direct coupling through the waveguide (Fig. 4-12) can be produced by coupling the microwaves through a larger cavity. Special axisymmetric microwave couplers can convert the

microwaves from the rectangular waveguides to circular applicators. In a circular applicator the plasma is symmetrical and can have a nearly uniform radial electric field profile. An example of an axisymmetric applicator that produces plasmas for processing wafers 3–4 inches in diameter [18] is shown in Fig. 4-14.

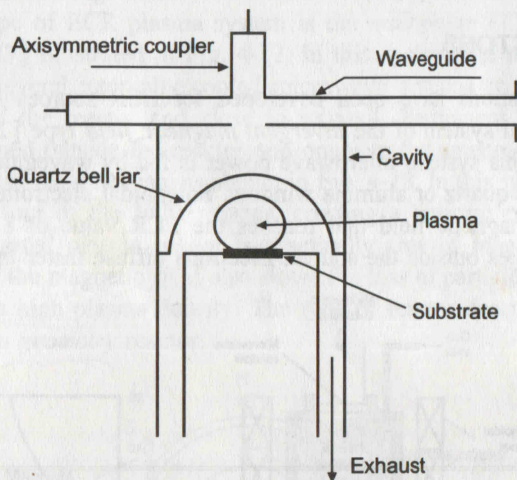


Fig. 4-14 An axisymmetric microwave coupler (from [18], reprinted with permission from *Research & Development Magazine*, October, 1989, by Cahners Publishing Company).

Microwave reactors have been designed for plasma treatment of even larger areas. A reactor designed for large-area etching of polymers [19, 20] combines a long and narrow microwave applicator ($42 \times 7.5 \text{ cm}^2$) with a translational movement of the substrate, in a direction perpendicular to the applicator.

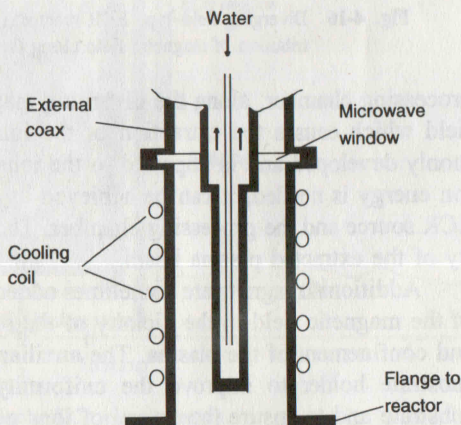


Fig. 4-15 Coaxial microwave coupling to a plasma reactor.

Microwave power can be coupled into a plasma also by using coaxial applicators. As illustrated in Fig. 4-15, the central conductor of the coax is in direct contact with the plasma and has to be generally water cooled. The insulator that separates the central conductor from the external one has also to provide a vacuum seal at the insertion in the reactor.

4.5 ECR REACTORS

Several configurations have been developed for ECR sources for cold plasma reactors. A typical system of the *divergent magnetic field* type [21] is illustrated in Fig. 4-16. In this system, microwave power is fed by waveguide into the ECR cavity, through a quartz or alumina window. Solenoidal electromagnets (see Fig. 4-16) create a magnetic field that reaches the ECR value of 875 gauss in the source and diverges outside the source. Electrons diffuse faster than ions into the

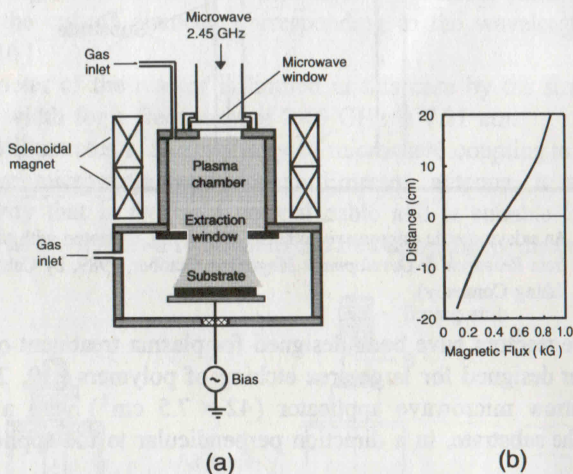


Fig. 4-16 Diverging field-type ECR reactor: (a) plasma source and reactor; (b) distribution of magnetic field along the plasma.

processing chamber, along the diverging magnetic field lines, creating an electric field which causes the extraction of the ions. A potential of 15–20 eV is commonly developed and is imparted to the ions extracted from the source. If higher ion energy is needed, it can be achieved by placing extracting grids between the ECR source and the processing chamber. The grids can also improve the uniformity of the extracted plasma beam.

