

2

Pattern Transfer with Dry Etching Techniques

I think there is a world market for maybe five computers.

Thomas Watson, Chairman of IBM, 1943

Science has a way of getting us to the future without consulting the futurists and visionaries.

Robert Park, *Voodoo Science*

Introduction

Lithography steps precede a number of subtractive and additive processes. Materials are either removed from or added to a device, usually in a selective manner, transferring the lithography patterns onto integrated circuits (ICs) or three-dimensional micro- or nanomachines. This chapter deals with material removal by dry etching processes, whereas in Chapter 3 we focus on additive technologies.

Table 2.1 lists the most important subtractive processes encountered in miniaturization science, including wet and dry etching, focused ion-beam (FIB) milling, laser machining, ultrasonic drilling, electrical discharge machining (EDM), and traditional precision machining. Applications (which mostly involve Si), typical material removal rates, relevant references, and some remarks on the techniques supplement the list. One of the most widely used subtractive techniques for micromachining listed in Table 2.1 is etching. Etching can be described as pattern transfer by chemical/physical removal of a material from a substrate—often in a pattern defined by a protective maskant layer such as a resist or an oxide. From the etching processes listed in Table 2.1, we will review gas and vapor phase dry etching processes including chemical, physical, and physical-chemical etching. Etching in the liquid phase is covered separately in Chapter 4. Maskless material removing technologies, such as FIB, mechanical precision machining, and laser and ultrasonic drilling, will be discussed in Chapter 7.

When introducing resist stripping in Chapter 1, we learned that the popularity of dry stripping of resists (ashing) and the need for better critical dimension (CD) control precipitated major research and development efforts in all types of plasma-based dry etching processes. The preference for dry stripping over wet stripping methods is based on a variety of advantages:

fewer disposal problems; less corrosion of metal features in the structure and less undercutting and broadening of photoresist features; that is, better CD control (nanometer dimensions) (see Inset 2.1) and, under the right circumstances, a cleaner resulting surface. Also, with the new generations of ICs, all with sub-quarter-micron geometries, surface tension might preclude a wet etchant from reaching down between photoresist features, whereas dry etching prevents any such problem. As in IC manufacture, dry etching has evolved into an indispensable technique in miniaturization science. After the success of wet-etched Si micromachined products in the 1980s and early 1990s, the maturation of flexible, generic, and fast anisotropic deep reactive ion etching (DRIE) techniques in the late 1990s spawned a second wave of Si miniaturized commercial products.

Scanning electron micrograph of 0.25- μm -wide microcavities in $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}/\text{GaAs}$ etched down to 2.8 μm with vertical profile and smooth surface after dry etching using an ECR source. The etch was carried out in 10% Cl_2 in Ar and the plasma was generated with 50 W microwave power at the electron cyclotron source and 70 W RF power at the stage, the pressure was 0.5 mTorr. (Courtesy of Dr. S.W. Pang, University of Michigan.)



Inset 2.1

TABLE 2.1 Partial List of Subtractive Processes Important in Micromachining (see also Chapter 7)

| Subtractive technique | Applications | Typical etch rate | Remarks | References |
|--|---|---|--|-------------------|
| Wet chem. etch.: iso | Si spheres, domes, grooves | Si polishing at 50 $\mu\text{m}/\text{min}$ with stirring (RT, acid) | Little control, simple | Ch. 4, Ref. 1 |
| Wet chem. etch.: anis | Si angled mesas, nozzles, diaphragms, cantilevers, bridges | Etching at 1 $\mu\text{m}/\text{min}$ on a (100) plane (90°C, alkaline) | With etch-stop more control, simple | Ch. 4, Ref. 1 |
| Electrochem. etch | Etches p-Si and stops at n-Si (in n-p junction), etches n-Si of highest doping (in n/n ⁺) | p-Si etching 1.25–1.75 $\mu\text{m}/\text{min}$ (100) plane, 105–115°C (alkaline) | Complex, requires electrodes | Ch. 4, Refs. 2, 3 |
| Wet photoetch | Etches p-type layers in p-n junctions | Etches p-Si up to 5 $\mu\text{m}/\text{min}$ (acid) | No electrodes required | Ch. 4, Ref. 4 |
| Photo-electrochem. etch | Etches n-Si in p-n junctions, production of porous Si | Typical Si etch rate: 5 $\mu\text{m}/\text{min}$ (acid) | Complex, requires electrodes and light | Ch. 4, Ref. 5 |
| Dry chem. etch. | Resist stripping, isotropic features | Typical Si etch rate: 0.1 $\mu\text{m}/\text{min}$ (but, with more recent methods, up to 6 $\mu\text{m}/\text{min}$) | Resolution better than 0.1 μm , loading effects | Ch. 2, Refs. 6, 7 |
| Physical/chem. etch | Very precise pattern transfer | Si etch rate: 0.1 to 1 $\mu\text{m}/\text{min}$ (but, with more recent methods, up to 6 $\mu\text{m}/\text{min}$) | Most important dry etching technique | Ch. 2, Refs. 7, 8 |
| Physical dry etching, sputter etching, and ion milling | Si surface cleaning, unselective thin film removal | Typical Si etch rate: 300 $\text{Å}/\text{min}$ | Unselective and slow, plasma damage | Ch. 2, Ref. 8 |
| Vapor phase etching with XeF ₂ (and other interhalogens) | Isotropic Si etching in presence of Al and SiO ₂ | Typical Si etch rate: 1–3 $\mu\text{m}/\text{min}$ | Very selective, fast, and very simple | Ch. 2, Ref. 9 |
| Focused ion-beam (FIB) milling | Microholes, circuit repair, microstructures in arbitrary materials | Typical Si etch rate: 1 $\mu\text{m}/\text{min}$ | Long fabrication time: >2 h including setup | Ch. 7, Ref. 10 |
| Laser machining (with and without reactive gases) | Circuit repair, resistor trimming, hole drilling, labeling of Si wafers | Typical rate for drilling a hole in Si with a Nd:YAG (400W laser): 1 mm/s (3.5 mm deep and 0.25 mm dia.) | Laser beams can focus to a 1 μm spot, etch with a resolution of 1 μm^3 | Ch. 7, Ref. 11 |
| Ultrasonic drilling | Holes in quartz, silicon nitride bearing rings | Typical removal rate of Si: 1.77 mm/min | Especially useful for hard, brittle materials | Ch. 7, Ref. 12 |
| Electrical discharge machining (EDM) | Drilling holes and channels in hard brittle metals | Typical removal rate for metals: 0.3 cm ³ /min | Poor resolution (>50 μm), only conductors, simple, wire discharge machining resolution much better | Ch. 7, Ref. 13 |
| Mechanical turning, drilling and milling, grinding, honing, lapping, polishing, and sawing | Almost all machined objects surrounding us | Removal rates of turning and milling of most metals: 1 to 50 cm ³ /min, for drilling: 0.001 to 0.01 cm ³ /min | Prevalent machining technique | Ch. 7, Ref. 14 |

Note: Boldface type indicates techniques reviewed in Chapter 2. RT = room temperature, chem. etch = chemical etching, iso = isotropic, anis = anisotropic.

Dry Etching: Definitions and Jargon

Dry etching covers a family of methods by which a solid surface is etched in the gas or vapor phase, physically by ion bombardment, chemically by a chemical reaction through a reactive species at the surface, or by combined physical and chemical mechanisms. Plasma-assisted dry etching is categorized according to the specific setup as either *glow discharge* (diode setup) or *ion beam* (triode setup). Using glow discharge techniques,

plasma is generated in the same vacuum chamber where the substrate is located; when using ion-beam techniques, plasma is generated in a separate chamber from which ions are extracted and directed in a beam toward the substrate by a number of grids. Figure 2.1 represents the various dry etching diode and triode techniques.¹⁵ It is also common to differentiate between (1) chemical plasma etching (PE), (2) synergetic reactive ion etching (RIE), and (3) physical ion-beam etching (IBE).¹⁶ Each of these techniques will be discussed in detail below; here, we

present a short synopsis. In sputter/ion etching and ion-beam milling or IBE (see shaded box in Figure 2.1), etching occurs as a consequence of a physical effect, namely momentum transfer between energetic Ar^+ ions and the substrate surface. Some type of chemical reaction takes place in all the other dry etching methods. In the case of physical/chemical RIE, impacting ions, electrons, or photons either induce chemical reactions or, in sidewall-protected ion-assisted etching, a passivating layer is cleared by the particle bombardment from horizontal surfaces only. As a result, in the latter case, etching occurs almost exclusively on the cleared planar surfaces. In reactive PE, neutral chemical species such as chlorine or fluorine atoms generated in the plasma diffuse to the substrate, where they react to form volatile products with the layer to be removed. The only role of the plasma is to supply gaseous, reactive etchant species.

Finally, plasma etching systems can also be divided into single-wafer and batch reactors. In Table 2.2, we review the most common dry etching methods, give a typical etch rate, and clarify the associated jargon. Of the techniques listed, PE and RIE are the most widely used in IC manufacture and micromachining.

In selecting a dry etching process, the desired shape of the etch profile and the selectivity of the etching process require careful consideration. Figure 2.2 shows different possible etch profiles,⁶ where, depending on the mechanism employed, isotropic, directional, or vertical etch profiles are obtained. In dry etching, anisotropic etch profiles—directional or vertical—can be generated in single crystalline, polycrystalline, and amorphous materials. The anisotropy is not a result of anisotropy in the etching rate of single crystals as in the case of anisotropic wet chemical etching (Chapter 4); rather, the degree of anisotropy is controlled by the plasma conditions. Selectivity of a dry etch refers to the difference in etch rate between the mask and the film to be etched, again controllable by plasma conditions.

