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PLASMA DEPOSITION AND ETCHING REACTORS FOR SEMICONDUCTOR APPLICATIONS

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Abstract - Design considerations for plasma deposition and etching reactors are given both from a technical and practical viewpoint. It is shown that careful attention is required in the mechanical, electrical and gas-handling components of these reactors to ensure reproducible and reliable results, to minimize radiation damage to semiconductor devices, to minimize various kinds of contamination, to minimize maintenance frequency and to guarantee safe operation while dealing with gases that may be toxic, carcinogenic, flammable, explosive, corrosive or some combination of these.

INTRODUCTION

Numerous reactors for plasma deposition of inorganic (1) and organic (2) films and for plasma etching to clean substrates or delineate patterns (3) have been described in the literature. From the standpoint of the reactor itself, the only significant differences among these processes are the thermal treatment of the substrate, the nature of the gases used, and the vacuum pumping system required to accommodate the process gases safely and with adequate throughput.

In general there are two types of reactor used for semiconductor applications: tunnel and parallel-plate. Because of well-known problems with uniformity of etching or deposition in tunnel reactors (1,3), these devices are mainly employed for removal of organic resist materials, a relatively simple process. This paper will concentrate on parallel plate reactors.

In most parallel-plate reactors, the substrates upon which films are to be deposited or from which they are to be etched, are located on the electrode facing the powered electrode (Fig. 1A). However, for some etching processes (known variously as "reactive sputter etching" or "reactive ion etching") the substrates are attached to the powered electrode (Fig. 1B). Recently it has been shown that both configurations are essentially the same (4). Most commercial reactors are designed and operated in such a way as to cause the formation of a very high plasma potential, leading to substantial ion bombardment of both electrodes and all other surfaces in contact with the discharge. These designs lead to some irreducible minimum substrate bombardment potential which is often higher than necessary for anisotropic etching or conformal coverage during deposition. These high levels of bombardment can lead to contamination and/or radiation damage during the processing of semiconductor devices.

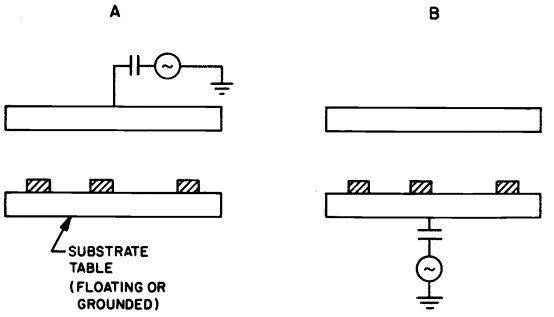

Fig. 1. Parallel-plate reactors. A. Substrates on floating or grounded electrode. B. Substrates on an rf sputtering target ("reactive sputter etching", also known as "reactive ion etching").

In this paper, we shall discuss guidelines for the design of etching and deposition reactors to ensure control of the substrate electrical condition, gas flow and uniformity of deposition or etching while minimizing contamination from bombardment of surfaces in contact with the glow discharge. In addition, optimized vacuum pumping systems for safe, efficient, low-maintenance handling of the gases used in these processes will be discussed.

ELECTRICAL CONFIGURATION

In a recent publication (4) it has been clearly demonstrated that plasma reactors are inevitably sputtering systems. That is, all surfaces in contact with the rf glow discharge are subject to ion and electron bombardment. This bombardment can result in radiation damage to surface-sensitive devices (e.g. MOS) and contamination from sputtering of solid or gaseous materials from surfaces in contact with the discharge. The irreducible minimum bombarding potential at the substrates is determined by the plasma potential. The plasma potential is the reference potential of all glow discharges and is the most positive potential in the discharge. The smallest difference between the plasma potential and the next most positive surface in contact with the discharge is necessarily equal to the ionization potential of the gas in the system (5). In most practical systems the plasma potential is usually considerably more positive than this.

It has been demonstrated amply in the literature of rf sputtering that the difference between the plasma potential and the next most positive surface is dependent both on system geometry and operating conditions. In general, the plasma potential becomes more positive with increasing applied voltage, decreasing pressure, decreasing inter-electrode separation (obstruction) and increasing ratio of the area of the powered electrode to that of other surfaces in contact with the discharge (constriction) (4,6-13).

Thus, to minimize the plasma potential, the following must be done:

- use the highest gas pressure and lowest applied voltage possible;
- use a wide inter-electrode separation;
- minimize the area of the powered electrode in relation to all other surfaces in contact with the discharge.

