

Dry Etch Process Application Note

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Etch Process Overview

The etching process removes selected areas from wafer substrates. The two types of etching processes used in semiconductor manufacturing are wet etching and dry etching.

Wet etch processes can lead to undercutting, resulting in an isotropic etch profile where the vertical etch rate is approximately equal to the horizontal etch rate (Figure 1(A)).¹ As semiconductor manufacturers continue to shrink feature sizes, this undercutting becomes more intolerable, making wet etching a less desirable technique for material removal.

Dry etching is one of the most widely used processes in semiconductor manufacturing. Dry etching uses plasma generated free radicals to remove material only from the area dictated by a photoresist pattern created during the photolithography step (Figure 2).¹ Only dry etching provides the ability to control sidewall anisotropic etching through plasma-generated non-reactive and reactive ions (Figure 1(C) and 1(D)).

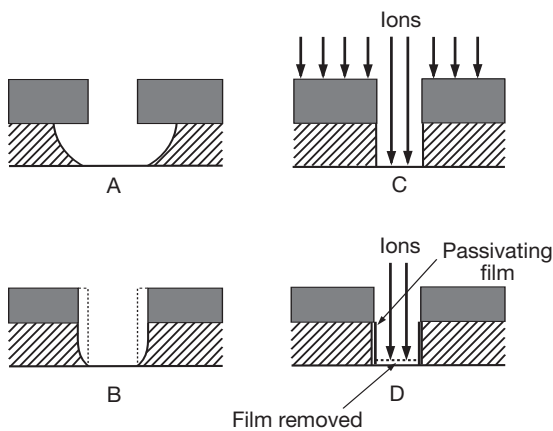


Figure 1. Plasma etching in integrated circuit manufacture: (a) example of isotropic etch; (b) sidewall etching of the resist mask leads to a loss of anisotropy in film etch; (c) illustrating the role of bombarding ions in anisotropic etch; (d) illustrating the role of sidewall passivating films in anisotropic etch.

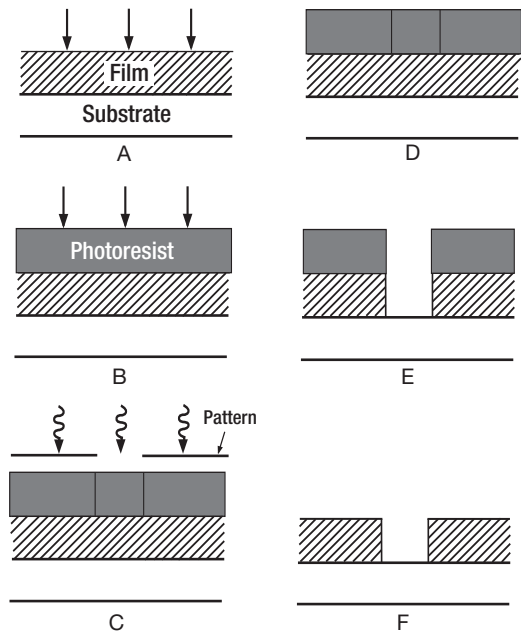


Figure 2. Deposition and pattern transfer in manufacturing an integrated circuit: (a) metal deposition; (b) photoresist deposition; (c) optical exposure through a pattern; (d) photoresist development; (e) anisotropic plasma etch; (f) remaining photoresist removal

Plasma is ionized gas formed by the application of strong radio frequency (RF), or microwave electric fields, under vacuum conditions. The plasma generates electrons, ions, bombarding ions, and free radicals that are chemically reactive species, such as fluorine or chlorine. These reactive ions have high material removal energy, hence etching profiles are dependent on ion density and energy (Figure 3).¹ Energetic ion bombardment can increase surface chemical reactions, clear inhibitor surface films, and physically sputter materials from or implant ions into the surface.

