

Plasma Processing for Silicon-Based Integrated Circuits

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During the last quarter century or so, plasma processing has become a critical industrial technology for the development and manufacture of semiconductor devices. Gaseous plasmas have been used for sputter and chemical vapor deposition of thin films, pattern transfer in mask fabrication, etching of thin films, resist stripping, surface modification and as an ion source in ion implantation. It is the most pervasive technology in the manufacture of silicon-based integrated circuits.

The debut of plasma etching, in particular, in the mid 70s was due to two factors, namely, the need to maintain tight dimensional tolerances during image transfer from the resist mask onto an underlying film, and the need to minimize ecological and safety concerns related to the disposal of large volumes of corrosive chemicals used in wet etching. Other important benefits of plasma processing are potential for low temperature chemical reactions (critical for resist masks), ease of process control, and greater cleanliness due to vacuum processing. This paper gives a brief overview of this process technology to cover applications in etching, resist stripping, and plasma-enhanced chemical vapor deposition (PECVD), along with a brief discussion of the evolution of plasma reactors.

What Is a Plasma?

A plasma, or ionized gas, is an electrical discharge that is sometimes called the "fourth state of matter." It is generally formed by applying an electric field to a volume of gas, although extremely high temperatures can also be used. The electric field causes ionization of the gas (at near room temperature), and thus current flow. Plasmas are composed of electrons, ions, and a variety of neutral species. When viewed macroscopically, plasmas are electrically neutral, but at

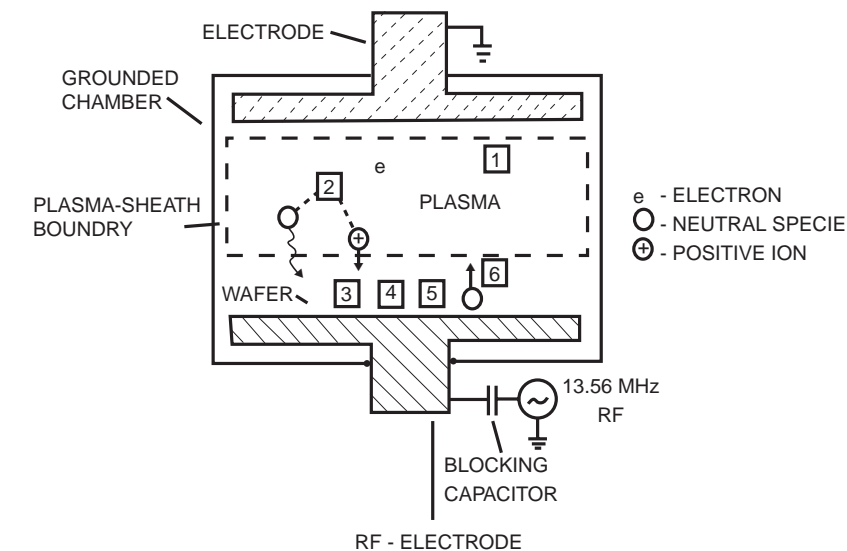


Fig. 1. Basic processes in plasma etching. The numbers in the square brackets refer to the six basic processes. [1]: Electron impact ionization and dissociation, $CF_4 + e^- \rightarrow CF_3 + F + 2e^-$; [2]: Diffusion and transport of species to the wafer surface; [3]: Adsorption/chemisorption of species on wafer surface sites, $CF_3(g) \rightarrow CF_3(ads)$; [4]: Surface diffusion and dissociation, $CF_3(ads) \rightarrow CF_2(ads) + F(ads)$; [5]: Reaction of adsorbed species with surface silicon atoms, $Si + 4F(ads) \rightarrow SiF_4(ads)$; [6]: Desorption of reaction products, $SiF_4(ads) \rightarrow SiF_4(g)$.

the microscopic level, local charge imbalances can occur. Many types of plasmas exist; they differ primarily in electron concentration, n_e , and average electron energy, kT_e , where k is the Boltzmann's constant and T_e is the electron temperature.¹ For instance, high-pressure arcs are characterized by $n_e \cong 10^{16} \text{ cm}^{-3}$ and $kT_e \cong 0.5 \text{ eV}$, while plasmas filling interplanetary space have $n_e \cong 10 \text{ cm}^{-3}$ and $kT_e \cong 25 \text{ eV}$.

Plasmas used in thin film processing applications are low pressure discharges, normally excited by radio-frequency (rf) or microwave electric fields.² These plasmas are characterized by pressures between 0.1 mtorr and 10 torr, n_e between 10^8 and 10^{12} cm^{-3} , and kT_e between 1 and 10 eV. Such glow discharges are called non-equilibrium plasmas because T_e is much larger than the ion temperature (T_i) or the gas temperature (T_g); typically, $T_e/T_i > 10$, and $T_g < 500 \text{ K}$. Glow discharge plasmas are weakly ionized, that is, the ratio of n_e to the neutral species con-

centration is 10^{-4} to 10^{-6} . Thus, atoms, radicals, and molecules are primarily responsible for etching or deposition reactions due to their high concentrations relative to those of ions. However, high density discharges, such as electron cyclotron resonance plasmas often have charged particle densities ~10% of the neutral particle density.