At low pressures, in the 10^{-3} to 10^{-4} Torr range (see Figure 2.1), anisotropic etching is easy, but accomplishing selectivity is difficult. Physical ion-beam etching at those pressures results in tapered profiles as shown in Figure 2.2A, low selectivity, and low etch rates. At higher pressures (1 Torr) in plasma etching, chemical effects dominate, leading to better selectivity and higher etch rates than in the case of ion beams, but etched features are isotropic (Figure 2.2B). Reactive ion etching enables profile control due to the synergistic combination of physical sputtering with the chemical activity of reactive species with a high etch rate and high selectivity. In the extreme case of aniso-

tropic etching, vertical sidewalls result (no lateral undercut) with perfect retention of the CDs (see Figure 2.2C and D). In the case of isotropic etching, dimensionality losses are incurred with an etch depth on the order of the lateral dimensions as illustrated in Figure 2.3. To ensure uniform etch rates over the whole wafer and between wafers, isotropic overetching may be required, further compromising the dimensionality. Figure 2.3 compares the etch profile of no overetching with a 25% overetch. Making the initial lithography smaller compensates for the loss of dimensionality incurred by overetching.

A sharp vertical sidewall is not always the desired edge profile. For example, with line-of-site deposition methods such as resistive evaporation (see Chapter 3), a tapered sidewall is easier to cover than a vertical wall. Another example in which a nonvertical process has the advantage is illustrated in Figure 2.4. To take away the layer shown on the vertical walls, an anisotropic etchant would require extensive overetching, whereas an isotropic etchant will remove the material quickly.

Plasmas or Discharges

Most dry etching systems find their common base in plasmas or discharges, areas of high energy electric and magnetic fields that rapidly dissociate a suitable feed gas (e.g., sulfur hexafluoride, SF_6 for Si etching) to form neutrals, energetic ions (SF_5^+ and F^-), photons, electrons, and highly reactive radicals (F°). A surface in contact with a plasma is exposed to fluxes of atoms, molecules, ions, electrons, and photons. This bombardment stimulates the production of outgoing fluxes of neutrals, ions, electrons, and photons, leading to a modified or etching surface layer.¹⁷ We will start our foray into the physics and chemistry of plasmas by looking at the simplest plasma setup—a dc-diode glow discharge in a low-pressure Argon atmosphere. After a discussion of the spatial zones in a glow discharge, we explain the Paschen curve and then introduce RF plasmas.

Physics of DC Plasmas

The simplest plasma reactor consists of opposed parallel-plate electrodes in a chamber maintainable at low pressure, typically ranging from 0.001 to 10 Torr. The electrical potentials established in the reaction chamber, filled with an inert gas such as argon at a reduced pressure, determine the energy of ions and electrons striking the surfaces immersed in the discharge. Using the setup shown in Figure 2.5A and applying 1.5 kV between

TABLE 2.2 Some Popular Dry Etching Systems

| | CAIBE | RIBE | IBE | MIE | MERIE | RIE | Barrel etching | PE |
|-----------------|----------------|----------------|----------------|-----------------------|-----------------------|-----------------------|--------------------|--------------------|
| Pressure (Torr) | $\sim 10^{-4}$ | $\sim 10^{-4}$ | $\sim 10^{-4}$ | 10^{-3} – 10^{-2} | 10^{-3} – 10^{-2} | 10^{-3} – 10^{-1} | 10^{-1} – 10^0 | 10^{-1} – 10^1 |
| Etch mechanism | Chem./phys. | Chem./phys. | Phys. | Phys. | Chem./phys. | Chem./phys. | Chem. | Chem. |
| Selectivity | Good | Good | Poor | Poor | Good | Good | Excellent | Good |
| Profile | Anis. or iso. | Anis. | Anis. | Anis. | Anis. | Iso. or anis. | Iso. | Iso. or anis. |

Note: CAIBE = chemically assisted ion beam etching; RIBE = reactive ion beam etching; MIE = magnetically enhanced ion etching; MERIE = magnetically enhanced reactive ion etching; RIE = reactive ion etching; PE = plasma etching.

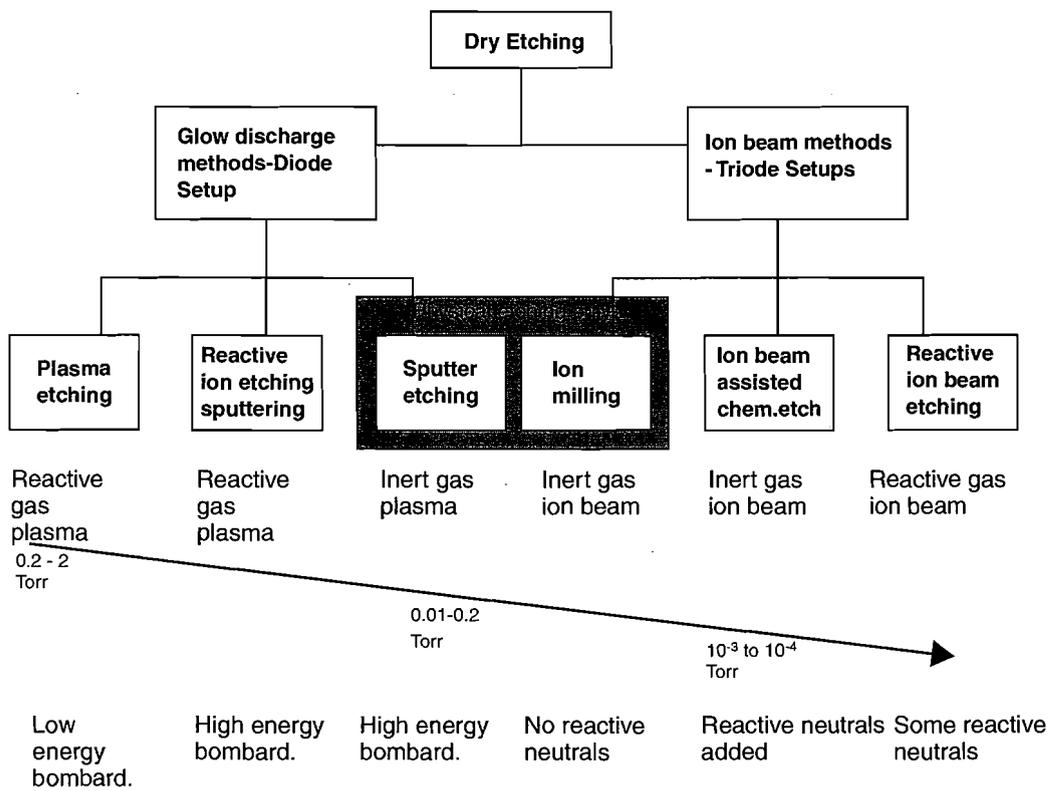


Figure 2.1 Various dry etching techniques. (Adapted from H. W. Lehmann in *Thin Film Processes II*, J. L. Vossen, and W. Kern, Eds. Academic Press, Boston, 1991.¹⁵)

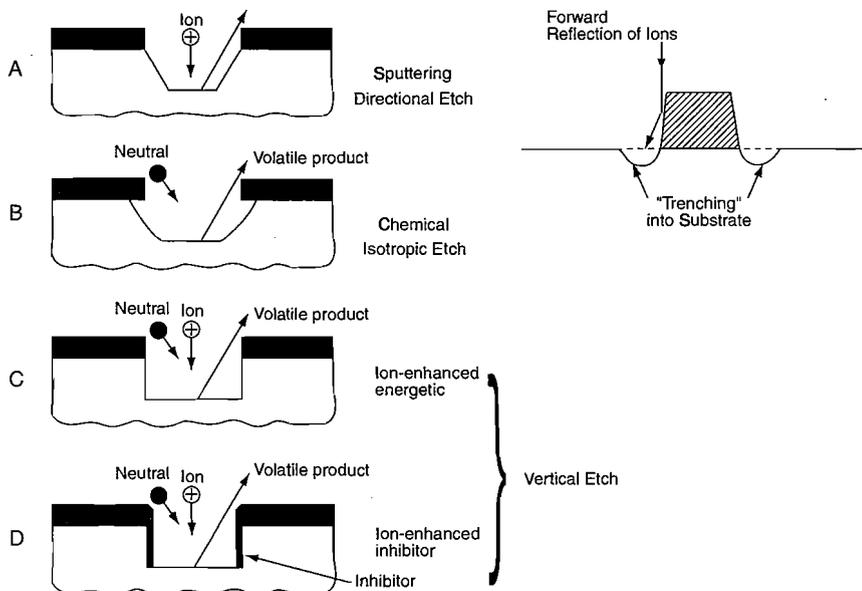


Figure 2.2 Important dry etching profiles associated with different dry etching techniques. (A) Sputtering and formation of trenches (ditches) in physical ion etching. The mask is etched most rapidly in the neighborhood of the mask corner. The slope becomes less steep and not all ions arrive at the etch bottom parallel to the sides. Some of them collide with the sides of the mask or substrate before arriving at the etch surface. Consequently, an increase in the number of incident ions close to the edges occurs, locally increasing the etch rate and forming ditches (see inset on the right). (B) Chemical etching in a plasma at low voltage and relative high pressure leads to isotropic features and lateral undercuts. (C) Ion-enhanced etching: physical-chemical is the most perfect image transfer as the undercutting is limited by the combined action of physical and chemical etching. The low pressure and high voltage lead to directional anisotropy. (D) Ion-enhanced inhibitor. Sidewalls are protected from undercutting by a surface species (e.g., a polymer) which starts etching when hit by a particle such as an ion, a photon, or an electron. Since very few particles hit the sidewalls (high voltage and high pressure), undercutting is suppressed. (Left side of figure is from D. L. Flamm, *Solid State Technology*, October, 49-54, 1993.⁶ Copyright 1993 PennWell Publishing Company. Reprinted with permission.)

