Chapter 8 Microsystem Fabrication Processes

8.1 Introduction

- Knowledge of fabrication processes
  - Required for the analyses in the design process;
  - To ensure the manufacturability of the design.

8.2 Photolithography

- Photolithography
  - The only viable (可行的) way for producing high-precision patterning (圖案) on the substrates.

8.2.1 Overview

- Photolithography involves:
  (a) the use of an optical image, and (b) a photosensitive film to produce a pattern on a substrate.

- Applications of the patterns created by photolighography:
  - In microelectronics, necessary for the p-n junctions, diodes, capacitors, etc.
  - In Microsystems, served as masks (遮蔽物)
    (a) for cavity etching in bulk micromachining, or
    (b) for thin film deposition and etching of sacrificial layers in surface micromachining, as well as
    (c) for the primary circuitry of electrical signal transduction in sensors and actuators.

- Photolithography needs: (Fig. 8.1)
  (a) Photoresist
    - change their solubility when exposed to light
    I) Positive photoresists: become more soluble under light;
    II) Negative photoresists: become more soluble under shadow.
  (b) Mask (often mad of quartz)
  (c) UV light or other source for exposure (曝光)
  (d) Development (顯影)

- A clean room is need for photolithography.
  - Example: Class 10 means that the number of dust particles 0.5 microns or

larger in a cubic foot of air in the room is less than 10.

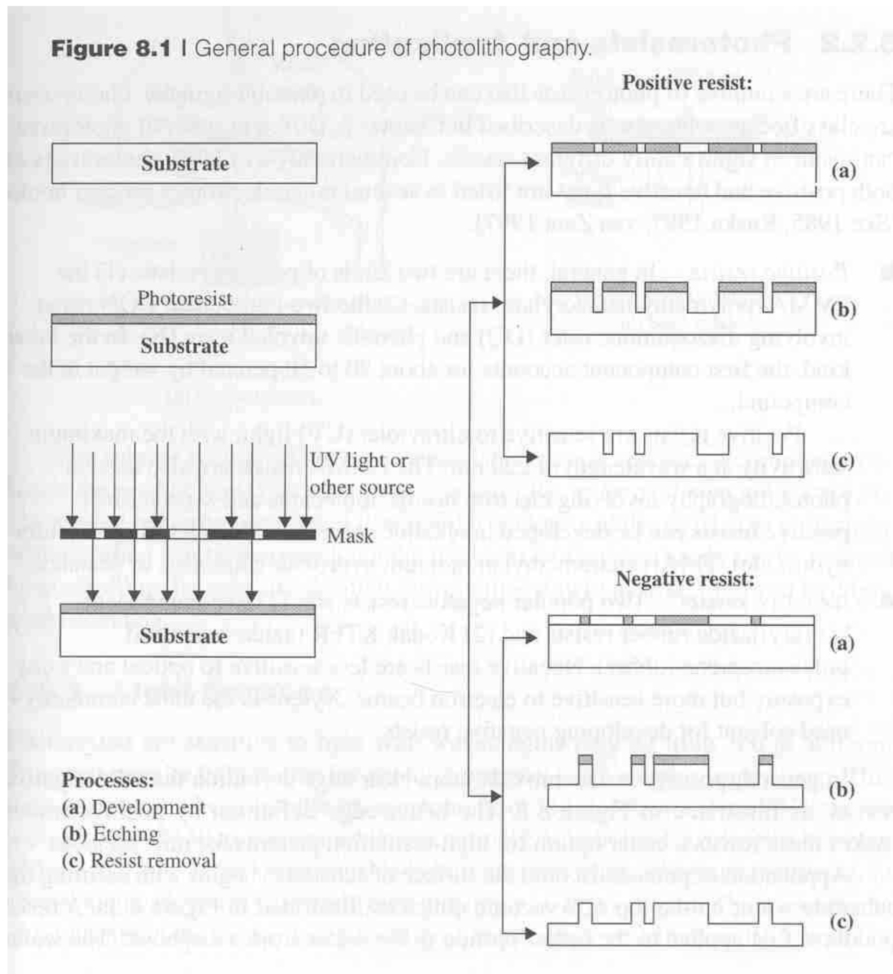


Figure 8.1 I General procedure of photolithography.

8.2.2 Photoresist and Application

- Positive photoresist:
  - 2 kinds:
    (a) PMMA (polymethymethacrylate) resists
    (b) Two-component DQN resist involving diazoquinone ester (DQ, account for 20~50% by weight) and phenolic novolak resin (N).
  - Sensitive to UV light with the maximum sensitivity at a wavelength of 220 nm.
  - PMMA resists: can use electron beams, ion beams, and x-rays.
  - Development solvents: alkaline solvents (鹼性溶劑) such as KOH, TMAH (tetramethylammonium hydroxide), ketones (酮), or acetates (醋酸鹽).