Plasma Chemical Reactions

In the plasma, electrons gain energy by the applied electric field. These energetic electrons then transfer their energy to gas molecules by electron impact collisions, resulting in molecular excitation, dissociation, and ionization. In this way, highly reactive chemical species are produced for etching or deposition of films at low temperatures. Furthermore, the chemical processes occurring at surfaces exposed to the plasma are modified by radiation (e.g., ions, electrons, photons). The synergistic combination of these physical

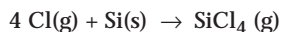
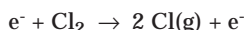
processes from ions with chemical reactions from atoms and molecules often result in etch rates and feature profiles, and deposition rates and film properties, that are unattainable with either a strictly chemical (e.g., down stream etching) or a strictly physical process (e.g., sputter deposition).

The chemistry and physics of glow discharges are extraordinarily com-

plex, since these discharges have both chemical and electrical attributes. Due to velocity differences between electrons and the higher mass positive ions, surfaces such as the wafer and chamber walls, assume a time-average potential that is negative with respect to the plasma. This causes a charge imbalance region, termed a sheath, to form near all surfaces in contact with the plasma. The electric field across this sheath repels electrons and attracts (accelerates) positive ions. Since the sheath thickness is generally small (typically 0.01-1 cm, depending upon the pressure, applied rf frequency, gas composition, rf power, etc.), the electric field and thus the energy of ions striking the surfaces can be large (20-500 eV).³

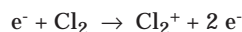
and adsorption/chemisorption onto surface sites subsequently occurs. Surface diffusion and reactant desorption can also occur. Reaction of the adsorbed species with surface atoms or with other adsorbed species then takes place to form a reaction product. If the primary product is volatile, etching occurs; if the primary product is involatile, a film is deposited. A simple

example of the types of plasma reactions occurring during silicon film etching in a chlorine plasma can be described by:



Of course, many steps are embedded in the second reaction; for example, a number of chlorine atoms chemisorb onto the silicon surface, probably first forming $SiCl_2(ads)$, followed by complete chlorination to form $SiCl_4$, which then desorbs to complete the etching process.

The adsorption steps are enhanced by ion bombardment, since high energy ions (>10 eV) are capable of breaking surface bonds, and thus creating adsorption sites. Surface reaction kinetics are also enhanced by ion bombardment, as is product desorption. As in the case of atoms, ions are formed primarily by electron impact collisions such as:



Ion-Enhanced Chemical Reactions

As described above, the electric fields in the plasma are such that positive ions are accelerated toward reactor surfaces, while negative ions are repelled. Ion bombardment plays an especially important role in producing anisotropic etch profiles. When ion bombardment (a physical process) occurs during the reaction of neutral species with a wafer surface (a chemical process), an enhancement of the individual (physical or chemical) etch rate often takes place. Since ions generally impinge vertically onto the etching surface due to the sheath field, vertical etch rates are enhanced relative to lateral or purely chemical etch rates, resulting in anisotropic etch profiles (see Fig. 2). If pure chemical etch rates are unaffected by ion bombardment, isotropic etch profiles are observed. In this case, anisotropy is achieved by coating the sidewalls of the etching feature. Coating can be achieved either by the addition of a reactant that forms a deposit or sidewall film (e.g., oxygen for etching of silicon with chlorine to form SiO_2 on the sidewall) or by controllably ablating and redepositing the photoresist material. Ion bombardment then assists the removal of this coating from the horizontal surfaces, while the deposit remaining on the sidewalls inhibits lateral etching. Alternatively, anisotropy can be attained by lowering the substrate temperature, thereby reducing the ability of etch products to desorb unless assisted by ion bombardment as is the case at the bottom of the etching feature.

Similarly, ion bombardment during PECVD promotes film densification, removal of volatile reaction products, and step coverage due to the energy imparted to the film by impinging ions. Such processes permit the realization of film properties that may otherwise require significantly higher temperatures.

Plasma Modeling

Development of each generation of new reactors and optimization of processes to meet the demands of throughput and uniformity have become complex and as a result, modeling has become a valuable design tool. At first, modeling efforts were limited to simple, well-mixed reactor analysis⁴ to quickly learn the effects of process parameters such as pressure and power on plasma properties.