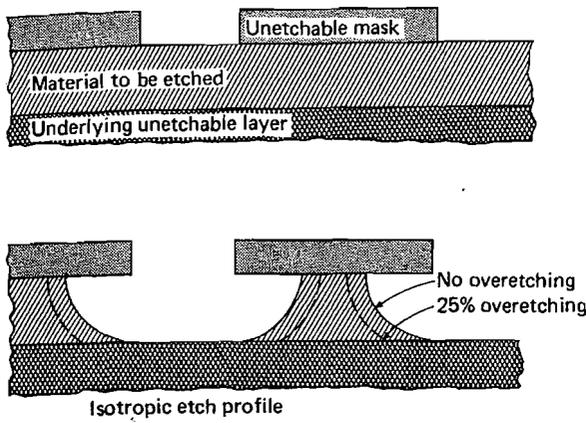


Figure 2.3 Example illustrating the loss of dimensionality incurred by an isotropic etch when the depth is of the order of the lateral dimensions involved. Making the initial lithography smaller compensates for the loss of dimensionality by overetching.

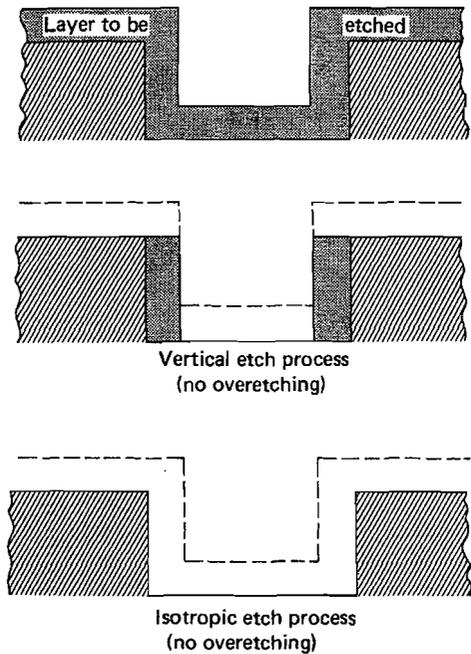


Figure 2.4 An example of dry etching illustrating a case where an isotropic etch is preferred to a vertical etch process. To clear the layer on the vertical walls, an isotropic etch only requires a minimal overetch while an anisotropic etch requires a substantial amount of overetching.

the anode and cathode, separated by 15 cm, results in a 100 V/cm field. Electrical breakdown of the argon gas in this reactor will occur when electrons, accelerated in the existing field, transfer an amount of kinetic energy greater than the argon ionization potential (i.e., 15.7 eV) to the argon neutrals. Such energetic collisions generate a second free electron and a positive ion for each successful strike. Both free electrons reenergize, creating an avalanche of ions and electrons that results in a gas breakdown emitting a characteristic glow (blue, in the case of Argon). Avalanching requires the ionization of 10 to 20 gas molecules by one secondary electron. At the start of a sustained

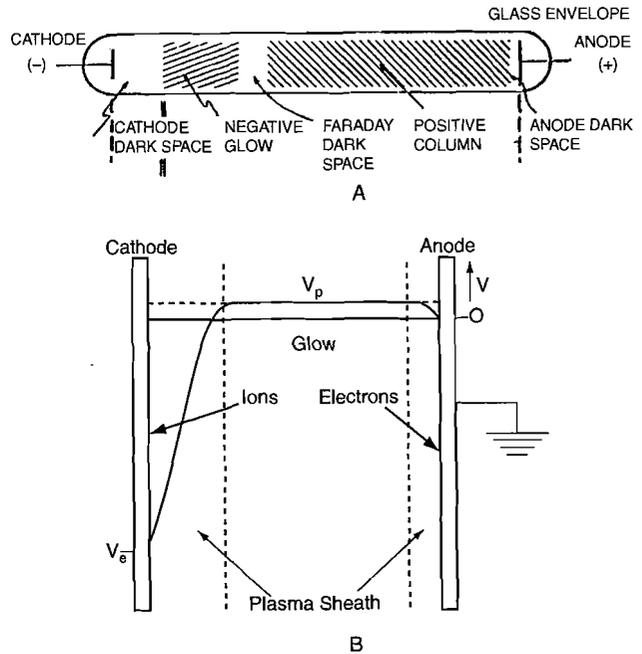


Figure 2.5 Voltage distribution in a dc diode discharge in equilibrium. (A) Structure of the glow discharge in a dc diode system. (B) Voltage distribution in a dc diode discharge in equilibrium.

gas breakdown, a current, typically several hundred milliamps, starts to flow, and the voltage between the two electrodes drops from 1.5 kV to about 150 V. The discharge current builds up to the point at which the voltage drop across a current limiting resistor is equal to the difference between the supply voltage (1.5 kV) and the electrode potential difference (150 V). Once equilibrium is reached, the glow region of the plasma, being a good electrical conductor, sustains a very low field only, and its potential is almost constant. The potential drops reside at electrode surfaces where electrical double layers are formed in “sheath fields,” counteracting the loss of electrons from the plasma (Figure 2.5B). The cathode sheath corresponds to the cathode dark space (also called the *Crookes* or *Hittorf* region). Positive ions entering this sheath are accelerated toward the electrode. To sustain a plasma, a mechanism to generate additional free electrons must exist after the plasma-generating electrons have been captured at the positively charged anode. Plasma-sustaining electrons are generated through the emission of secondary electrons (Auger electrons) when the cathode is struck by ions. The continuous generation of those “new” electrons prompts a sustained current and a stable plasma glow.

A striking characteristic of a plasma is its permanent positive charge with respect to the electrodes—a result of the random motion of electrons and ions. The positive charge of a plasma can be understood from kinetic theory, which predicts that, for a random velocity distribution, the flux of ions, j_i , and electrons, j_e , upon a surface is given by:

$$j_{i,e} = \frac{n_{i,e} \langle v_{i,e} \rangle}{4} \quad (2.1)$$

where n and $\langle v \rangle$ are the densities and average velocities, respectively. Because ions are heavier than electrons (typically 4000 to 100,000 times as heavy), the average velocity of electrons is higher. Consequently, the electron flux (according to Equation 2.1) is larger than the ion flux, and the plasma loses electrons to the walls, thereby acquiring a positive charge. The bombarding energy of ions is proportional to the potential difference between the plasma and the surface being struck by the ions. The reason behind the asymmetric voltage distribution at the anode and cathode as seen in Figure 2.5B is as follows: electrons near the cathode rapidly accelerate away from it due to their relatively light mass; ions, being more massive, accelerate toward the cathode more slowly. Thus, on average, ions spend more time in the Crookes dark space, and, at any instant, their concentration is greater than that of electrons. The net effect is a very large field in front of the cathode in comparison with that in front of the anode and in the glow region itself. Consequently, the greatest part of the voltage between the anode and the cathode, V_p , is dropped across the Crookes dark space, where charged particles (ions and electrons) experience their largest acceleration. This region is also called the *cathode-fall* region.

Glow discharges are nonequilibrium, as the average electron energy, $\langle v_e \rangle$, also called *electron temperature*:

$$\langle v_e \rangle = kT_e \quad (\text{e.g., } 1 - 10 \text{ eV}) \quad (2.2)$$

is considerably higher, in the range of 1 to 10 eV, than the average ion energy, $\langle v_i \rangle$, also called *ion temperature*:

$$\langle v_i \rangle = kT_i \quad (\text{e.g., } 0.04 \text{ eV}) \quad (2.3)$$

which is much colder, typically having energies of 0.02 to 0.1 eV. So a discharge or plasma cannot be described adequately by one single temperature [$T_e(\text{electrons})/T_i(\text{ions}) = 10$ to 100]. High-temperature electrons in a low-temperature gas are possible due to the small mass of electrons (m_e) as compared with ions and neutrals. In collisions between electrons and argon atoms (M_A), due to an m_e/M_A ratio of 1.3×10^{-5} , electrons have a very poor energy transfer and stay warmer longer than the heavier ions and neutrals. In a plasma with an ionization fraction of 10^{-4} , there are many more cold gas atoms than ions, and the ions quickly reach the background gas temperature as a result of the many collisions between ions and neutrals.¹⁸ Electrons can attain a high average energy, often many electron volts (equivalent to tens of thousands of degrees above the gas temperature), permitting electron-molecule collisions to excite high-temperature-type reactions forming free radicals in a low-temperature neutral gas. Generating the same reactive species without a plasma would require temperatures in the $\sim 10^3$ to 10^4 K range, destroying resists and damaging most inorganic films.

A plasma is typically weakly ionized: the number of ions is small compared with the number of reactive neutrals such as radicals. The ratio between ionized and neutral gas species in a glow discharge plasma is of the order of 10^{-6} to 10^{-4} . This fact, as we will see below, is crucial in understanding which entities are responsible for the actual etching of a substrate placed in a

glow discharge. The degree of ionization in a plasma depends on a balance between the rate of ionization and the rate at which particles are lost by volume recombination and by losses to the walls of the apparatus. Wall losses generally dominate volume recombination. Accordingly, the occurrence of a breakdown in a given apparatus depends on the gas pressure (particle density), the type of gas, electric field strength (electron velocity), surface-to-volume ratio of the plasma, and distance between the anode and the cathode (see also Paschen's law in the section below).

The choice of a dry etching technique depends on the efficiency or "strength" of the particular plasma. Plasma strength is evaluated by parameters such as average electron energy, $\langle v_e \rangle$ (Equation 2.2); average ion energy (Equation 2.3); electron density (e.g., between 10^9 and 10^{12} cm^{-3}); plasma ion density (e.g., 10^8 to 10^{12} cm^{-3}); neutral species density (e.g., 10^{15} to 10^{16} cm^{-3}); and ion current density (e.g., 1 to 10 mA/cm^2). A quantity of particular use in characterizing a plasma's average electron or ion energy is the ratio of the electrical field to the pressure:

$$kT_{i,e} \sim \frac{E}{P} \quad (2.4)$$

With increasing field strength, the velocity of free electrons or ions increases because of acceleration by the field ($\sim E$), but velocity is lost by inelastic collisions. Since an increase in pressure decreases the electron or ion mean free path, there being more collisions, the electron or ion energy decreases with increasing pressure ($\sim 1/P$).