Dry Etch Technologies/Tools

There are different chamber geometries and plasma driving frequencies used in commercial

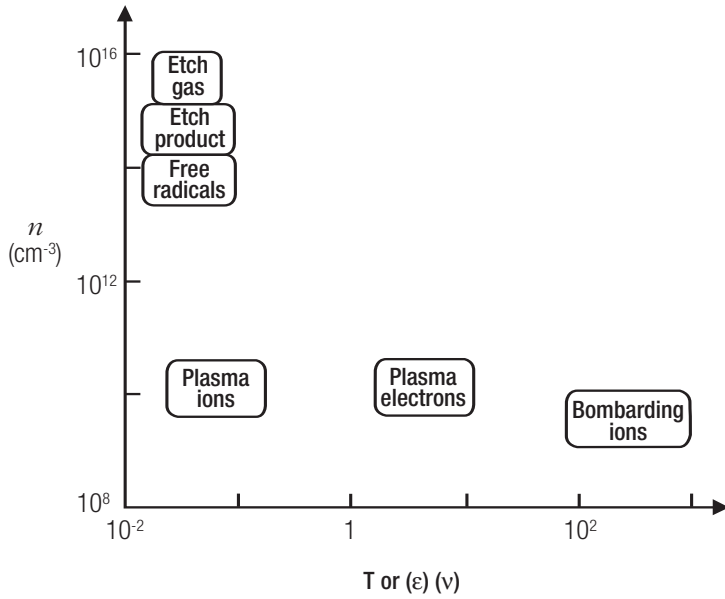


Figure 3. Densities and energies for various species in a low-pressure capacitive RF discharge.

plasma etch tools. The most widely used are described:

Reactive Ion Etcher (RIE) – This tool consists of a vacuum chamber containing two parallel plate electrodes driven by a 13.56 MHz RF power supply. The wafer is placed on the powered electrode (cathode) and the anode is

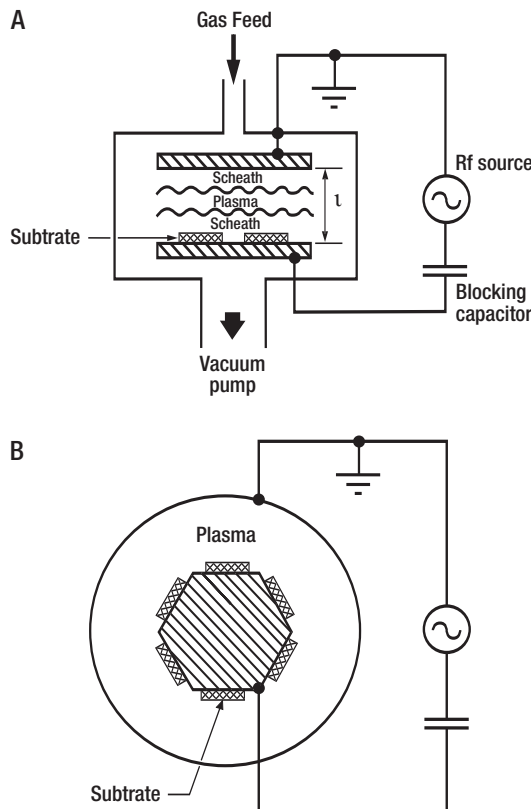


Figure 4. Capacitive RF discharges in (a) plane parallel geometry and (b) coaxial "hexode" geometry.

grounded. Etch feedstock gases flow through the plasma and etch products are removed by the vacuum pump (Figures 4, 5).¹

For anisotropic etching, pressures are typically in the 10-100 mtorr range, and power densities are 0.1-1 W/cm². Plasma densities are relatively low approximately 10⁹-10¹¹ cm⁻³, and ion acceleration energies are in the 200-1000 V range.

Figure 5 shows that ions in the bulk plasma can be accelerated by sheath fields to high energies as they flow to the substrate, leading to energetic-ion enhanced processes. The crucial limiting feature of RIE tools is that the ion-bombarding flux and bombarding energy cannot be varied independently. The low ion flux and high bombarding energies lead to low throughput and undesirable damage, or loss of linewidth control.

Magnetically Enhanced Reactive Ion Etcher (MERIE) – A reactive ion etcher in which a direct current (dc) magnetic field of 50–300 G is applied parallel to the powered electrode on which the wafer sits. The magnetic field increases the plasma density and reduces the sheath voltage. This leads to higher flux of ions and lower bombarding energies. In this respect, MERIE tools are an improvement over RIE tools, but MERIE systems do not have good uniformity due to magnetic field induced nonuniform plasma generation.