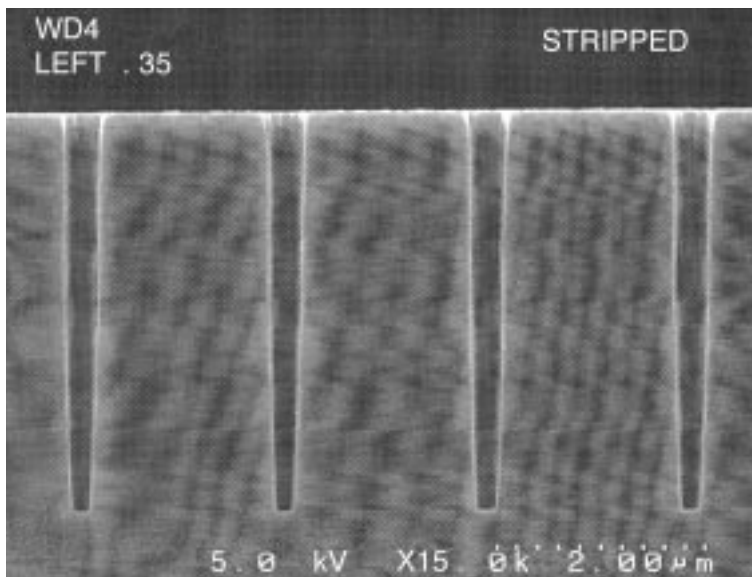


Fig. 2. Anisotropic etch profile of contact holes in SiO_2 . (Photo courtesy of Infineon Technologies Dresden GmbH. © 1999 Lam Research Corporation. SEM used by permission).

Plasma-enhanced etching or plasma-enhanced chemical vapor deposition (PECVD) can be considered to consist of six basic steps as shown in Fig. 1. Generation of reactive species is important since many of the etch gases or deposition precursors used are unreactive at low temperatures unless they are dissociated. Diffusion of the resultant species to the wafer surface

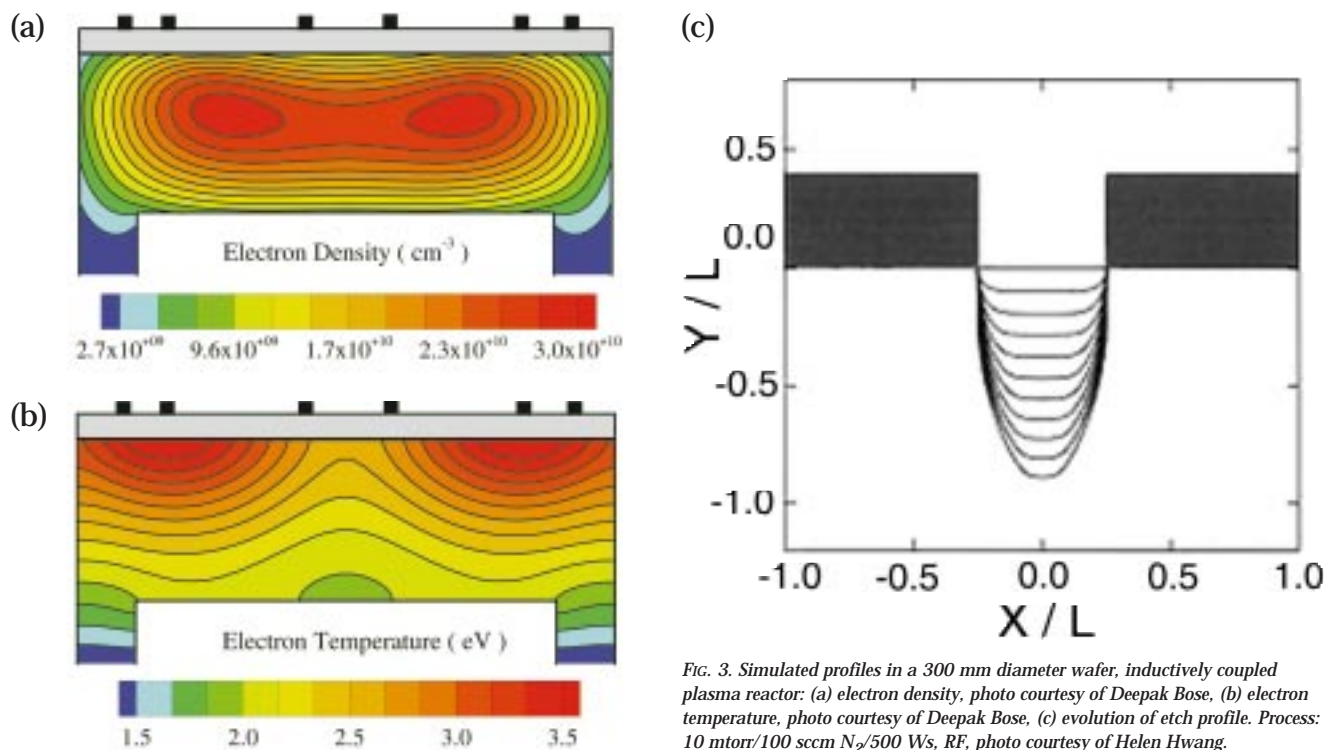


Fig. 3. Simulated profiles in a 300 mm diameter wafer, inductively coupled plasma reactor: (a) electron density, photo courtesy of Deepak Bose, (b) electron temperature, photo courtesy of Deepak Bose, (c) evolution of etch profile. Process: 10 mtorr/100 sccm N_2 /500 Ws, RF, photo courtesy of Helen Hwang.