How do we use the described dc plasmas for dry etching? In one of the arrangements, the substrate to be etched is placed on the cathode (target) of a dc diode system. An argon plasma in this setup will produce sufficiently energetic ions (between 200 and 1000 eV) to induce physical etching, that is, ion etching or sputtering. In sputtering, atoms (from the substrate) are billiard-ball-wise ejected from the bombarded substrate. The low pressure in sputter etching (10 to 200 mTorr) gives rise to a long mean free path, and the externally applied voltage concentrates across the cathode plasma sheath where ions are accelerated before hitting the cathode. Each ion will collide numerous times with other gas species before transversing the plasma sheath, as the sheath thickness is larger than the mean free ion path. As a result of these collisions, ions lose much of their energy and move across the sheath with a drift velocity that is less than "free fall" velocity. But these vertical velocities are still very large as compared with the random thermal velocities in the glow discharge region. The resulting bombarding ion flux, j_i , is given by:

$$j_i = qn_i\mu_i E \quad (2.5)$$

where E = electric field
 n_i = ion density
 μ_i = ion mobility
 q = charge

Reducing the pressure in the reactor increases the mean free path. Consequently, ions accelerating toward the cathode at

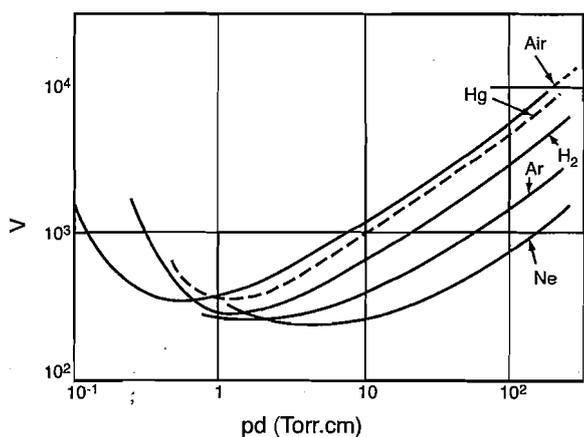


Figure 2.7 The dc breakdown voltage as a function of gas pressure P and electrode spacing d for plane parallel electrodes in air and some other gases. Such curves are determined experimentally and are known as *Paschen curves*.

TABLE 2.3 Minimum Breakdown Voltage (V_{min}) and Pressure/Distance Product ($P \times d$) at the Minimum Voltage for Various Gases, as Deduced from Their Paschen Law Curves

| Gas | V_{min} in Volts (V) | $P \times d$ at V_{min} (Torr cm) |
|------------------|------------------------|-------------------------------------|
| Air | 327 | 0.567* |
| Ar | 137 | 0.9 |
| H ₂ | 273 | 1.15 |
| He | 156 | 4.0 |
| CO ₂ | 420 | 0.51 |
| N ₂ | 251 | 0.67 |
| N ₂ O | 418 | 0.5 |
| O ₂ | 450 | 0.7 |
| SO ₂ | 457 | 0.33 |
| H ₂ S | 414 | 0.6 |

*At 1 atmosphere = 760 mm Hg or 760 Torr, $d = 7.460 \times 10^{-4}$ cm or ~ 8 μ m.

Source: After Naidu et al., 1995.²⁷

Physics of RF Plasmas

In an RF-generated plasma, a radio-frequency voltage applied between the two electrodes causes free electrons to oscillate and collide with gas molecules, leading to a sustainable plasma. RF-excited discharges can be sustained without relying on the emission of secondary electrons from the cathode. Electrons pick up enough energy during oscillation in an RF field to cause ionization, thus sustaining the plasma at lower pressures than in a dc plasma (e.g., 10 vs. 40 mTorr). Another advantage that RF has over dc is that RF allows etching of dielectrics as well as metals. The RF breakdown voltage of plasma shows the Paschen behavior of dc plasma; that is, a minimum in the required voltage as a function of the pressure with the mean free path of electrons, λ_e , substituting spacing, d , between electrodes.

In the simplest case of RF ion sputtering, the substrates to be etched are laid on the cathode (target) of a discharge reactor, for example, a planar parallel plate reactor as shown in Figure 2.8. The reactor consists of a grounded anode and powered cathode or target enclosed in a low-pressure gas atmosphere (e.g., 10^{-1} to 10^{-2} Torr of argon). RF plasma, formed at low gas pressures, consists of positive cations, negative anions, radicals, and photons (the UV photons create the familiar plasma glow). As with a dc plasma, neutral species greatly outnumber electrons and ions—the degree of ionization only being on the order of 10^{-4} to 10^{-6} for parallel-plate gas discharges. The RF frequency typically employed is 13.56 MHz (chosen because of its noninterference with radio-transmitted signals). The RF power supply is rated between 1 and 2 kW. With one of the two electrodes capacitively coupled to the RF generator, this electrode automatically develops a negative dc bias and becomes the cathode with respect to the other electrode (see Figure 2.9A). This dc bias (also called *self-bias* V_{DC}) is induced by the plasma itself and is established as follows. When initiating an ac plasma arc, electrons, being more mobile than ions, charge up the capacitively coupled electrode; since no charge can be transferred over the capacitor, the electrode surface retains a negative dc bias.

The energy of charged particles bombarding the surface in a glow discharge is determined by three different potentials established in the reaction chamber: the plasma potential V_p ; that is, the potential of the glow region, the self-bias V_{DC} , and the bias on the capacitively coupled electrode ($V_{RF,pp}$) (see also Figure 2.9B). The following analysis clarifies how these potentials relate to one another and how they contribute to dry etching.

The self-bias buildup, V_{DC} on an insulating electrode by the electron flux (Equation 2.1) is given by:

$$V_{DC} = \frac{kT_e}{2e} \ln \frac{T_e m_i}{T_i m_e} \quad (2.6)$$

where T_e and T_i are the electron and ion temperatures defined by Equations 2.2 and 2.3, and m_e and m_i are the electron and ion masses, respectively.²⁹ In the plasma, there are equal amounts of hot electrons ($T_e = 2 \times 10^4$ K) and cold positive ions

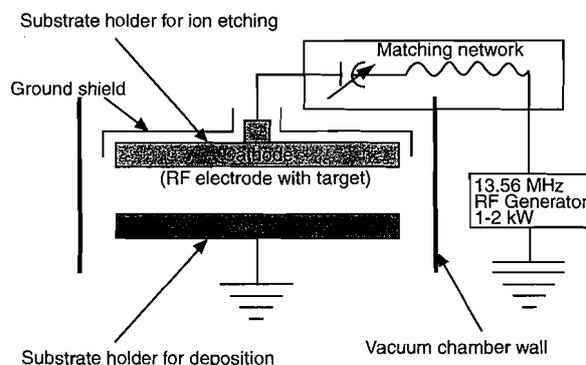


Figure 2.8 Two-electrode setup (diode) for RF ion sputtering or sputter deposition. For ion sputtering, the substrates are put on the cathode (target); for sputter deposition (see Chapter 3), the substrates to be coated are put on the anode.

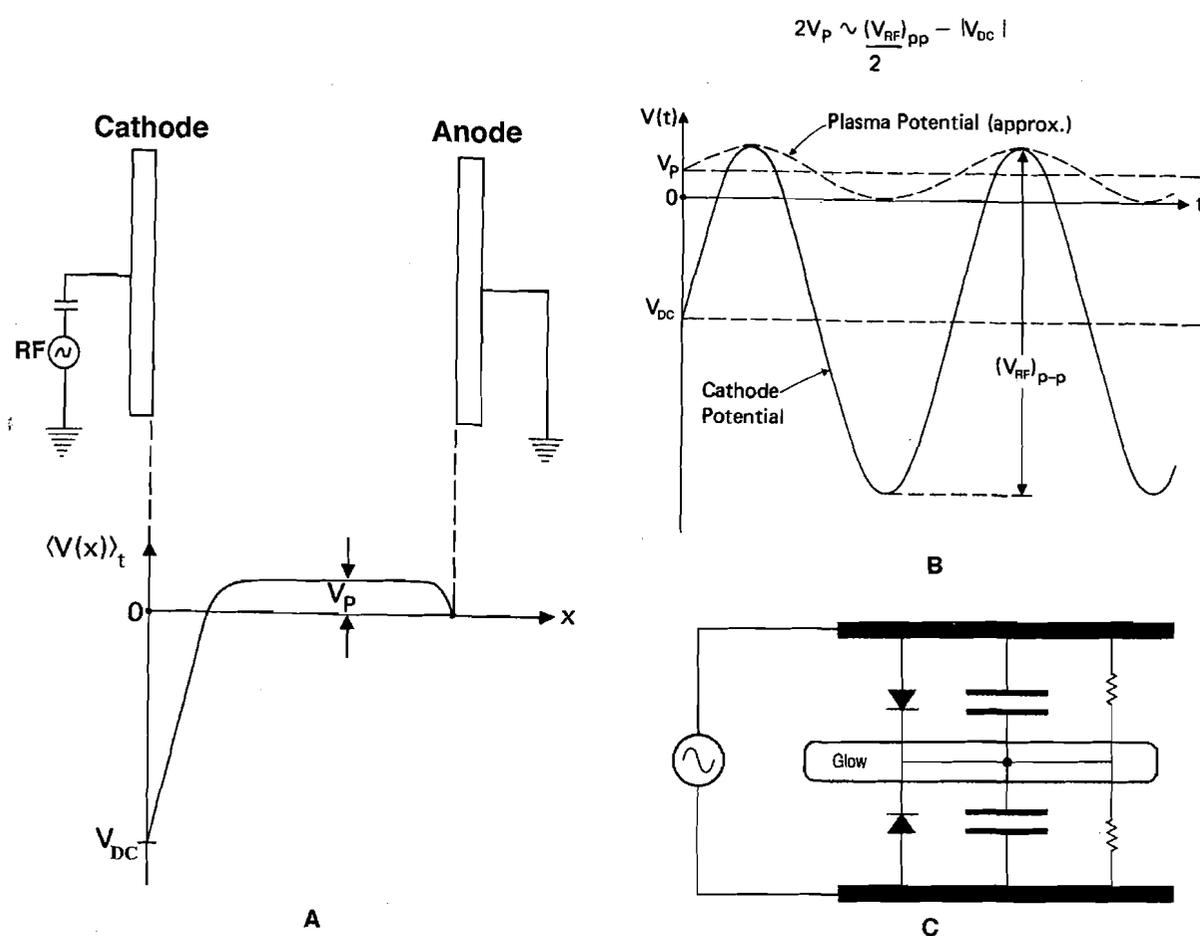


Figure 2.9 RF plasma. (A) Approximate time-averaged potential distribution for a capacitively coupled planar RF discharge system. (B) Potential distribution in glow discharge reactors— V_p : plasma potential; V_{dc} : self-bias of cathode electrode; $(V_{RF})_{pp}$: peak-to-peak RF voltage applied to the cathode. (C) Equivalent electrical circuit of an RF plasma.