Additional magnets are sometimes added outside the source to permit shaping of the magnetic field in the vicinity of the substrate and to achieve better control and confinement of the plasma. The auxiliary magnets can be located behind the substrate holder to improve the uniformity of ion current density across the substrate and to ensure the arrival of ions perpendicular to the surface.

The normal ion incidence on the substrate is especially important in etching where ion bombardment contributes to etching anisotropy. In film deposition, the normal arrival of the ion on the coated surface is essential for preventing void formation when filling features of high-aspect ratio [22]. If additional substrate bias is required, it can be achieved by connecting a RF power supply to the sample holder as indicated in Fig. 4-16.

Another type of ECR plasma system is the *multipolar ECR*, or *distributed ECR*, reactor [23] illustrated in Fig. 4-17. In this system, the microwave power is fed through several internally cooled microwave antenna rods, located inside the periphery of the reactor and close to its wall. Permanent samarium cobalt magnets positioned outside the reactor and opposite the antennas create resonant field cusps next to the antennas, as shown in Fig. 4-18. In this type of reactor the plasma diffuses out of the ECR regions, creating a uniform plasma inside the reactor. The internal plasma region is practically free of magnetic fields. The configuration of the magnetic field also slows the loss of particles to the wall and helps maintain a high plasma density. The type of reactor described here is also named *multicusp geometry* reactor.

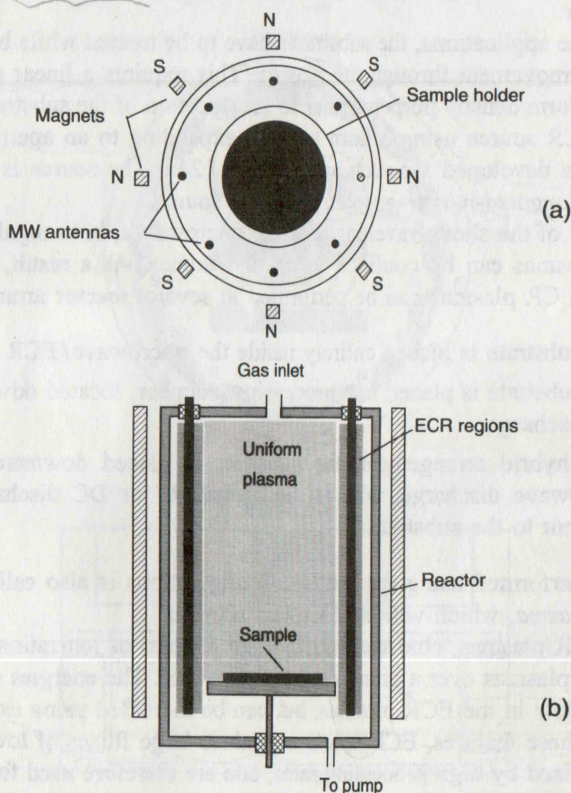


Fig. 4-17 Multipolar ECR plasma reactor.

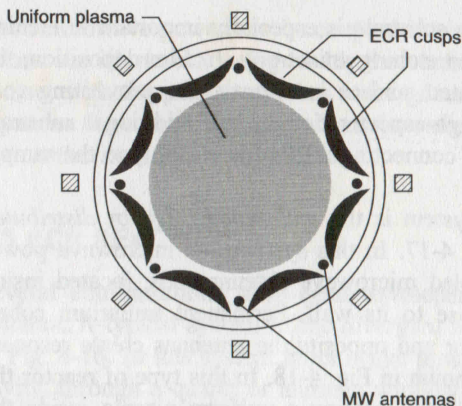


Fig. 4-18 ECR region in multipolar ECR reactor.

In the diverging field ECR plasma system shown in Fig. 4-16, the ions flow along the magnetic field lines, making it a line-of-sight process, while in the multipolar ECR the plasma is essentially isotropic in the internal processing region of the reactor.

For some applications, the substrates have to be treated while having a linear translational movement through the plasma. This requires a linear plasma source having a uniform density perpendicular to the direction of the substrate movement. A special ECR source using a horn antenna expanding to an aperture of $60 \times 9 \text{ cm}^2$ has been developed for such applications [24]. The source is called by the authors an *elongated-mirror-geometry (EMG)* source.