However, more recently, two- and three-dimensional models of plasma reactors have become common. These models typically involve large scale computer simulations of the reactor through solutions to the charged species transport and Maxwell's equations. In some cases, Monte Carlo schemes or hybrid (Monte Carlo-Continuum) approaches have been used to self consistently obtain the electron energy distribution function.⁵ Fluid flow effects, asymmetric location of inlets and pumping ports and similar issues have also necessitated coupling in the plasma analysis to gas flow studies.⁶ Figure 3 shows electron density and electron temperature in a 300 mm diameter wafer, inductively coupled plasma reactor at 10 mtorr, 500 W power, and 100 sccm nitrogen flow. The electron temperature is high near the roof of the reactor where most of the power deposition occurs. The electron density peaks away from the centerline which is typical for small aspect ratio chambers.

In addition to the predictions of plasma properties for reactor and process design, insight into etch and deposition profile evolution is important. Feature scale or topography modeling has advanced to a point that it is now possible to couple it with reactor simulations. This coupling allows self consistent inputs of ion flux, ion angular distribution, etc. from the reactor model to the feature evolution code. Figure 3c shows an example of RIE

(reactive ion etching) lag effect in polysilicon etching with chlorine plasmas. A tapered profile results since atomic chlorine is blocked by the mask and a narrow opening, both leading to low surface coverage for chlorine atoms.⁷

Simulations are valuable to provide mechanistic insights and to understand the effects of various parameters on figures-of-merit for the process. Advances in modeling and the power of engineering workstations and desktop computers would make the concepts of "virtual reactor" and "virtual prototyping" a reality within a decade.

Etching of Dielectrics, Silicon, and Metal

The most common dielectric films used in the fabrication of silicon-based devices are: thermal and deposited silicon oxides, various silicate glasses (e.g., BPSG, PSG), and silicon nitride. Some common applications of oxide etching are: contact holes over Si (single crystal or poly), intermetal vias and lines, hard masks, and spacers. Most important challenges of oxide etching are achieving CD (critical dimension) control, high etch selectivity to resist mask and underlying films (e.g., Si, nitride), and process repeatability. Process repeatability is specially problematic due to the necessity of using polymerizing plasmas to achieve high selectivity to Si or silicon nitride and to obtain vertical etch profiles.

Both selective etching of oxide and etch profile control are achieved by manipulating polymerization in the etching plasma. High selectivity to silicon (high oxide:silicon etch rate ratio) is generally achieved by operating the process close to polymer point (i.e., on the boundary between etching and polymer deposition). For fluorocarbon plasmas that are normally used for oxide etching, F:C ratio ≥ 4 favor Si etching.⁸ Ratios < 4 , known as fluorine deficient plasmas, operate near the polymerization point and therefore achieve selective oxide etching. F-deficient plasmas are obtained from gases such as CHF_3 , C_2F_6 (F:C = 3), C_4F_8 (F:C = 2), and CH_3F (F:C = 1). Additive gases can also be used to tailor F:C ratios. For example, addition of O_2 to a CF_4 plasma (F:C=4) increases the ratio to > 4 due to oxidative removal of polymer formed at a Si interface, with resultant loss of selectivity to Si. Addition of H_2 , on the other hand, decreases the ratio because of F-scavenging by H to form HF and thereby etching the oxide very selectively. Polymer point can be moved in either direction, etching or polymer deposition, by controlling ion bombardment energy or wafer temperature. Anisotropy, for example, is achieved (for etching contact holes or vias) by using ion bombardment dependent polymer deposition. While the polymer film is removed by ion bombardment on the etching front (horizontal plane), polymer deposited on

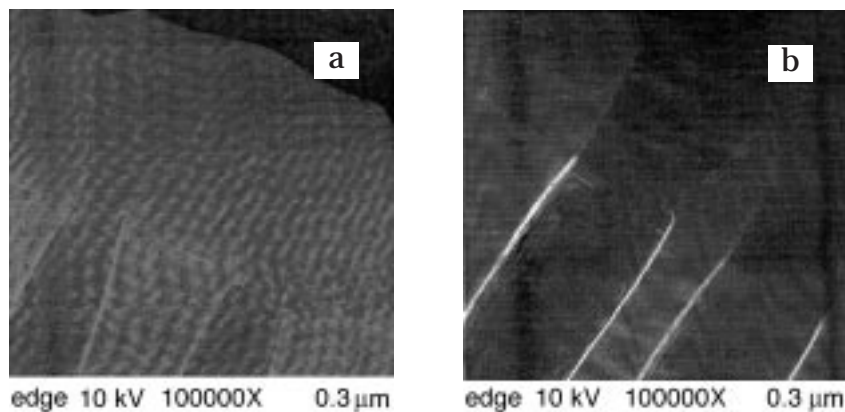


FIG. 4. Sidewall passivation in deep silicon trench etching: a) before the removal of passivating film (b) after the removal of passivating film. (Photo courtesy of Infineon Technologies Dresden GmbH).

the walls of the etched feature blocks lateral etching thereby resulting in a vertical profile. The negative aspect of the use of polymerizing plasmas is the indiscriminate nature of polymer deposition, which also occurs on the reactor surfaces and causes poor process repeatability and high particle counts. Consequently, high oxide selectivity processes suffer from frequent chamber cleaning, adding to increased down time and cost of ownership.