($T_i = T_{gas} = 500$ K). For a common RF power density of 4 kWm^{-2} the self-bias is about 300 V, so that the powered electrode (the cathode) is bombarded with 300 eV positive ions.³⁰

The electron loss creates an electric sheath field in front of any surface immersed in the plasma, counteracting further electron losses. This sheath or dark space forms a narrow region between the conductive glow region and the cathode (the Crookes dark space) where most of the voltage (V_{DC} in Figure 2.9A) is dropped as in the dc plasma case. The cathode, being capacitively coupled, effectively acts as an insulator for dc currents. The thickness of the sheath is typically 0.01 to 1 cm, depending on pressure, power, and frequency. The other electrode is grounded and conductive (no charge buildup and no voltage buildup) and automatically becomes the anode with respect to the capacitively coupled electrode.

The time-average of plasma potential V_p , dc cathode potential (self-bias potential) V_{DC} , and peak-to-peak RF voltage $(V_{RF})_{pp}$ applied to the cathode are approximately related as (see Figure 2.9B):

$$2V_p \sim \frac{(V_{RF})_{pp}}{2} - |V_{DC}| \quad (2.7)$$

Clearly, the magnitude of the self-bias depends on the amplitude of the RF signal applied to the electrodes. In the RF discharge, the time-averaged RF potential of the glow region, referred to as the *plasma potential* V_p , is more significantly positive with respect to the grounded electrode than in the case of a dc plasma.

Positive argon ions from the plasma are extracted by the large field at the cathode and sputter that electrode at near-normal incidence, with energies ranging from a few to several hundred electron volts, depending on plasma conditions and chamber construction. One of the most important parameters determining plasma condition is total reactor pressure. As pressure is lowered below 0.05 to 0.1 Torr, the total ion energy, E_{max} , rises as both the self-bias voltage and the mean free path of the bombarding ions increase. Subsequently, ion-substrate bombardment energy rises sharply with decreasing pressure. The maximum energy of positive ions striking a substrate placed on the cathode is proportional to:

$$E_{max} = e(|V_{DC}| + V_p) = eV_T \quad (2.8)$$

with $V_T = |V_{DC}| + V_p$, whereas the maximum energy for a substrate on the grounded electrode (i.e., the anode) is proportional to:

$$E_{max} = eV_p \quad (2.9)$$

Typical values are 300 eV for the cathode and less than 20 eV for the anode.³⁰ Equations 2.8 and 2.9 can be deduced from an inspection of Figure 2.9A. The situation in which the wafers are put on the cathode is referred to as *reactive ion etching* or *reactive sputter etching*. Chamber construction, especially the ratio of anode to cathode area, influences the rates of V_T/V_p and, consequently, as calculated from Equations 2.8 and 2.9, the energy of the sputtering ions on these respective electrodes. Etching of the anode should be avoided; that is, V_p should be kept small (say, less than 20 eV). To deduce the influence of the geometry of the anode and cathode on dry etching, we compare the sheath voltages in front of the anode and cathode using the Child–Langmuir equation expressing the relationship between the ion-current flux, j_i , the voltage drop, V , over the sheath thickness of the dark space, d , and the mass of the current carrying ions, m_i . The relation can be deduced from Equation 2.5, assuming the presence of a space-charge limited current:

$$j_i = \frac{KV^2}{\sqrt{m_i}d^2} \quad (2.10)$$

in which K is a constant.³¹ The current density of the positive ions must be equal on both the anode $j_i(P)$ and cathode $j_i(T)$; that is, $j_i = j_i(P) = j_i(T)$, resulting in the following relation for the sheath voltages:

$$\text{(cathode)} \frac{V_T^{3/2}}{d_T^2} = \frac{V_p^{3/2}}{d_p^2} \text{(anode)} \quad (2.11)$$

The plasma behaves electrically as a diode (a large blocking voltage drop toward the capacitively coupled cathode and a small voltage drop on the anode/plasma interface) in parallel with the sheath capacitance. As soon as any electrode tends to become positive relative to the plasma, the current rises dramatically, causing the plasma to behave as if a diode were present in the equivalent electrical circuit of the plasma. Hence, a planar, parallel setup also is called a *diode* setup. The equivalent electrical circuit representing an RF plasma is represented in Figure 2.9C. The dark spaces in a plasma are areas of limited conductivity and can be modeled as capacitors:

$$C \sim \frac{A}{d} \quad (2.12)$$

The plasma potential is determined by the relative magnitudes of the sheath capacitances which, in turn, depend on the relative areas of anode and cathode. An RF voltage will split between two capacitances in series according to:

$$\frac{V_T}{V_p} = \frac{C_p}{C_T} \quad (2.13)$$

Using Equations 2.12 and 2.13, we can write:

$$\frac{V_T}{V_p} = \left(\frac{A_p}{d_p}\right)\left(\frac{d_T}{A_T}\right) \quad (2.14)$$

and substituting into Equation 2.11, we obtain:

$$\frac{V_T}{V_p} = \left(\frac{A_p}{A_T}\right)^4 = R^4 \quad (2.15)$$

where A_p is the anode area and A_T the cathode area. If there were two symmetric electrodes, both blocked capacitively, sputtering would occur on both surfaces. If the area of the cathode were significantly smaller than the other areas in contact with the discharge, the plasma potential would be small, and little sputtering would occur on the anode, whereas the cathode would sputter very effectively. Since the cathode in a setup such as that represented in Figure 2.8 usually is quite large ($>1 \text{ m}^2$), allowing many silicon wafers or other substrates to be etched simultaneously, the grounded area needs to be larger yet. In actual sputtering systems, the anode and the entire sputtering chamber are grounded, creating a very small dark space where hardly any sputtering takes place. Other researchers have assumed the conservation of the positive ion current; that is, $j_i(P) \times A_p = j_i(T) \times A_T$ instead of current density, and they find an exponent 2 in deriving Equation 2.15. The exponential in Equation 2.15 in practical systems is indeed usually closer to 2.²¹

Higher ion energies (V_T large) translate into lower etch selectivity and can be a cause of device damage (Inset 2.2). Consequently, a key feature for good etch performance (Inset 2.3) is effective ionization to produce very high quantities of low-energy ions and radicals at low pressures. In answer to this need, equipment builders have come up with low-energy, high-density plasmas, e.g., magnetrons, inductively coupled plasmas (ICPs),³² and electron cyclotron resonances (ECRs)³³ (see below).

Device damage comes in many “flavors,” including:

- Alkali (sodium) and heavy metal contamination
- Catastrophic dielectric breakdown
- Current-induced oxide aging
- Particulate contamination
- UV damage
- Temperature excursions that can activate metallurgical reactions
- “Rogue” stripping processes that simply do not remove all the residue
- Plasma-induced charges, surface damage, ion implantation

Inset 2.2

Etch performance

Etch performance is judged in terms of etch rate, selectivity, uniformity (evenness across one wafer and from wafer to wafer), surface quality, reproducibility, residue, microloading effects, device damage, particle control, post-etch corrosion, CD, and profile control. Selectivity as high as 40:1 might be required in the future for ICs and even more for micromachines. It is generally believed that "radiation" damage of a plasma can be minimized by keeping ion energies low. It is also generally believed that a lot of the radiation damage can be annealed out. In reality, very little is understood of the damage a plasma can do. The higher the etch rate the better the wafer throughput. Good selectivity, uniformity, and profile control are more easily achieved at lower etch rates. Trenches of various depth are made in Si in the manufacture of MOS devices. Shallow trenches (0.5 to 1.5 μm) are used to aid in reducing the effects of lateral diffusion during processing and to make flat structures (planarization). Deeper trenches (1.5 to 10 μm) are used to create structures that become capacitors and isolation regions in integrated circuits. For the shallowest trenches, photoresist is adequate as a mask. For deeper etching, a silicon dioxide mask may be needed. In micromachining, one would like to obtain aspect ratios of 100 and beyond, so the difficulty in masking keeps mounting. With aspect ratios above 2:1 or 2.5:1, the etching action at the bottom of a trench tends to slow down or stop altogether.