- Negative photoresist:
  - 2 popular ones:
    (a) Two-component bis (aryl)azide rubber resists;

(b) Kodak KTFR (azide-sensitized polyisotroprene rubber)

- Less sensitive to optical and x-ray exposure, but more sensitive to electron beams.
- Xylene (二甲苯): the most commonly used solvent for development.

● Comparison of positive photoresist with negative photoresist:
  - Positive photoresist provide more clear edge definition (i.e., high-resolution patterns) [see Fig. 8.2]

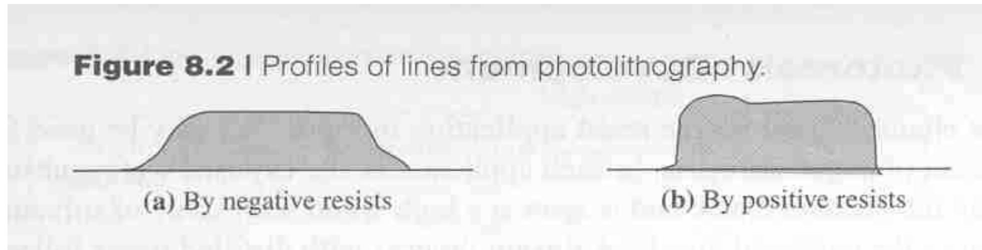


Figure 8.2 I Profiles of lines from photolithography.

● Spincoating: the way of photoresist application onto the substrate surface.
  - Typically 0.5~2 μm thick with ±5 nm variation (upto several mm)
  - Common problem: the bead of resist at the wafer edge (see Fig. 8.3b)
  - Improve uniformity & reduce the bead thickness: often by spinning slowly at first, followed by high-speed spinning.

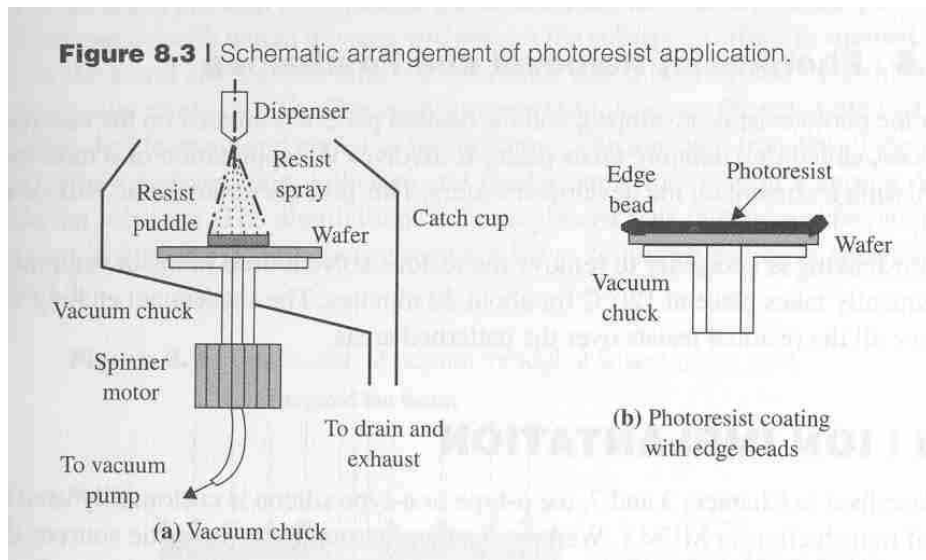


Figure 8.3 I Schematic arrangement of photoresist application.

8.2.3 Light Sources

● Photoresist: sensitive to light with wavelengths ranging from 300~500 nm.
  - Most popular source: the mercury (汞) vapor lamp (provide 310~440 nm wavelengths).
  - Deep UV light: wavelengths of 150~300 nm

- Normal UV light: wavelengths of 350~500 nm
- X-rays (for LIGA): wavelengths of 0.4~5 nm (i.e., 4~50 angstrom)

8.2.4 Photoresist Development

- Negative resists: can use the same chamber in Fig. 8.3. Steps:
  - Wafer is secured on the vacuum chuck.
  - Then, the wafer is spun at a high speed with spray of solvent.
  - Rinsing (清洗) with distilled water follows the development.

- Positive resists:
  - Developed in batches in a tank.
  - Require a more controlled chemical reaction (by projecting the developer agent onto the wafer).
  - Finally, rinsing with distilled water

8.2.5 Photoresist Removal and Postbaking

- Photoresist removal:
  - Can use a mild oxygen plasma treatment, which can remove the bulk of the resist.

- Postbaking:
  - To remove the residue solvent used in development.
  - 120℃ for 20 minutes.

8.3 Ion Implantation

- P-type or n-type silicon: used for signal transduction in MEMS.
  - Example: p-type silicon piezoresistors.