Plasma etching characteristics of silicon nitride are in between those of silicon and oxide. For example, while etching without ion bombardment (high selectivity conditions), silicon etch rate > nitride etch rate > oxide etch rate. Effectiveness of carbon (or polymer passivation) blocking for selective etching is: Si > Si-nitride > Si-oxide. Any further discussion on this topic is intentionally omitted here.

Silicon etching here pertains to both single crystal silicon and doped polycrystalline silicon (commonly used for wiring and as contact plug to Si substrate in MOS devices. Some common applications of silicon etching are in the fabrication of gate structure, deep trench for DRAM capacitors, shallow trench isolation, and poly-Si recess etch. Some of the earlier chlorofluorocarbon (CFC) gases used to etch Si in the 70s and 80s have been since discontinued because of their carcinogenic properties.

Heinecke proposed the following mechanism for Si etching in a fluorine plasma:⁹ "The highly electronegative fluorine atom for instance may become strongly chemisorbed on the surface of silicon wafers placed in the discharge. The strong dipole field may then drag the small atoms into the silicon lattice to form various silicon fluoride com-

pounds which are volatile even below room temperature; hence silicon is removed."

Silicon, therefore, etches quite readily by F if no native oxide is present on the surface. Selective etching of Si with respect to oxide is much simpler as compared to oxide over Si, due to the physical/chemical nature of oxide etching. Because of the weak Si-Si bond (78 kcal/mol) as compared to Si-O in SiO₂ (191 kcal/mol), etching of SiO₂ requires bond breaking by high energy ions, while Si has a finite etch rate even in the absence of ion bombardment. Any halogen plasma with low energy ions will selectively etch Si, in comparison to SiO₂. Common gases used for selective etching of Si are HBr, HCl, NF₃, SF₆, and CF₄.

Because of the naturally high etch rate of Si in halogen plasmas (in the absence of native oxide), the etch profiles tend to be inherently isotropic, particularly in F-plasmas, unless additive gases (e.g., CFC₃, O₂) are used to form side wall passivation or blocking films (very similar to forming polymer passivation film in the case of anisotropic etching of oxide). For example, deep anisotropic etch profiles are obtained in silicon by simultaneously balancing etching and deposition reactions using a complex mixture of HBr, NF₃, and O₂.¹⁰ The side wall passivation film formed on an as-etched trench, prior to its removal, is shown in Fig. 4a. Figure 4b shows the same profile after wet etching of the passivation layer. High aspect ratio trenches etched in c-Si with and oxide mask using this mechanism are shown in Fig. 5. The etch rate of Si is affected by doping as follows: n-type > undoped Si > p-type. Heavily doped n-type silicon etches faster due to Coulombic attraction

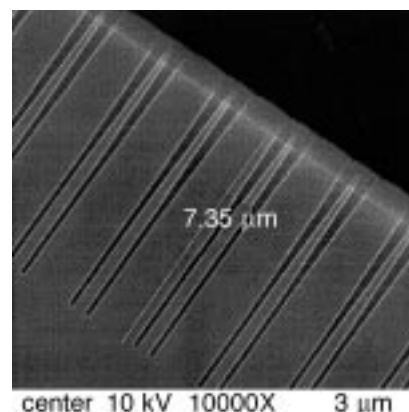


FIG. 5. High aspect ratio deep trench etch profile in c-silicon. (Photo courtesy of Infineon Technologies Dresden GmbH).

between uncompensated donors (e.g., As⁺ and chemisorbed halogens (e.g., F⁻), whereas Coulombic repulsion between uncompensated acceptors (e.g., B⁻) and chemisorbed halogens (e.g., F⁻) reduces the etch rate of heavily doped p-type Si. It is therefore necessary, during deep trench etching, to have additive gases to provide adequate side wall protection and prevent lateral etching when etching through the heavily doped layers.¹¹

Metal etching presents several unique challenges for fine-line patterning. Due to the requirements of high electrical conductivity and superior electromigration resistance, metal stacks are currently the norm. For instance, aluminum is separated from silicon by a barrier (e.g. Ti, TiN) layer and is often capped with an antireflection coating (e.g., TiN or SiN_x) to inhibit reflection and eliminate standing waves from light exposure during lithography. This stack must be etched anisotropically and controllably with smooth side walls and high selectivity to underlying film (usually PECVD oxide).