The latter item implies that the powered electrode should be small in relation to the size of the vacuum vessel. (In some cases the high gas pressure--low voltage conditions will be found inconsistent with other process boundary conditions, necessitating some compromise.)

While contamination and radiation damage are to be avoided, substrate bombardment during film etching and deposition can have beneficial side effects. In plasma etching, bombardment is a necessary condition for anisotropic etching (3,14-16), which is frequently desirable. In deposition it has long been found that irregular surface geometries can be coated conformally (1,2). It has been speculated (4) this may have to do with resputtering of deposited material at a shallow angle giving rise to the well known good conformal coverage characteristic of bias sputtering and ion plating processes (17-23).

This apparent dilemma rapidly leads one to the conclusion that plasma deposition and etching reactors should be configured electrically in a way similar to that of a bias sputtering system. That is, the overall mechanical design should be such as to minimize the plasma potential and both electrodes should be independently powered (Fig. 2). In this way, the substrate electrode can be powered with the minimum potential required to obtain the good features of ion bombardment while minimizing the deleterious effects. Rf circuitry for accomplishing this is well established (24).

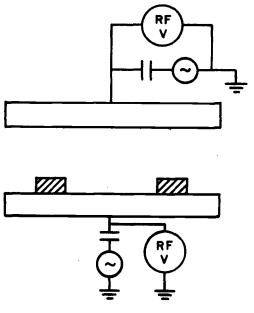

Fig. 2. Preferred electrical configuration. Both electrodes are powered independently and both are either power- or voltage-controlled.

When plasma processes are operated at high pressures (greater than about 0.15 torr) the processes are mainly discharge-current dependent. However, it is difficult to measure discharge current directly in a quantitative way, so it is advisable to use automatic power control to maintain process stability, and to simply monitor the voltages on the electrodes. At lower pressures, the processes are more voltage dependent, so automatic voltage control is more useful. It is helpful if both are available with provision for either voltage or power control to override the other.

In plasma etching, end-point detection is extremely useful. Most of the literature on end-point detection emphasizes optical emission spectral (25-27) or mass spectral techniques (28-29) which can determine changes in discharge species at the end-point of the etching. However, as has been shown recently (30), a change in discharge electrical impedance occurs at the etching end-point. Thus, if one is operating in a constant power mode, a change in voltage signals the end-point and visa versa. Since power and voltage monitors are included for other reasons, they constitute essentially free end-point detectors. In addition, they are less prone to breakdown than mass or optical spectrometers and are simpler to use.

ELECTRODE AND VACUUM CHAMBER MATERIALS

While minimizing the plasma potential assists in minimizing sputtering effects, some sputtering must inevitable occur. In plasma etching it is necessary to fabricate electrode surfaces from a material that will be etched by whatever etching gas one is using. Otherwise, material sputtered from one or both of the electrodes will deposit onto the substrates being etched, act as a local etch mask and produce a very rough surface (4). In plasma deposition, the electrode surfaces should either be heavily coated with or completely fabricated from a material which will not adversely contaminate the films being deposited. For example, Si is a good electrode choice for the deposition of Si, SiO_2 or Si_3N_4. Si is also a good choice for etching of Si-based films; but Al is a bad choice in both cases.

In addition to questions of contamination, the electrode material is important for other reasons as well, especially in plasma etching. It has been shown that the etch rate and selectivity of plasma etching processes are markedly affected by the electrode material employed (31,32). A further advantage of consumable or etchable electrode materials has to do with the "loading effect" (33). Basically, because more reactive gas is consumed when a full load of substrates is in the reactor as compared to only a few substrates, the plasma etch rate decreases as the substrate load increases. The use of consumable electrodes effectively results in a fully loaded system regardless of the number of substrates being etched, thus removing an annoying variable from this process, albeit with some loss of throughput for lightly-loaded runs.

If the other surfaces interior to the vacuum system (e.g. chamber walls) are far enough away from the active part of the glow discharge, the materials of which they are constructed are of little consequence, at least in the context of interactions with the glow discharge. However, normal, good vacuum practices should not be overlooked. In the case of plasma etching, it is preferable to construct other parts of the system out of materials that do not etch in the reactive gas used and to ensure that elastomer seals do not come into contact with the glow discharge.

GAS FLOW AND UNIFORMITY

In both plasma etching and plasma deposition the reactive gases entering the vacuum system are partly consumed. The rate of consumption depends, in part, on the location of the gas inlet vis-a-vis the pumping port. Figure 3 shows the preferred gas flow configuration to balance reactive-gas consumption and the electrical conditions in the discharge (34). The pumping port is located at the center of the substrate electrode and the gas inlet is radially disposed about the periphery of that electrode. Since the substrate area to be etched or deposited upon is largest near the edge of the substrate electrode and smallest at the center, this configuration places the unreacted gas where it is most needed--in the vicinity of the area requiring most of it. As the gas is depleted by reaction in the plasma, it proceeds to the area in the center of the electrode where it is least needed.