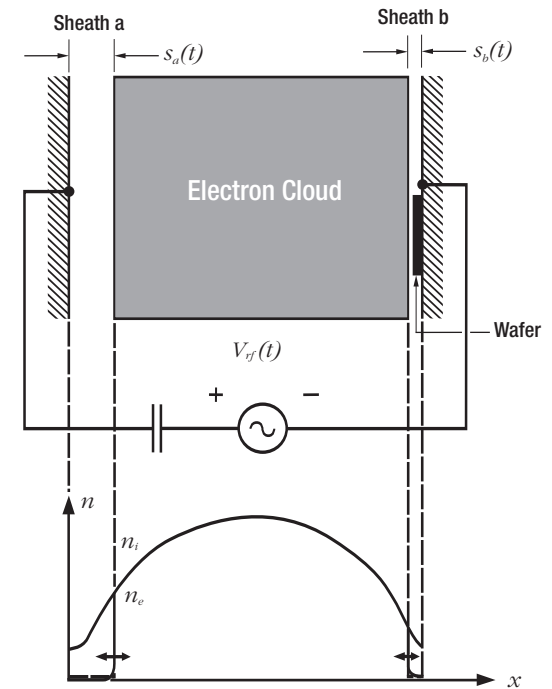


Figure 5. The physical model of an RF diode.

Inductively Coupled Plasma or Transformer Coupled Plasma (ICP or TCP) tools – These systems use a low-pressure, high-density plasma source that has two independently driven RF sources. The powered electrode, on which the wafer sits, controls the ion bombarding energy. A powered multiturn RF coil controls the ion/radical fluxes across the dielectric discharge chamber. Typical high-density plasma source parameters include: pressures 0.5-50 mtorr, power of 100-5000 W, plasma density of 10^{10} - 10^{12} cm^{-3} , and ion acceleration energies of 20-500 V.

The higher ion fluxes and lower ion bombarding energies provide higher throughput, better linewidth control and less plasma damage versus RIE tools.

The ability to control fluxes and bombardment energies provides users the ability to tailor the anisotropic etch mechanism better than with RIE tools.

Electron Cyclotron Resonance (ECR) tool – This system uses a low-pressure, high-density plasma source with two independently driven sources and electromagnetic coils. A RF bias is applied to the electrode on which the wafer sits; this controls the ion bombarding energy. Microwaves (power 2.45 GHz) are injected axially through a dielectric window into the source plasma; a large resonant magnetic field is used (>300 G). The source plasma that controls the ion/radical flux streams out into the process vacuum chamber where the wafer is located. Due to higher driving frequency there is a higher ion flux generated than with ICP tools, thus providing for faster dry etching (and, thus, higher throughput). The drawback of ECR tools is the magnetic field induced plasma nonuniformities translate to wafer etching nonuniformity.

Helicon discharges – This system is similar to an ICP tool, but has a weak dc axial magnetic field together with an RF-driven antenna. The antenna is placed around the dielectric cylinder that forms the source vacuum chamber. This allows excitation of a helicon wave within the source plasma. The magnetic field provides for more efficient power transfer to the plasma, but also results in nonuniformity issues.

Photoresist Stripper System – Next-generation resist strip systems are ICP tools. The crucial issue is to be able to control ion fluxes and bombardment energies. The typical dry etch strip process involves two steps -- the first is

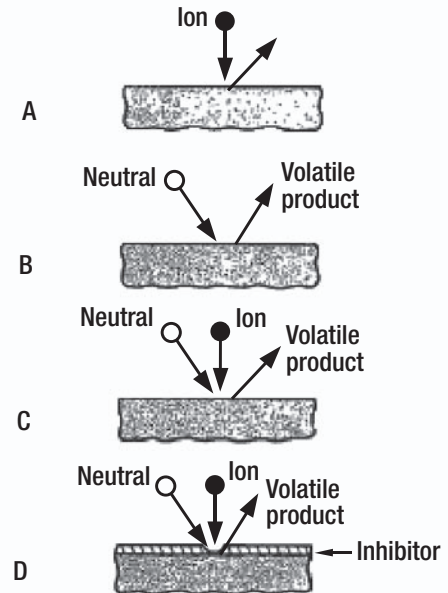


Figure 6. Four basic plasma etching processes: (a) sputtering; (b) pure chemical etching; (c) ion energy-driven etching; (d) ion-enhanced inhibitor etching.