Normally, BCl₃/Cl₂ mixtures are used to etch Al stacks, due to reasonable volatility of AlCl₃ and Al₂Cl₆. Unfortunately, post-etch corrosion can occur when etched Al films are exposed to humid air; this is of particular concern when copper has been added to the aluminum film to reduce electromigration. Since aluminum corrosion leads to device failure and degradation of reliability, post-etch treatments are needed to either remove the chlorine left in contact with the aluminum (or copper) and re-establish a passivating oxide coating on the stack, or form a protective layer over the stack for inhibiting moisture penetration.

The use of copper metallization requires both barrier and adhesion layers (e.g., TiN, TiW). Again, this stack presents new challenges for controlling sidewall smoothness and slope of etched profile. Normally, chlorine-based plasmas are needed at elevated wafer temperatures (>200°C) due to low volatility of copper chlorides; either SiO₂ or SiN_x are used as the masking material. As a result of the difficulties in plasma-enhanced etching of copper, alternative methods for patterning have been explored. For instance, IR radiation has been used in a reactive ion etching reactor to enhance anisotropic copper etching by electronically exciting and aiding desorption of the CuCl₂ etch product. Chemical mechanical polishing (CMP) of copper, in a damascene process, has been developed to eliminate the need for plasma-enhanced copper etching altogether.

High dielectric constant films such as barium strontium titanate (BST) and lead zirconium titanate (PZT) are of current interest for building stacked capacitors for high capacitance DRAM applications. The stability of these materials in contact with metals is problematic; as a result, platinum, ruthenium, and ruthenium oxide are being investigated as electrode layers for BST and PZT. For example, platinum films have been etched in Ar/Cl₂ mixtures using an inductively coupled plasma (ICP) reactor.¹²

Photoresist Stripping and Ashing

Stripping or ashing of resist mask is performed after each etching step in IC fabrication. It is crucial that the resist be removed effectively, completely, and quickly, without altering existing device critical dimensions, structures, or properties. Downstream plasma reactors generating O₂-based plasmas using RF or microwave sources at low (~1 torr) or high (~1 atm) pressures are commonly used for this application.^{16,17} In these plasmas, oxygen is dissociated into oxygen atoms which react with the photoresist material to form volatile products: CO, CO₂, and H₂O. Removal rates can be high (~1 μm/min) at temperatures above 150°C; and radiation damage to existing films and devices can be minimal with properly designed downstream configurations.

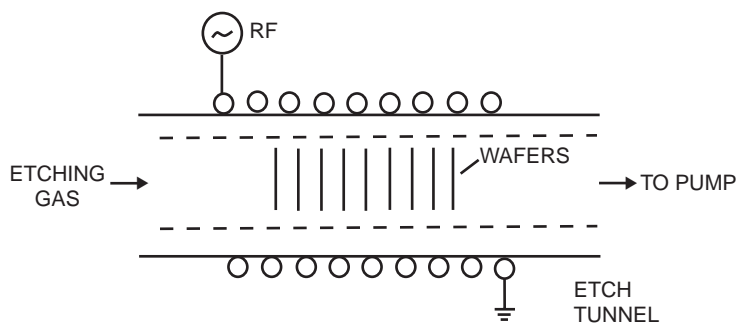


Fig. 6. Barrel plasma reactor.

Plasma-Enhanced Chemical Vapor Deposition (PECVD)

PECVD has been used to deposit a large number of insulators, semiconductors, and conductors.¹³ Because the high energy electrons present in plasmas can overcome kinetic barriers for deposition reactions, unique material structures, properties, and compositions can be achieved relative to thermally-activated CVD films. The primary films formed via PECVD for silicon-based ICs are silicon dioxide and silicon nitride, although the technique is being explored to deposit new low- and high-k films.

The plasma parameters of importance for PECVD are analogous to those discussed above for etching. However, the “figures of merit,” or the results desired, are different. Deposition rate, step coverage, and film properties (e.g., density, stress, resistivity) are major concerns. Plasma complexity remains a primary issue, but control can be more difficult than in the case of etching, since film properties, and thus film composition and bonding structures are critical.

As in etching, ion bombardment of growing film surfaces in the presence of neutral reactants alter film nucleation, growth kinetics, composition, physical and chemical structure, and stress. Depending on ion flux and energy, the synergy resulting from chemical and physical processes in PECVD can result in material properties unattainable with purely chemical (CVD) or purely physical (sputtering) deposition methods. Plasma-surface interactions impart energy to surfaces, thereby promoting processes such as surface diffusion (to improve step coverage or epitaxial growth), adsorption (to enhance adhesion), chemical reaction (to enhance deposition rates), desorption (to remove residual impurities), and sputtering (to alter surface topography).