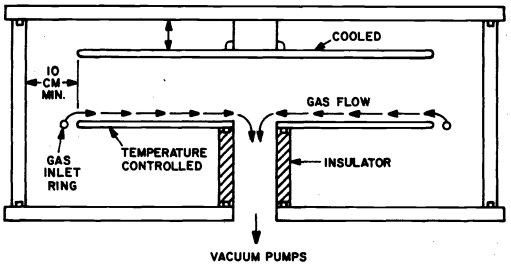

Fig. 3. Radial-flow reactor with adjustable electrode separation, cooled primary electrode and temperature-controlled substrate electrode.

In addition, the electrical conditions near the center of the electrode favor more complete reaction of the depleted gas arriving there because of the electron distribution in the plasma. The rf glow discharge is largely sustained by secondary electrons generated at the electrodes. These electrons are mainly responsible for decomposing the reactive gas into active species that result in etching or deposition. The secondary-electron current density varies from a maximum at the center of the electrodes to a minimum at the edge because of the axial magnetic field created by the current flowing between the electrodes. The magnetic field causes the electrons to follow a helical path of radius (r)

$$r = \frac{m\ v\ \sin\phi}{eB} \qquad (1)$$

where: m is the mass of the electron, v is the velocity of the electron, ϕ is the angle from the normal to the surface at which the electron is emitted, e is the electronic charge and B is the magnetic flux density. Thus, the higher the magnetic field (i.e. the higher the current) the more the electrons are pinched toward the center of the electrode.

The higher electron density near the center of the electrode results in more efficient decomposition of the depleted reactive gas at the center. Thus, one can balance gas flow and electrical conditions to arrive at a situation where gas consumption can be adjusted by electrical conditions so that deposition and etching are uniform across a large substrate electrode. For proper control of gas mixtures, mass flow controllers with automatic ratio controllers are quite helpful and easily lend themselves to process automation.

Since thermal effects play a significant role in etching and on deposition rates, it is imperative to control the substrate temperature. In general, the substrate temperature required for etching is low (<50°C); but temperatures for deposition may range from room temperature to 350-400°C depending on the material to be deposited.

Figure 3 also shows our design guide for the minimum spacing between the electrodes and the chamber wall (10 cm). Empirically, this distance has been shown to eliminate wall effects (12). Aside from constriction of the glow discharge, chamber walls that are too close to the electrodes act as recombination sites for ions and electrons, thus depleting the discharge near the edge of the substrate electrode, leading to non-uniformity in that region. Finally to accommodate different operating pressures, the upper electrode position is adjustable to provide a variable inter-electrode spacing.

VACUUM PUMPING SYSTEM

Some of the gases used for plasma etching and deposition are toxic, corrosive, flammable, explosive, carcinogenic, or some combination of these. This fact requires that one pay particular attention to the vacuum pumping system employed to minimize danger to operating personnel, pump maintenance (or outright destruction), and air pollution, and to ensure process quality (35). After considerable investigation, the pumping package shown in Fig. 4 has been developed. The rationale for each of the components of this system is related to process quality, safety and maintenance.

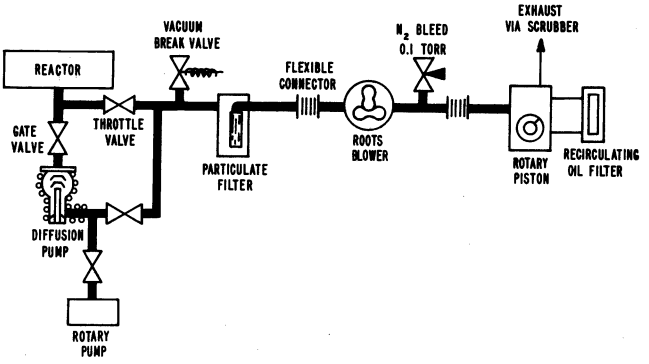

Fig. 4. Vacuum pumping system.