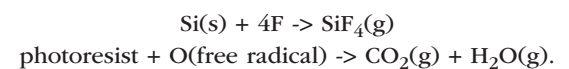
a fast bulk photoresist removal step (isotropic etch); the second is the slow, controlled sidewall angle-dependent removal of photoresist (anisotropic etch).

Dry Etch Processes

There are four low-pressure plasma processes used to remove layers on wafers/display glass substrates (Figure 6):¹

Sputtering – The non-selective removal of surface atoms due to plasma-induced nonreactive feedstock gas ions vertically striking the surface target. There is no ability to control the etch profile.

Pure Chemical Etching – The isotropic and selective removal of surface atoms by plasma-induced gaseous etchant atoms or molecules (free radicals) that chemically react with the surface layer, forming gaseous volatile etch products. Some examples are:



Ion-Enhanced Energy-Driven Etching – The highly anisotropic etching of surface layers due to plasma-induced gaseous etchants and energetic ions. The etch rate is determined by the energetic ion bombardment. The selectivity is worse than pure chemical etching due to vertically striking ions.

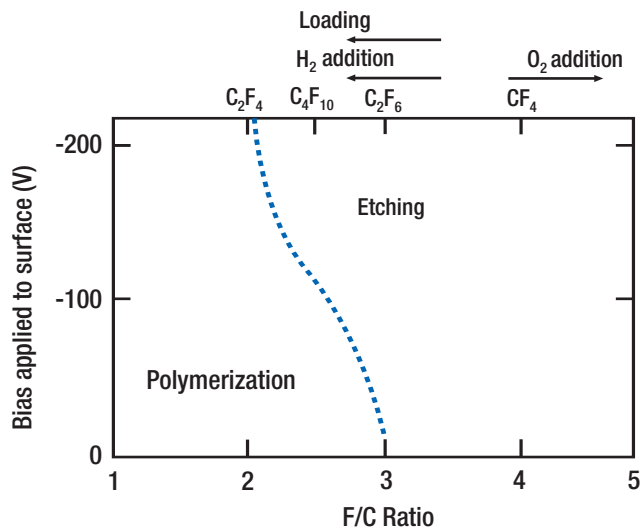


Figure 7. The influence of fluorine to carbon (F/C) ratio and electrode bias voltage on etching and polymerization processes in a fluorocarbon discharge.

Ion-Enhanced Inhibitor Etching – The plasma supplies etchants for chemical etching, energetic ions for anisotropic etching, and inhibitor precursor molecules that adsorb or deposit on the substrate to form a protective layer or polymer film. The ion-bombarding flux prevents the inhibitor layer from forming (or clears it as it forms), exposing the surface to the chemical etchant. Where the vertically striking ions do not fall, the inhibitor protects the surface from being etched.

Inhibitor precursor molecules include CF_2 , CF_3 , CCl_2 , and CCl_3 molecules, which can deposit on the substrate to form fluoro- or chloro-carbon polymer films.

Dry Etch Chemical Framework

Dry etch plasmas are complex due to dissociated reactive species of feedstock gases. Feedstock gas selection is dictated by etch process requirements on etch rate, material to etch, selectivity, anisotropy, and uniformity. The chemical constituents in plasma may include the following (Principles of Plasma Discharges and Materials Processing, 1994, pg. 489):

Saturates: CF_4 , CCl_4 , CF_3Cl , COF_2 , SF_6 , etc.

Unsaturates: C_2F_6 , C_3F_8 , C_2F_4 , CF_2 , CF_3 , CCl_3 , etc.

Etchants (molecular species and free radicals): F, Cl, Br, O (for resist), F_2 , Cl_2 , Br_2 , etc.