Because of the short wavelength of the microwaves, both regular microwave and ECR plasmas can be confined to small volumes. As a result, processing in microwave/ECR plasmas can be performed in several reactor arrangements:

- The substrate is placed entirely inside the microwave/ECR discharge.
- The substrate is placed in a processing chamber, located downstream from the discharge.
- In a hybrid arrangement, the substrate is placed downstream from the microwave discharge, with an additional RF or DC discharge sustained adjacent to the substrate.

Processing performed using the last two configurations is also called *processing by remote plasma*, which will be discussed later.

The ECR plasmas, characterized by high degrees of ionization, can produce high-density plasmas over a broad range of pressures. The energies of the ions are intrinsically low in the ECR plasmas, but can be increased using extraction grids. Because of these features, ECR reactors produce large fluxes of low-energy ions, are characterized by high processing rates, and are therefore used for single-wafer processing, for etching of wafers, or for deposition of coatings. The large mean free path of the particles at the low operating pressures of the ECR plasmas results

in directionality of the ion and neutral beams. When used for anisotropic etching, ECR reactors cause lower wafer damage than reactive ion etching performed in RF reactors at much higher ion energies.

4.6 MAGNETICALLY ENHANCED REACTORS

The high-density plasmas obtained in the ECR reactors are a result of the interaction between the electric field at microwave frequencies and the superposed magnetic field. The value of the magnetic field has to be adjusted to create resonance between the frequency of the electric field and the electron cyclotron frequency. Magnetic fields can be used to enhance plasma densities also at nonresonant conditions. Two types of magnetically enhanced plasma reactors are described in the following.

The *magnetically confined reactor (MCR)*, is essentially a triode reactor that uses additional magnetic fields to confine the plasma and to reduce the loss of

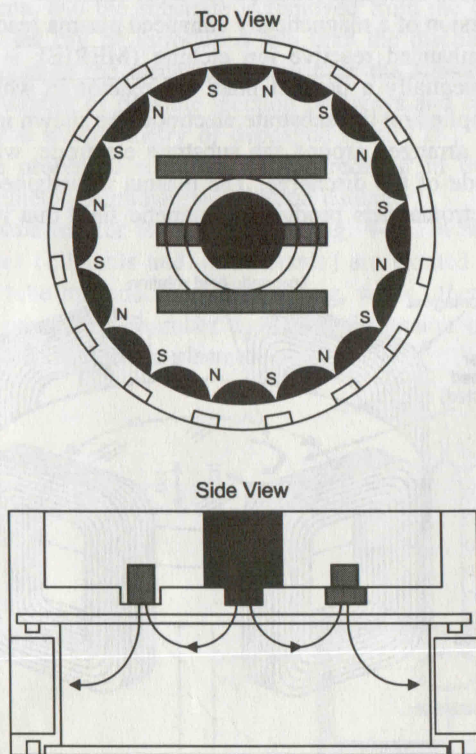


Fig. 4-19 Magnet arrangement in a magnetically confined reactor. The arrows indicate the magnetic field lines (from [25], reprinted with permission).

charged species to the walls. The triode reactor, similar to the one shown in Fig. 4-8, uses two power supplies at different frequencies: one for exciting the plasma and one for biasing the substrate electrode. A 13.56-MHz power supply is used to sustain the plasma, while a 100-kHz power supply provides the bias to the substrate. The magnetic confinement is produced by permanent magnets arranged around the perimeter of the reactor and imbedded in the grounded upper electrode, as illustrated in Fig. 4-19.

The power supplied by the high-frequency field controls the amount of dissociation and generation of reactive species. The low-frequency field controls the ion flux to the substrate and enhances the directionality of the process, especially in etching.

The confinement of the plasma by the magnetic fields results in an enhanced plasma density. The arrangement of the magnets keeps the magnetic field lines away from the processed wafer (see Fig. 4-19), preventing a direct influence of the magnetic field on the process. The MCR is used at pressures of a few mtorr [25, 26]. Being based on RF power supplies and using a magnetic field that is independent from the frequency of the electric field, the equipment used for the MCR is much simpler than that required for ECR reactors.