Inset 2.3

Physical Etching: Ion Etching or Sputtering and Ion-Beam Milling

Introduction

Bombarding a surface with inert ions (e.g., argon ions), in a setup as shown in Figure 2.8, translates into ion etching or sputter etching (dc or RF). With ions of sufficient energy impinging vertically on a surface, momentum transfer (sputtering) causes bond breakage and ballistic material ejection, throwing the bombarded material across the reactor to deposit on an opposing collecting surface, if the surrounding pressure is low enough. The kinetic energy of the incoming particles largely dictates which events are most likely to take place at the bombarded surface; that is, physisorption, surface damage, substrate heating, reflection, sputtering, or ion implantation. At energies below 3 to 5 eV, incoming particles are either reflected or physisorbed. At energies between 4 and 10 eV, surface migration and surface damage result. At energies >10 eV (say, from 5 to 5000 eV), substrate heating, surface damage, and material ejection (i.e., sputtering or ion etching) takes place. At yet higher energies, $>10,000$ eV, ion implantation (i.e., doping) takes place. The energy requirements for these various processes are summarized in Table 2.4 (see also Figure 2.11).

TABLE 2.4 Energy Requirements Associated with Various Physical Processes

| Ion energy (eV) | Reaction |
|-----------------|-------------------------|
| <3 | Physical adsorption |
| 4–10 | Some surface sputtering |
| 10–5000 | Sputtering |
| 10k–20k | Implantation |

The deposition phenomenon mentioned above can be used to deposit materials in a process called *sputter deposition* (Chapter 3). A low pressure and a long mean free path are required for

material to leave the vicinity of the sputtered surface without being backscattered and redeposited.

In what follows, we shall consider two purely physical dry etching techniques at energies >10 eV: sputtering or ion etching and ion-beam milling.

Sputtering or Ion Etching

The gradient in the potential distribution around the target lying on the cathode in Figure 2.5B accelerates the ions, prompting them to impinge on the substrate in a direction normal to the surface. The etch rate in the direction of the impinging ions (V_z) becomes a strong function of E_{max} (Equations 2.8 and 2.21). The impinging ions erode or sputter etch the surface by momentum transfer. This offers some advantages: volatility of the etch products is not as critical as for dry chemical etching; only a billiard-ball effect plays a role in physical etching. As a consequence, differences in etch rates for various materials are not large (sputter yields for most are within a factor of three), and the method entails directional anisotropy. Physical etching is inherently material nonselective, because the ion energy required to eject material is large as compared with differences in chemical bond energy and chemical reactivity. When no reactive etching processes are available for a given material, physical etching is always an option. Directional anisotropy remains as long as the dimensions of the surface topographical structures are small compared with the thickness of the sheath between the bulk plasma and the etched surface. However, etch rates are slow, typically a hundred to a few hundred angstroms per minute. The use of a magnetron can help improve the speed of the etch rate. In both dc and RF diode sputtering, most electrons do not cause ionization events with Ar atoms. They end up being collected by the anode, substrates, etc., where they cause unwanted heating. A magnetron adjusts this situation by confining the electrons with magnetic fields near the target surface; consequently, current densities at the target may increase from 1 to 100 mA/cm².

As sputter etching is nonselective, it introduces a masking problem. Another hurdle is the need for rather high gas pressure to obtain sufficiently large ion currents, resulting in a short mean free path, λ_i , of the ions. With a mean free path smaller than the interelectrode spacing, considerable redeposition of sputtered atoms on the etching substrate lying on the cathode can occur. Electrical damage from ion bombardment also must be taken into account when critical electronic components reside on the substrate.

Ion-Beam Etching or Ion-Beam Milling

Ion-beam milling (IBM) is a process wherein the plasma source for ion etching is decoupled from the substrate, which is placed on a third electrode. A decoupled plasma is also called a *remote plasma*, and the equipment needed is called a *triode setup*. The plasma source can be an RF discharge or a dc source (Penning source). In a typical dc triode setup, as shown in Figure 2.10, control of the energy and flux of ions to the substrate in the substrate chamber happens independently. The sample being etched can be rendered neutral by extracting low-energy electrons from an auxiliary thermionic cathode (i.e., a hot filament neutralizer), thus making this dc equipment usable for sputtering insulators as well as conductors. In ion-beam milling, as in ion etching, noble gases are generally used, as they exhibit higher sputtering yields due to heavy ions and avoid chemical reactions. The argon pressure in the upper portion of the chamber can be quite low, 10^{-4} Torr, resulting in a large mean free ion path. Adding a hot wire (Kaufman source) or a hollow cathode can enhance ionization at those low pressures. In a Kaufman source, electrons are emitted by a hot filament (typically tantalum or

tungsten) and accelerated by a potential difference between the cathode filament and an anode. A hollow cathode is a metal cylinder with a hole several millimeters in diameter. When the pressure is decreased, the hollow cathode starts to emit extremely strong light (negative glow) when the cathode sheath thickness reaches about the same dimensions as the diameter of the hole. The hollow cathode bounces electrons back and forth within the negative glow, thereby enhancing the plasma density considerably beyond that of a normal discharge.²¹

The discharge voltage in ion-beam etching must be larger than the gas ionization potential (15.7 eV for argon) and typically is operated at several times this value (about 40 to 50 V) to establish a glow discharge. Ions are extracted from the upper chamber by sieve-like electrodes (extraction grids), formed into a beam, accelerated, and fired into the lower chamber where they strike the substrate. Achievable ion energies range from about 30 eV to several keV. Beam divergence through collisions with residual gas molecules in the substrate chamber usually limits the lowest practical ion energy to a few hundred eV. Typical etch rates with argon ions of 1 keV energy and an ion current density of 1.0 mA/cm² are in the range of 100 to 3000 Å/min for most materials such as silicon, polysilicon, oxides, nitrides, photoresists, and metals. Inert ion beam etching (IBE) in an ion miller is, in principle, capable of very high resolution (<100 Å), but aspect ratios are usually less than or equal to unity, and selectivity is poor. The use of the extraction grid also raises the potential for contaminating the ion beam with sputtered grid material.

Higher plasma ion densities may be created by employing magnetic coils in a magnetron sputtering machine to increase the electron path length. Just as the ionospheric van Allen belts are confined by the Earth's dipole field, plasma remains confined within the magnetic envelope generated by the coils, thus preventing electron loss to plasma-exposed surfaces. This principle is exploited, for example, in magnetically enhanced ion etching (MIE) (see coils in Figure 2.10). A magnetic field is applied so that electrons cannot pass directly from the anode to the cathode but, rather, follow helical paths between collisions, greatly increasing their path length and ionization efficiency. To understand this enhancement in ionization efficiency, consider an electron moving with a velocity v_e . This velocity will be affected by both the electric and the magnetic fields, and the force on the electron is given by:

$$\vec{F} = e(\vec{E} + \vec{v}_e \times \vec{B}) \tag{2.16}$$

in which all quantities, except for the electron charge, are vectors. The direction of the force vector on the electron is perpendicular to both the magnetic field and the direction of the velocity; consequently, the electron will spiral around the magnetic field lines. With an angle ϕ between the momentary electron velocity vector and the magnetic field vector, the radius r of the electron orbit is:

$$r = \frac{m_e v_e}{eB \sin \phi} \tag{2.17}$$

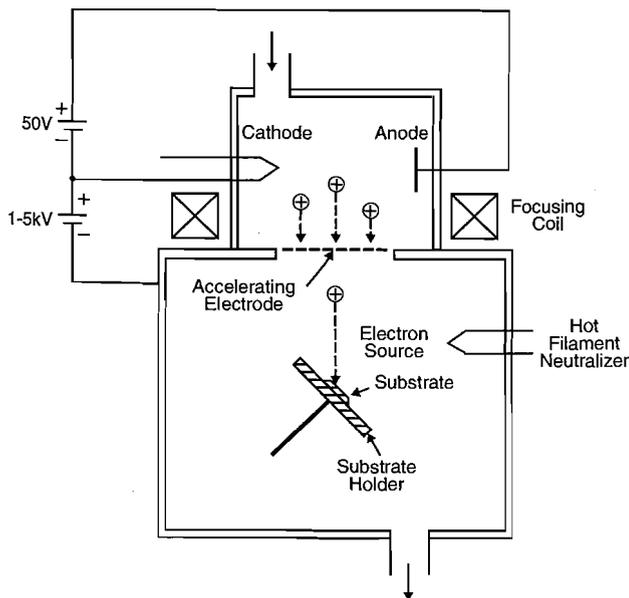


Figure 2.10 Ion-beam etching (IBE) apparatus (triode). In an ion-beam apparatus, the beam diameter is approximately 8 cm. Substrates are mounted on a moveable holder allowing etching of large substrates. Coils focus the ion beam and densify the ion flux in magnetically enhanced ion etching (MIE).

where m_e is the mass of the electron. The circular motion of electrons in the presence of a magnetic field can also be described in terms of an angular frequency ω_{ec} , which can be calculated from the electron velocity v_e and the radius r of the electron helix as described in Equation 2.17:

$$\omega_{ec} = \frac{v_e}{r} \quad (2.18)$$

Equation 2.17 is derived by equating the magnetic and centripetal forces. When the electron is moving at right angles to the magnetic field, this expression reduces to:

$$r = \frac{m_e v_e}{eB} \quad (2.19)$$

At an electron temperature of 2 eV, the mean electron velocity is $9 \times 10^5 \text{ m s}^{-1}$ (see Equation 2.2). According to Equation 2.17, with a magnetic field of 5×10^{-3} Tesla (T) applied, electrons will be forced into a circular path with a radius of about 1 mm.³⁴ At a higher electron temperature of 100 eV, the cyclotron radius of an electron in a field of 0.01 T (or 100 Gauss) is 3.2 mm. These cyclotron radii are of the order of the mean free path and smaller than the smallest dimension of the average dry etch reactor. By lengthening the electron path considerably, electrons are prevented from reaching the reactor walls where they would be lost. Any velocity of an electron parallel to the magnetic field will change the circular path into a helix. In principle, ions also will move in helical paths; however, the radius r (see Equation 2.17), because of the heavy mass of ions, is so large that the effect can be neglected. Clearly, from the above, a magnetic field can lower wall recombination by confining the electrons, hence making relatively low field strengths adequate for obtaining high plasma densities. When plasma density is increased with magnetic confinement, the degree of ionization is between 10^{-2} and 10^{-4} , compared to 10^{-4} to 10^{-6} for simple plate discharges, resulting in an increased etch rate.