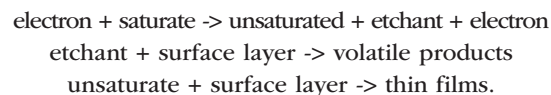
Oxidants: O, O_2 , etc.

Reductants: H, H_2 , etc.

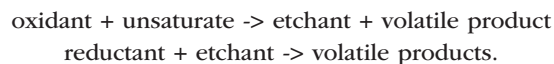
Nonreactive Gases: N_2 , Ar, He, etc..

Saturates are feedstock gases that get broken up in the plasma to form free radicals (etchants). These free radicals react with the surface layer and produce etch volatile product (gaseous molecular species) that detach from the layer and are subsequently pumped out of the plasma tool.

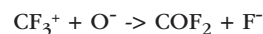
These species react with each other and the surface layers in the following reactions:



If oxidants or reductants are added to the process gas mixture (commonly O_2 or H_2 respectively, or gases that contain these atoms), then the additional reactions can occur:



The ratio of etchant to unsaturate flux at the surface layer is an important process parameter; a high ratio can lead to isotropic etching, while a low ratio can lead to thin-film deposition. Oxygen can be added to increase the etchant percentage by converting unsaturates to etchants. For example:



Hydrogen can be added to reduce the etchant percentage, as in:



to push the process toward increased polymerization (Figure 7).¹

Thus, controlled addition of oxygen can lead to increased etch rates by increasing more free radicals and volatile etch products; and controlled addition of hydrogen can lead to decreased etch rates by decreasing free radicals. The user can tailor etch profiles by controlled addition of oxygen and hydrogen or gases that contain these molecules.

Contaminants in Dry Etch Process

The following gaseous contaminants can be found in typical vacuum chambers due to process gases and gas line system components: H_2O , O_2 , CO, CO_2 , CH_4 , non-methane

hydrocarbons (NMHC), H₂, N₂. A typical vacuum chamber wall surface has 5–20 physisorbed water layers. At typical operating pressures used in dry etch processing (<200 mtorr), gases absorbed onto chamber walls tend to desorb. Thus, this outgassing will react with the plasma feedstock gases and surface layers.

Oxygen, hydrogen, and moisture contamination leads to uncontrolled changes in etch rate and contributes to etch process variation. Carbon monoxide and carbon dioxide contamination are sources of both carbon and oxidants. Carbon acts as a reducing agent; inhibitor films can form on surface layers and lead to decreased etch rates. Methane and NMHCs contamination are also sources of carbon that can lead to decreased etch rates. Nitrogen contamination is nonreactive, but can lead to increased sputtering or plasma-induced surface damage. Thus, gaseous contaminants found in gas line systems and process feedstock gases can lead to process variability that ultimately translates to manufacturing yield losses, decreased tool uptime or higher tool cost of ownership.

POU Purification for Dry Etch Processing

The placement of purifier assemblies on the gas lines directly prior to vacuum chamber entry (i.e. at the point-of-use) offers the best protection for dry etch process control.

Pall AresKleen™ purification media are capable of removing gaseous contamination such as water, oxygen, carbon monoxide and carbon dioxide to sub-ppb levels from various process feedstock gases. Figure 8 demonstrates AresKleen™ INP medium oxygen contamination removal efficiency from nonreactive gases (N₂). The nitrogen gas flow rate was increased during the oxygen challenge testing to show relative independence of removal efficiency to intermittent flow peaks.

In addition, AresKleen SIP medium has demonstrated the ability to remove volatile metal carbonyl (Fe(CO)₅, Ni(CO)₄) impurities to less than 1 ppb levels from carbon monoxide feedstock gas.² Carbon monoxide is used to enhance selectivity and anisotropy in dielectric etch processes. The unique medium is composed of an inorganic support and reactive alkali metal; both support and metal have an affinity for gaseous impurities. The purification medium removes contaminants by irreversible mechanisms, thus ensuring a consistent supply of sub-ppb contaminant-free gas.