A different version of a magnetically enhanced plasma reactor used especially for magnetically enhanced reactive ion etching (MERIE), is the *rotating field reactor*. This is essentially a parallel plate RF reactor in which a time-varying magnetic field is applied on the substrate electrode. As shown in Fig. 4-20, several electromagnets are arranged around the substrate electrode, which in most cases serves as the cathode of the discharge. The plasma is sustained by a 13.56-MHz generator. The electromagnets produce a magnetic field that rotates slowly, at a

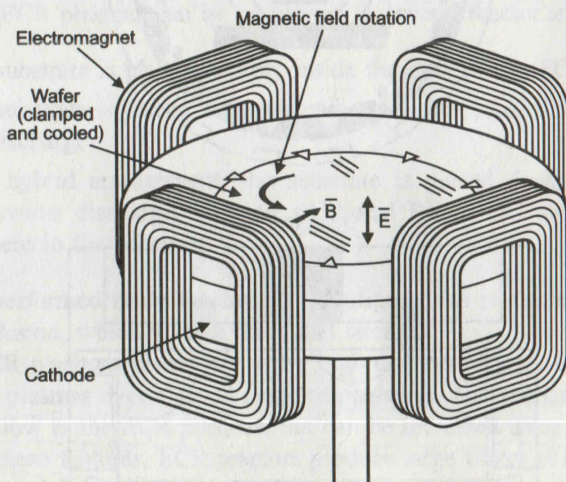


Fig. 4-20 Cathode and electromagnets in a rotating field reactor (from [27], reprinted with permission).

frequency of 0.5 Hz, in the plane of the electrode. This arrangement produces a high flux of low-energy ions, resulting in high processing rates with reduced substrate damage [27]. Both MCR and rotating field reactors are considered alternatives to ECR reactors, especially for plasma etching.

4.7 REMOTE PECVD REACTORS

In the reactors previously discussed, the processed samples are inserted directly in the plasma excited in the feed gases. The processing in such reactors is sometimes called processing by *direct PECVD*. A different type of cold plasma processing is by *remote PECVD* [28]. The remote PECVD is also called *downstream processing*.

The distinction between direct and remote PECVD is made primarily on the basis of whether reactant or diluent gases are directly excited by the plasma. In the direct processes described before, all process gases are exposed to the plasma. In addition, the processed samples are immersed in the plasma discharge.

By contrast, in the remote PECVD processes, not all reactant gases are excited in the plasma, and the substrate is removed from the discharge region of the plasma. The gases can be introduced into both the discharge region and the reaction chamber outside the discharge, often near the substrates. This arrangement reduces the number of possible reaction pathways and can improve control of the process or the stoichiometry of deposited films [28]. Physical effects of the plasma on the processed substrate can be reduced in the remote reactors, minimizing or completely eliminating radiation damage.

A remote plasma reactor is illustrated in Fig. 4-21. In such a system some of the process gases (dilutants and/or reactants) are excited in the plasma sustained in a quartz tube by inductive RF coupling, while other reactant gases are introduced in the processing chamber through a dispersion ring. The processed substrate is supported outside the plasma.

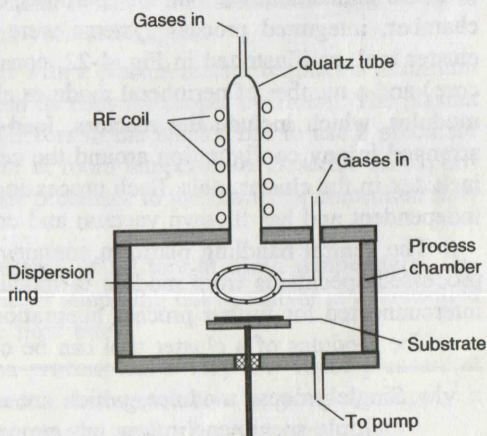


Fig. 4-21 Reactor chamber and RF plasma source for remote PECVD.

Hybrid systems combine characteristics of both direct and remote processes. This is the case in some RF triode-type reactors in which the substrate sits below a grid that replaces one of the electrodes and it is not exposed directly to the discharge. A regular ECR reactor can also be considered a hybrid processing system because the substrate is generally outside the plasma chamber while all the gases may be excited in the plasma.

An ECR reactor can also be used as a remote PECVD reactor. The gases can be introduced both in the ECR plasma chamber and in the processing chamber, and as mentioned earlier, the substrate can be placed outside the plasma. For example, to deposit silicon dioxide by the remote process, oxygen is introduced into the system via the plasma chamber (the ECR source), while silane enters directly in the reaction chamber. The oxide is formed by the reaction that takes place on the substrate surface between a silane molecule and incident oxygen ions. For deposition of silicon nitride the arrangement is similar, but in this case the plasma gas is changed to nitrogen [22].

Remote plasma reactors are used when it is necessary to avoid direct contact of the processed sample with the plasmas, to prevent damaging of sensitive samples. They are used for deposition of inorganic or organic coatings or for plasma treatment of polymers.