The cyclotron resonance frequency of an electron estimated from Equation 2.18 is about 10^8 s^{-1} , which is in the microwave range. If the RF excitation frequency is in the same range, resonance takes effect, causing an additional increase in the RF energy transfer efficiency. Microwave energy may be injected into a plasma to energize the ECR ion source as reviewed further below.

When inert argon ions in a triode setup as shown in Figure 2.10 are replaced with reactive ions, reactive ion-beam etching (RIBE) occurs. The ions not only transfer momentum to the surface, they also react directly with the surface, which means that a chemical/physical mechanism is involved. Direct reactive ion etching of a substrate is the exception rather than the rule, and it is the radicals generated in the plasma that usually dominate the chemical reactions at the surface.

Systems using a hot filament to produce a plasma have a relatively short lifetime in the presence of reactive gases, as conventional filament materials tend to etch away (e.g., tungsten

in the presence of halides forms volatile tungsten halides).³⁴ The latter type of plasma source problem is avoided by using microwave excitation (see below).

Ion-beam etching may cover an area of 3 to 8 cm. This also is referred to as *showered ion etching*. Yet another type of IBE, a maskless technique called *focused ion beam* (FIB), in which the beam is made extremely narrow and used as a direct writing tool, will be discussed in more detail in Chapter 7.

Because of its low etch rate and low selectivity, IBE is used more for fundamental mechanistic studies rather than for patterning. For example, in IBE, the substrate can be tilted relative to the direction of ion bombardment, and, as the ion energy at the substrate and the angle of incidence are known, fundamental information such as sputter yields can be obtained.³⁴ The sputter yield S is defined as the mean number of atoms removed from the surface per incident ion. The sputtering yield depends on the incident ion energy, the mass of the incident ion, the mass of the substrate atom to be etched away, the angle of the incident ion with respect to the substrate, the crystallinity and the crystal orientation of the substrate, the temperature of the substrate during etching, and the partial pressure of oxygen in the residual gas. The sputter yield as a function of the incident ion energy is shown in Figure 2.11. The sputtering yield increases with the incident ion energy and reaches a broad maximum at energies between 5 to 50 keV. Beyond 50 keV, the sputtering yield decreases due to the deeper penetration of the ions in the substrate—that is, ion implantation.³⁵ The angular dependence of the sputtering yield S will be considered below when we discuss etching profiles in physical etching.

In Chapter 3, we will learn more about sputter deposition. In sputter deposition, the substrate on the cathode is replaced by a sputter target cathode, and materials sputtered from that target are deposited on the substrate that is now placed on the anode.

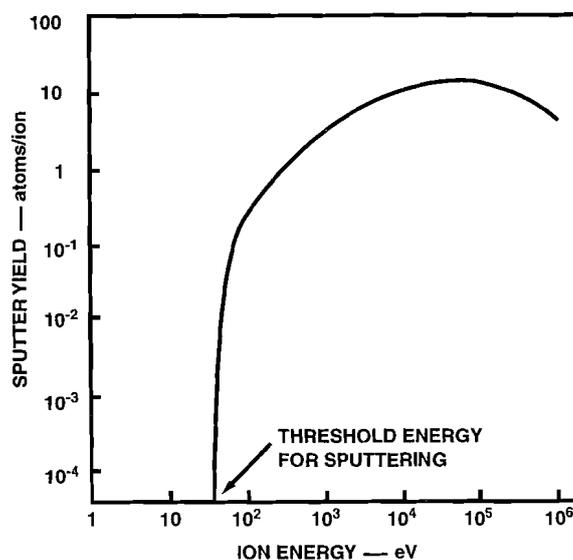


Figure 2.11 Sputter yield as a function of the energy of the bombarding ion.

Etching Profiles in Physical Etching

Introduction

The ideal result in dry or wet etching is usually the high-fidelity transfer of the mask pattern onto the substrate, with no distortion of critical dimensions. Isotropic etching (dry or wet) always enlarges features and thus distorts CDs. Chemical anisotropic wet etching is crystallographic. As a consequence, CDs can be maintained as long as features are strategically aligned along certain lattice planes (see Chapter 4, *Wet Bulk Micromachining*). With sputtering, the anisotropy is controllable by the plasma conditions.

As can be seen from Figure 2.5A, ion etching and ion milling do not lead to undercutting of the mask, but the walls of an etched cut are not necessarily vertical. A variety of factors contribute to this loss of fidelity in pattern transfer, and they are either caused by involatile sputtering reaction products or by special ion-surface interactions. We shall briefly review these dry physical ion etching problem areas.

Faceting Due to Angle-Dependent Sputter Rate

Even when starting out with a vertical mask sidewall, ion sputtering exhibits a tendency to develop a facet on the mask edge at the angle of maximum etch rate. This corner faceting is detailed in Figure 2.12A. The corner of the mask, always a little

rounded even when the mask walls are very vertical, etches faster than the rest and is worn off. Faceting at the mask corner arises because the sputter yield S for materials usually is a function of the angle at which ions are directed at the surface (see above). The sputter-etch rate of resist, for example, reaches a maximum at an incidence angle of about 60° , more than twice the rate at normal incidence.^{8,35} Sloped mask sidewalls may eventually be followed by sloped etch steps in the substrate. Faceting of the substrate itself will proceed along its own preferred sputtering direction angle. The faceting is more pronounced with an applied bias due to the increased electric field at corners. Usually, faceting affects only the masking pattern, and its influence on the fidelity of the pattern transfer process can be minimized by making the mask sufficiently thick. Faceting can also be minimized or eliminated by a more ideal resist profile, with very little rounding of the mask corners. In the case of a resist mask, postbake temperatures must be controlled so the reflow does not induce rounding of the resist features, leading to faceting.

It should be noted that some of the disadvantages of physical etching, such as resist corner faceting, can sometimes be exploited. For example, a gently sloping edge is advantageous to facilitate metal coverage or planarization, because a tapered sidewall is easier to cover than a vertical wall, especially when using line-of-site deposition methods. The method most often used to obtain such a taper is a controlled resist failure, that is,

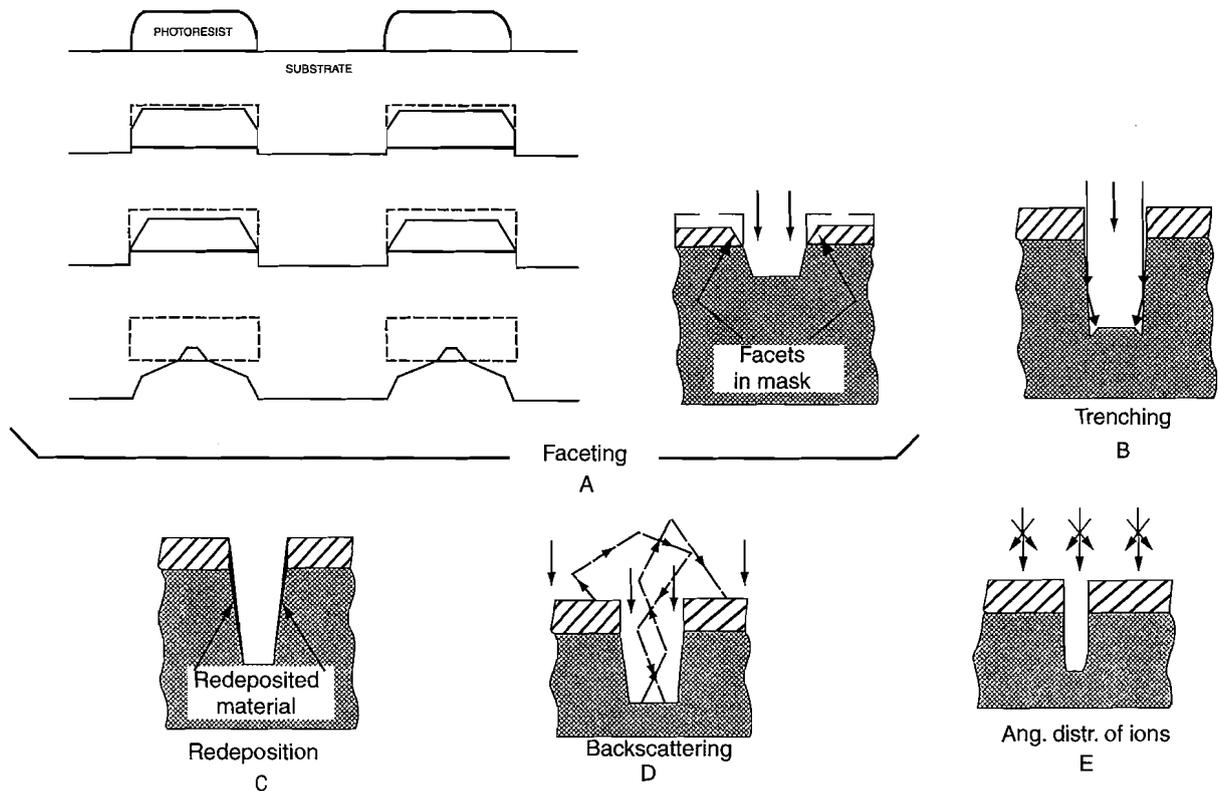


Figure 2.12 Limitations of dry physical etching. (A) Faceting. Sputtering creates angled features. An angled facet ($\sim 60^\circ$) in the resist propagates as the mask is eroded away. Sloped walls may also be created in the underlying substrate. (B) Ditching or trenching due to glancing incidence of ions. (C) Redeposition of material sputtered from the bottom of a trench. (D) Backscattering. (E) Angular distribution of incident ions. (Based on H. W. Lehmann, in *Thin Film Processes II*, Academic Press, Boston, 1991.¹⁵)

erodible or sacrificial masks (Inset 2.4). In other words, the "negative effect" described in connection with Figure 2.12A is put to good use.