Silicon dioxide, which is extensively used as a dielectric film in ICs has been deposited in a variety of PECVD reactors. Generally, nitrous oxide (N₂O) is the oxidant used with either silane (SiH₄) or tetraethoxysilane (TEOS) at temperatures between 150°C and 350°C. Since step coverage is frequently difficult with silane, TEOS is often the preferred choice. As a result of the reactive atmosphere and hydrogen-containing silicon reactants, hydrogen is incorporated into these films as Si-H, Si-OH and H₂O; concentrations are typically < 5%. These structures should be minimized in order to improve the electrical and chemical properties of these films.

Recent interest in low dielectric constant (k < 3.5) materials has resulted in the incorporation of fluorine into SiO₂ (k > 4) films. Addition of a F-containing vapor such as C₂F₆ or SiF₄ to the depositing plasma incorporates Si-F bonds in the SiO₂ film. Although the dielectric constant is reduced, the stability of these films to hydrolysis from atmospheric water vapor can be problematic. The use of high density plasma reactors appears to offer enhanced film stability, apparently as a result of the ability to control the ion flux and energy, and thereby film structure and density. Alternatively, high density reactors have been used to form even lower dielectric constant (k < 2.5) amorphous carbon films containing fluorine (a-C:F) from fluorocarbon sources such as C₄F₈ and C₂F₆.¹⁴

Silicon nitride is of interest as a passivation or protection coating on finished ICs and as an interlevel isolation dielectric. Typically, SiH₄ and ammonia (NH₃) are the reactants for PECVD of silicon nitride. As a result of the large amount of hydrogen in the reactants, and the lack of a strong oxidant for silicon, considerable hydrogen (10-30%, depending on the deposition temperature and extent of

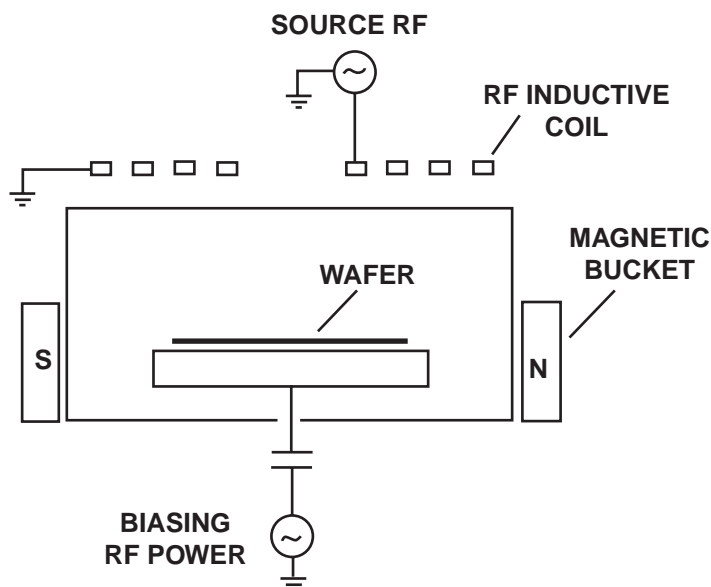


Fig. 7. Inductively coupled plasma (ICP) reactor.

ion bombardment) is incorporated into the deposited films (SiN_xH_y). This hydrogen is bonded to both silicon and nitrogen; the exact concentration and chemical distribution greatly affects the film properties such as refractive index, etch rate, stress, electrical resistivity, and thermal stability.

Recently, there has been an increased interest in developing high-k materials for applications in stacked capacitors for DRAMs. High dielectric constant films have been deposited in high density PECVD reactors. The reaction of pentaethoxy tantalum ($\text{Ta}(\text{OC}_2\text{H}_5)_5$) with oxygen in an electron cyclotron resonance (ECR) reactor at 500°C substrate temperature generated Ta_2O_5 films with an as-deposited dielectric constant of 20.3;¹⁵ similar studies at 95°C substrate temperature yielded films with $k = 14$.¹⁶ Strontium titanate and barium strontium titanate films have been formed in an ECR reactor using oxygen dissociation products to react with barium tetramethyl heptane dionate, strontium tetramethyl heptane dionate, and titanium isopropoxide vapors near a substrate heated to temperatures between 450° and 600°C .¹⁷ Dielectric constants in excess of 100 were obtained.

Plasma Reactors

Commercial plasma reactors come in many configurations to meet the many exacting demands of etching and deposition. Of the two main classes of reactors, namely, ion beam reactors and plasma reactors, only the latter are the most commonly used

type and therefore discussed in some detail. Ion beam reactors, on the other hand, are used only for specific etching applications where conventional plasma etching is not feasible, like the chemically hard to etch materials (e.g., ferroelectric film).

The first plasma reactor was introduced in 1967 for ashing organic materials. The first reactors were the barrel type, with volume loading of a batch of > 50 wafers in a quartz tube with inductive or capacitive electrodes powering the reactor with 13.56 MHz RF power supply. A perforated metal tunnel was later added to shield the wafers from ion bombardment. Etching, mostly due to neutral species, produced inherently isotropic profiles acceptable for the $> 2 \mu\text{m}$ devices of the 70s. Figure 6 is a schematic of a typical barrel reactor.