Pall OXP medium removes water impurity to less than 10 ppb levels from oxidant (O₂, N₂O, CO₂) feedstock process gases. Pall CLXP medium removes water impurity to less than 100 ppb from etchant (Cl₂, BCl₃) feedstock

Pall AresKleen™ purifier data

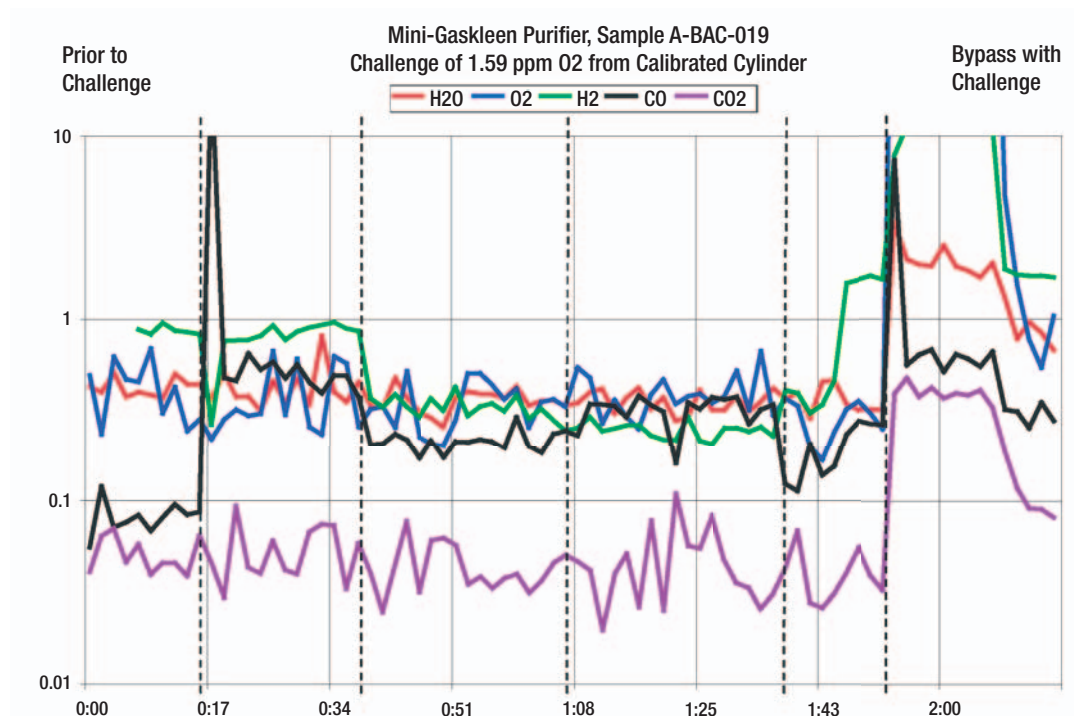


Figure 8. Mini-Gaskleen™ purifier efficiency testing.

process gases. The control of gaseous contaminants is key to having a reproducible dry etch process. Pall Gaskleen® purifier assemblies are available in Top Mount and in-line configurations. (Refer to Pall Filtration Purifiers Datasheets.)

Glossary

Anisotropic etch – the vertical etch rate is much greater than the horizontal etch rate.

Etch rate – the rate at which a given film is removed.

Isotropic etch – the vertical etch rate is equal to the horizontal etch rate.

Selectivity – the ratio of the selected (to be etched) layer etch rate to the etch rate of the underlying layer.

Uniformity – a measure of how far a given parameter, such as etch rate, varies from the average value across one wafer, from wafer to wafer in a batch, or from wafer batch to batch.

References

1. PRINCIPLES OF PLASMA DISCHARGES AND MATERIALS PROCESSING, Lieberman and Lichtenberg, WILEY-INTERSCIENCE, 1994.
2. Analysis performed by APCI, Allentown, PA, 2003.

Gas Filtration Purifiers Data Sheet A79a
Mini-Gaskleen™ Purifier

Gas Filtration Purifiers Data Sheet A88
Gaskleen® II Purifier

Gas Filtration Purifiers Data Sheet A87a
Gaskleen® ST Purifier

Gas Filtration Purifiers Data Sheet A81a
Maxi-Gaskleen™ Purifier

Gas Filtration Purifiers Data Sheet A86a
Gaskleen® 1½" C-seal Purifier

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