4.8 REACTOR CLUSTERS

Many manufacturing processes using PECVD consist of multiple steps, with one or more plasma reactors. This is especially the case in manufacturing micro-electronic components. For example, manufacturing of DRAM computer chips involves hundreds of process steps and the processing of the 64-Mbit DRAM chips will require up to 1000 steps [29].

For better control of the fabrication process and yield improvement, the wafers have to be moved between process steps without exposure to environment to avoid contamination. For this purpose, cluster tools that are modular, multi-chamber, integrated process systems were developed in the last few years. A cluster tool, as illustrated in Fig. 4-22, consists of a central handling station (the core) and a number of peripheral modules also called process stations. Processing modules, which include the reactors, load-locks, or inspection stations, can be arranged in any configuration around the central core. PECVD reactors are often included in the cluster tools. Each processing unit is mechanically and electrically independent and has its own vacuum and control system.

The central handling platform contains transport mechanisms that move the processed specimens from module to module. Several central platforms may be interconnected for further process integration.

The modules of a cluster tool can be of two types:

- Single-process modules, which are usually batch modules for processing multiple specimens in low rate processes.

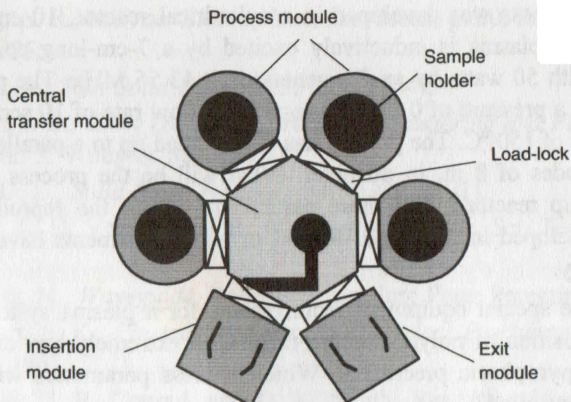


Fig. 4-22 Diagram of a cluster tool.

- Multiple-process modules, which consist of several fully separated internal stations, each providing a single-wafer processing environment. A multi-process module occupies only a single port of the central handling module. An internal transport mechanism moves the wafers from one process station to another within the module, while the central handler is free to serve other ports of the cluster.

4.9 QUESTIONS

1. A certain plasma process has an optimum for a residence time of 0.4 sec, when the process is performed in the pressure range of 100 mtorr to 1 torr. The process will be performed in a parallel plate reactor having two electrodes, 8 in. in diameter and 3 in. apart. One electrode serves as a showerhead for introduction of the gases in the system. What is the maximum range of mass flow controllers to be used with this reactor? Explain.
2. The mass flow controller to be used with a plasma reactor requires a minimum pressure difference of 10 psi between its ends for proper operation. The plasma process performed at a pressure of 5 torr in the reactor has to use a precursor that has a vapor pressure of 600 torr at room temperature. Describe an experimental arrangement for supplying the precursor to the reactor at controlled flow rate.
3. Another precursor has a vapor pressure of 50 torr at room temperature. Describe the experimental arrangement for supplying this precursor at a controlled flow rate. What is determining the flow rate?
4. One of the precursors for a plasma process has a very-low-vapor pressure at room temperature. What experimental arrangement is required to supply a controlled flow rate of this precursor to the reactor?

5. A plasma process was developed in a cylindrical reactor, 10 cm in diameter, in which the plasma is inductively excited by a 7-cm-long coil. The coil is powered with 50 watts by an RF generator at 13.56 MHz. The process has an optimum at a pressure of 0.1 torr, a total mass flow rate of 10 sccm and sample temperature of 150 °C. The process has to be scaled up to a parallel plate reactor with electrodes of 8 in. in diameter. What will be the process parameters in the scaled-up reactor? Will these parameters ensure the reproduction of the process developed in the small reactor, or will adjustments have to be made? Explain why.
6. Describe the special equipment requirements for a plasma system to be used for the deposition of polycrystalline films with extremely low oxygen content employing pyrophoric precursors. Which process parameters will have to be precisely controlled?
7. Which type of reactor appears to be most suitable for high rate reactive etching with minimal induced substrate damage?
8. List all hardware components required to set up a diverging field ECR reactor. What changes will be required for a multipolar reactor?
9. Design a parallel plate triode reactor and list the hardware components required for this reactor. Describe different equipment options.

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