Then followed the introduction of a family of capacitively coupled parallel plate reactors: anode, diode (or RIE), hexode, and triode (decoupled plasma). These reactors (except the anode) offered control of ion energy (a function of power and pressure) on the wafer, enabling them to readily achieve anisotropic etch profiles. Indeed, today's most commonly used reactor configurations are derivatives of these early RIE reactors with added plasma density enhancements. Some of these new systems are discussed now.

In the early 80s, significant efforts were expended to develop and commercialize high etch rate single wafer reactors to keep pace with the demanding process requirements of

the sub- $0.5 \mu\text{m}$ devices — improved anisotropy, very high selectivity, high degree of process uniformity on 200 mm diameter wafers. Single wafer etchers, of necessity, had to achieve high etch rates to make them economically comparable with batch systems, prevalent in those years. This requirement led to the invention and development of several high density plasma sources: highly confined high pressure plasmas (plasma density: 10^{11} ions/ cm^3), magnetically enhanced plasmas (5×10^{10} ions/ cm^3), ECR (electron cyclotron resonance) plasma source (10^{11} - 10^{12} ions/ cm^3), ICP (inductively coupled plasma) source (5×10^{11} ions/ cm^3), helicon plasma (2×10^{12} ions/ cm^3), and MORI source (10^{12} - 10^{13} ions/ cm^3). Many of these high density plasma reactors operate at medium-low pressures (< 100 mtorr) with resultant narrow ion angular distribution and low ion energy, which are both desirable for achieving anisotropy, etch selectivity, and for the control of ion damage.

In magnetron (MERIE) reactors, an applied magnetic field confines the electrons within the plasma, thereby increasing the number of electron-gas collisions and achieving a dense plasma. In an ECR reactor, the gas at < 10 mtorr is excited by 2.45 GHz microwave frequency. Because of the resonance between the electron cyclotron and the applied microwave frequencies, a high degree of ionization takes place giving rise to a dense plasma. In an ICP/TCP reactor, shown in Fig. 7, an inductive coil placed on top of the reactor generates an intense plasma. An optional magnetic bucket strategically placed outside the reactor improves uniformity of ion density across the wafer and therefore the ion-enhanced etch rate uniformity. In a helicon source, 13.56 MHz power is inductively coupled to a helicon antenna to achieve a dense plasma. Up to 50% ionization (10^{12} ions/ cm^3 @ 0.4 mtorr Ar) has been claimed. A multipolar magnetic bucket surrounds the wafer zone to achieve uniformity. Unlike the conventional RIE reactors, in most high density plasma sources or reactors, plasma generation (i.e. ion flux) and ion energy (ion voltage) are decoupled by independently biasing the wafer electrode and powering the source coil or antenna. Independent ion energy control offers several processing advantages, including the very important ion damage control to devices.

In the early 90s, a new concept of reactor system configuration came

into being, namely the clustered plasma reactors.¹⁸ In this arrangement, two or more reactors that are normally used for sequential etching steps (e.g., Al-Cu etch → resist strip → plasma passivation) are clustered together around a common wafer handling load-lock platform. Clustered processing offers: (1) superior interface quality control from ambient contamination, (2) lower particle generation due to reduced wafer handling, and (3) higher productivity due to reduced cycle time.

Summary and the Future

Heinecke wrote in 1976, "... silicon and its compounds can be etched in a CF₄ glow discharge through the formation of volatile compounds. Such a process, if applied to semiconductor processing, promises a number of advantages over liquid etching methods..."

Since then, plasma etching has seen an explosive growth in all aspects of development and manufacturing implementation. Today's gigabit devices would not have been possible without the successful application of plasma etching to pattern transfer. The impetus for such a growth has been due to plasma's inherent ability to promote low temperature chemical reactions and to achieve anisotropic etching. Both reactor and process technologies have evolved significantly over these years. High density plasma reactors with a variety of plasma sources have come into being and are used in today's fabrication lines. Medium to low pressure processing with decoupled plasma generation and ion energy control has become the norm today. Although more than a quarter century has passed since its first use in microelectronics, equipment and process issues have not changed much and remain the focus of intense development work. The issues have not changed because the frame of reference (e.g., larger wafers, complex device structures, nanometer patterns) for optimal solutions has changed. The future is certain to bring new plasma sources, energetic neutral beam technology, and fuller process control and diagnostic procedures. Increased sensitivity to particle contamination in the upcoming nanometer device generations is sure to bring new materials of construction for reactors and enhancements for in-line particle monitoring and control. The introduc-

tion of 300 mm diameter wafers will add new challenges in process and tool optimization for achieving the required uniformities. Another development that will gain momentum is the defining of alternate etching and cleaning gases to replace perfluorocarbon compounds to reduce global warming emissions. Plasma processing is also sure to find increasing applications in other Si-based devices such as microelectromechanical systems. ■

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