A major difference between this pumping package and those normally supplied on commercial reactors is that a diffusion pump is used. Most commercial reactors are equipped with only a mechanical pumping package. In terms of process quality, this is poor practice. Consider a process operating at a pressure of 150 mtorr. If only a mechanical pump is used, one has two unacceptable choices in terms of system operation. If the mechanical pump is used to evacuate the chamber to the blank-off pressure of the pump (typically 15-20 mtorr), mechanical pump fluid backstreams into the process chamber at a very high rate leading to oil contamination of substrate surfaces (36). This, in turn, leads to variability in the induction period for etching or to poor adhesion of deposited films. (Of course, this is not the case if a low-vapor-pressure pump fluid such as a perfluoro polyether (37) is employed.) If, on the other hand, one pumps the system only to the point where backstreaming does not occur (typically 100 mtorr), then there is a large concentration of residual gas in the chamber at the start of the process. The solution to this dilemma is to use a diffusion pump so that the chamber can be rough pumped to a point where backstreaming does not occur and then high-vacuum pumped to remove most of the residual gas prior to introducing the process gas. One can argue that the initiation of a glow discharge results in substantial outgassing from surfaces in contact with the glow discharge, and that the diffusion pump will not exhaust these adsorbed gases. While this is certainly true, it appears preferable to have only that source of background gas contamination at the initiation of the process rather than that source plus a high concentration of unpumped gases.

A second reason for including a diffusion pump relates to personnel safety. In many of these processes large quantities of free radicals, which may be carcinogenic, are produced. The use of a high-vacuum pumpout and a nitrogen purge prior to venting the system minimizes the exposure of operating personnel to these dangerous substances, while a N_2 purge alone does not.

Since only the mechanical pumping part of this package is used during processing, a small rotary pump is required to back the diffusion pump during processing.

In the vacuum line leading to the mechanical pumps, a throttle valve is included. It is used in conjunction with an automatic pressure controller.

In systems in which particulates can be generated, a porous inlet filter with a fiberglass cartridge filter is employed to minimize the entrance of particles into the mechanical pumps.

For processes requiring high gas-throughput, a mechanical booster pump (Roots blower) is required. To back the blower, a rotary piston (rather than rotary vane) pump is preferred because the internal tolerances on moving parts are larger. This is especially important for processes in which particulates are generated. The inlet filter minimizes particulate entry into the pumps but does not eliminate it completely. Furthermore, particles can be generated in the pump itself on the compression cycle. To further reduce particulate matter in the pump, a recirculating oil filter is used. This filter greatly extends the interval between oil changes. To minimize oil backstreaming from the mechanical pump a dry N_2 inlet bleed set at 0.1 torr is used.

Two bellows-type flexible connectors are used to damp vibrations from the pumps. Vibration isolation is very important to minimize flaking of built-up materials in the reactor.

When the reactive gases used or fragments of them are toxic, the pump exhaust line should be sealed and run to a scrubber to prevent air pollution (38). The scrubber should be one which exerts no significant back-pressure on the exhaust line, (e.g. water-mist scrubber). When the gases to be pumped burn to form colloidal dust upon exposure to air (e.g. SiH_4) the exhaust line from the pump should be run parallel to the floor for a minimum of 1 meter so that the dust collects in this line and does not fall back into the pump. Provision should be made for periodic removal of this dust in a way that prevents maintenance personnel from inhaling the dust and contact silicosis. When the gases to be pumped are explosive in contact with air (e.g. H_2), good practice dictates that a high flow of dry N_2 should be introduced into the exhaust line to dilute the explosive gas below the flammability limit. Otherwise, the exhaust line could explode.

All valves except the vacuum-break valve close automatically in the event of a power failure. The vacuum break valve opens a few seconds after all the other valves close to vent the mechanical pump line, thus eliminating oil from being sucked into the blower and roughing line.

Selection of the pump fluid used in the mechanical pumps is very important. Hydrocarbon and phosphate ester fluids are not recommended because they pose an explosion hazard (35,39), and are subject to polymerization by many of the corrosive gases used for plasma etching and the cleaning of plasma deposition reactors.

The most acceptable fluids appear to be chlorofluorocarbons (35), perfluoro polyethers (37) and perfluorinated alkyl polyethers. All of these have been tested with a very wide range of corrosive gases and have performed exceptionally well. In addition, the perfluoro fluids have very low vapor pressures, but they are 3-4 times more expensive than the chlorofluorocarbons.

CONCLUSION

Design considerations for plasma deposition and etching reactors have been outlined both from a technical and practical viewpoint. Careful attention is required in the mechanical, electrical and gas-handling components of such reactors in order to ensure reproducible and reliable results, to minimize radiation damage to semiconductor devices, to minimize various kinds of contamination, to minimize maintenance frequency and to guarantee safe operation.

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