Ditching or Trenching

When the slope of the side of the mask is no longer completely vertical, some ions will collide at a glancing angle with the sloping edges before they arrive at the etch surface. This gives a local increase in etch rate, leading to ditches (Figures 2.5A and 2.12B). For this mechanism to be active, there must be a sizable fraction of ions with at least slightly off-vertical trajectories, or the sidewall must have a slight taper as shown in Figures 2.5A and 2.12B.³⁶ The taper of the sidewall could result, for example, from redeposition (see next section) or faceting (see above). Since ditching is a small effect (say, 5%), it often goes unnoticed unless thick layers are etched.

Redeposition

Another sputtering limitation, already alluded to, is the redeposition of involatile products on step edges (Figure 2.12C). Redeposition involves sputtered involatile species from the bottom of the trench settling on the sidewalls of the mask and etched trench. The phenomenon manifests itself mainly on sloped sidewalls.

By tilting and rotating the substrate during etching (Inset 2.5), etch profiles can be improved. The reasons for tilting and rotating improvements are a combination of shadowing the bottom of the step (to reduce trenching), partially etching the sidewalls of the mask (to reduce redeposition), and gaining more nearly vertical edges on the etched profiles in the substrate.⁸ Especially with aspect ratios exceeding unity, redeposition becomes problematic, and reactive gas additives are necessary to generate volatile etch products. With aspect ratios above 2:1 or 2.5:1, the etching action at the bottom of too-fine features tends to slow down or stop

altogether. Reactive additives bring us into the realm of chemical-physical etching (discussed further below). For micromachining, tilting and rotating of substrates is a recurring topic. It is one of the desirable modifications of standard equipment used for micromachining applications.

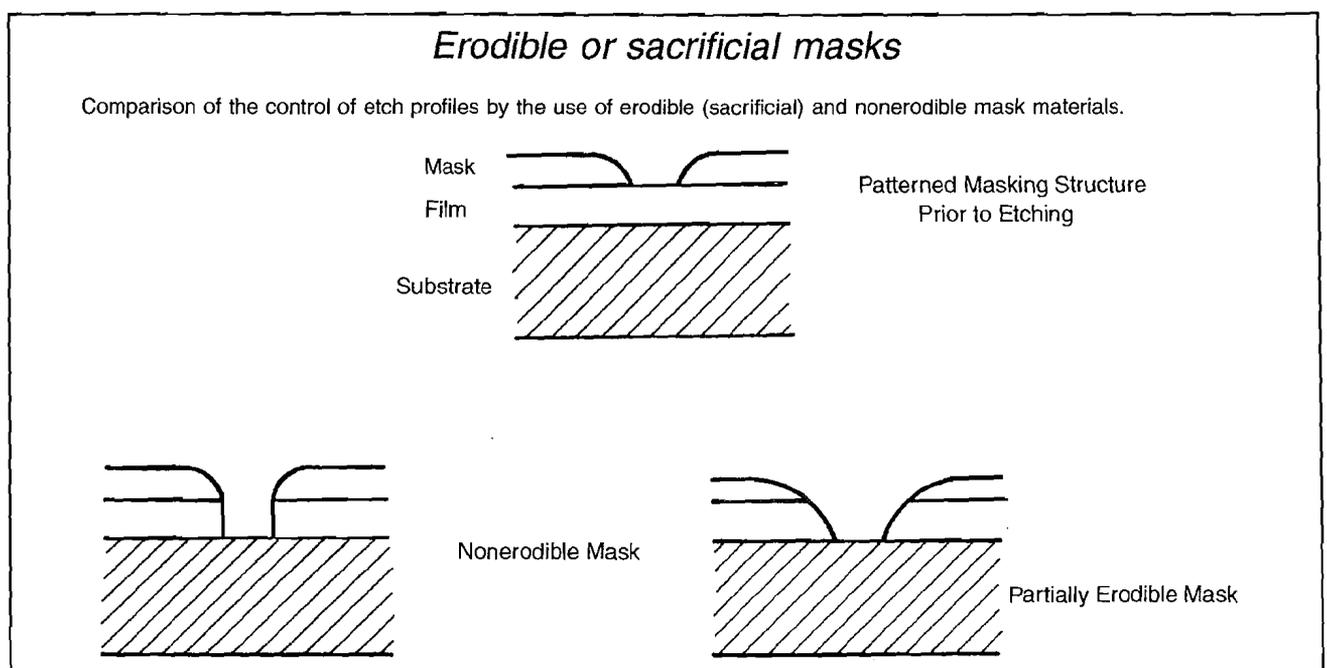
Redeposition may also be used to control sidewall profiles. The material redeposited on the sidewall protects the sidewalls, whereas the material redeposited at the bottom gets removed during the etching process. With the proper control of redeposition, one can achieve a highly anisotropic profile.

Backscattering

Backscattering, illustrated in Figure 2.12D, is a form of redeposition that is also associated with involatile etch products. A fraction of the sputtered and involatile species from the surface is backscattered onto the substrate after several collisions with gas phase species. This indirect redeposition may involve contaminants from the walls and fixtures in the vacuum chamber. Backscattering fixes the upper pressure limit for ion-enhanced etching. Significant redeposition can take place at pressures as low as 10 mTorr.¹⁵

Angular Distribution of Incident Ions

Off-vertical ion trajectories can also be caused by sheath scattering and field nonuniformities. Most ions impinge perpendicularly on the substrate. Scattering of a small fraction of ions in the sheath causes a distribution of impingement angles.¹⁵ This scattering in the sheath is responsible for hourglass-shaped etch profiles that have been observed in trench etching of silicon (see Figure 2.12E). Besides sheath scattering, there is a second active mechanism that may lead to skewing of ion directionality; namely, inhomogeneities in the electrical field at the substrate surface. When etching conductors, the bending of electric field

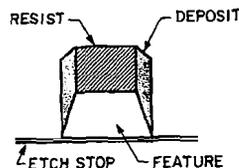
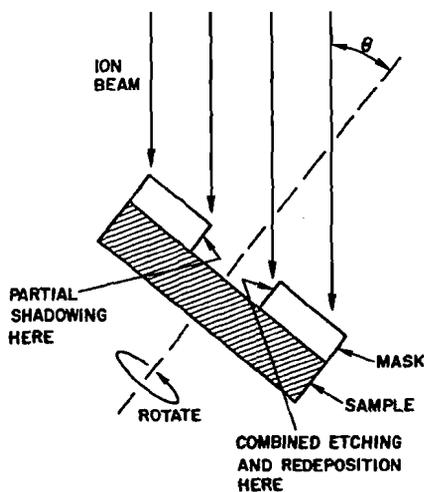


Inset 2.4

Rotating and redeposition

Typical configuration for tilting and rotating, as well as an example of redeposition in a high-aspect-ratio device. By tilting and rotating a sample during ion beam etching, better etching profiles can be obtained. The walls exposed to ion beam etching exhibit combined etching and redeposition while the unexposed walls are partially shadowed; rotation averages out these effects.

TILTING AND ROTATING



Inset 2.5

lines due to surface topography has the effect of enhancing ion flux at feature edges and leads to ditching. On the other hand, when etching insulators, charging effects may cause appreciable ion fluxes to the sidewalls of a trench and contribute to lateral etching. The latter will again lead to hourglass-shaped trenches. The importance of the effect is very much related to the electrical conductivity of the masking and etching surfaces, with the greatest significance for strongly insulating materials.³⁷

Physical Etching Summary

In physical etching, ion etching or sputtering, and ion-beam milling, argon or other inert ions extracted from the glow discharge region are accelerated in an electrical field toward the substrate, where etching is purely impact controlled. Sputtering is inherently nonselective, because large ion energies compared to the differences in surface bond energies and chemical reactivities are involved in ejecting substrate material. The method is slow compared to other dry etching means, with etch rates limited to several hundred angstroms per minute as compared with thousands of angstroms per minute and higher for chemical and ion-assisted etching (as high as 6 $\mu\text{m}/\text{min}$ with the newest deep RIE equipment). Sputter etching tends to form facets, ditches, and hourglass-shaped trenches, and it frequently redeposits material in high-aspect-ratio ($>2:1$) features. Electrical damage to the substrate from ion bombardment and implantation can be problematic. However, some of the reversible plasma damage can be removed by a thermal anneal. With the continuing increase in device complexity, which includes layers of different chemical composition, inert ion etching and ion-beam sputtering continue to find applications.

Plasma Etching (Radical Etching)

Introduction

In reactive plasma etching, which corresponds to a high-pressure RIE extreme, reactive neutral chemical species such as chlorine or fluorine atoms and molecular species generated in the plasma diffuse to the substrate where they form volatile products with the layer to be removed (Figure 2.5B). The only role of the plasma is to supply gaseous, reactive etchant species. Consequently, if the feed gas were reactive enough, no plasma would be needed. At pressures of $>10^{-3}$ Torr, the neutrals strike the surface at random angles, leading to isotropic, rounded features. A dry chemical etching regime can be established by operating at low voltages, eliminating impingement of high-energy ions on the sample, and facilitating surface etching almost exclusively by chemically active, neutral species formed in the plasma. The reaction products—volatile gases—are removed by the vacuum system. The volatility of the formed reaction product introduces a major difference with sputtering, where involatile fragments are ejected billiard-ball-wise and may be redeposited close by.

Reactor Configurations

Reactive plasma etching is one extreme of RIE and basically follows the same process we encountered when discussing dry stripping. Three different popular configurations for plasma etching (barrel reactor, downstream etcher, and parallel-plate system) have already been shown in Figure 1.6. In resist etching,