- Ion-implantation process: (Fig. 8.4)
  - Ions are produced by electron beams, and then extracted from the substance in the gaseous state.
  - The ion beam is then led into a beam controller (in which the size and direction of the beam can be adjusted).
  - The ions are then energized in the acceleration tube (or called accelerator).
  - Focused onto the substrate, which is protected by a shield, or mask (usually made of SiO_2).
  - The ions will transfer their energy to the substrate upon collision, and finally

come to a stop at a certain depth.

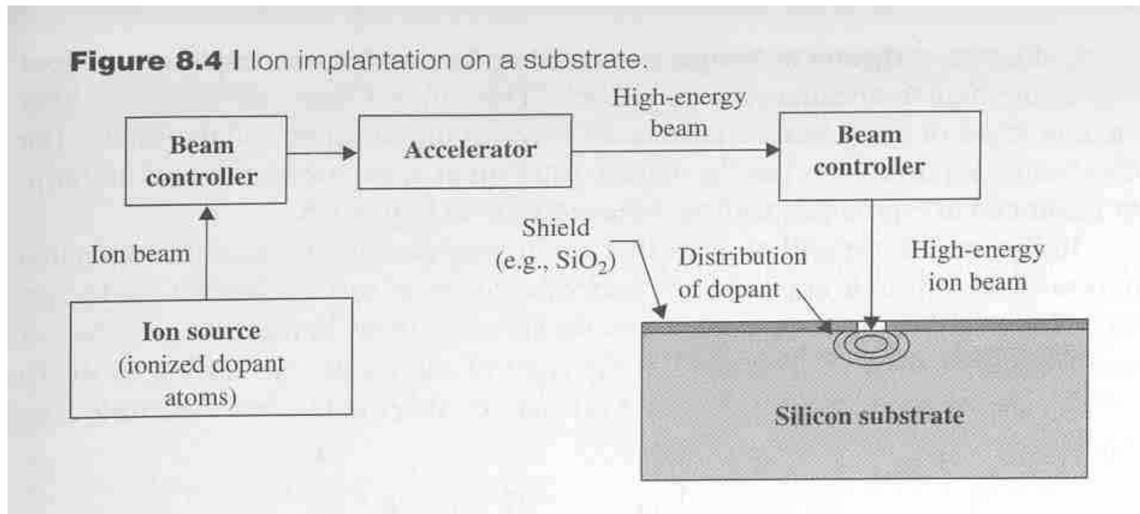


Figure 8.4 | Ion implantation on a substrate.

- Advantage over diffusion:
  - Does not require high temperature

    → Introduce little thermal stress and strain

- Disadvantage:
  - The dopant distribution is less uniform (see Fig. 8.5)

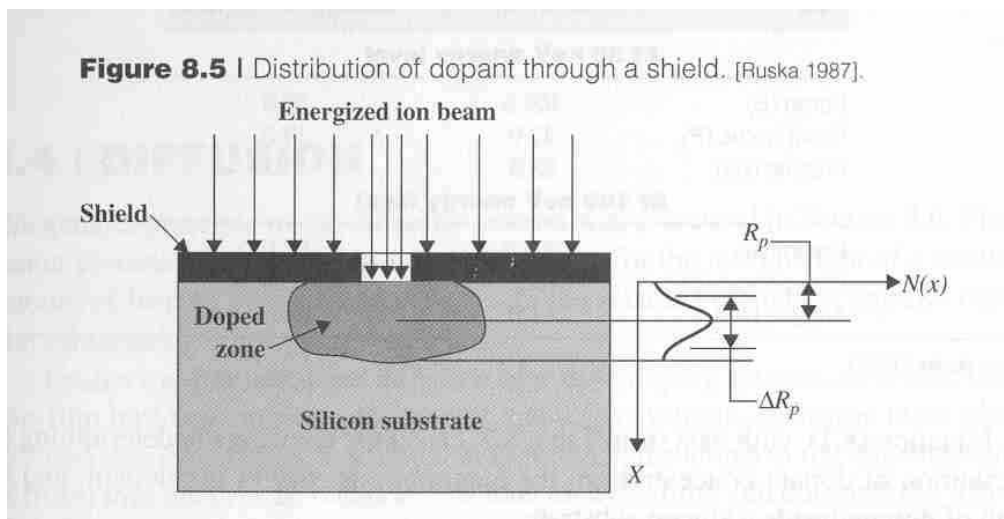


Figure 8.5 | Distribution of dopant through a shield. [Ruska 1987].

Table 8.1 | Ionization energy for dopants in silicon.

Dopants	Type	Ionization energy, eV
Phosphorus (P)	n	0.044
Arsenic (As)	n	0.049
Antimony (Sb)	n	0.039
Boron (B)	p	0.045
Aluminum (Al)	p	0.057
Gallium (Ga)	p	0.065
Indium (In)	p	0.160

Source: Ruska [1987].

- Dopant distribution
  - The highest concentration of the implanted dopant appears to be under the substrate surface, but not on the surface.
  - Gaussian distribution:

$$N(x) = \frac{Q}{\sqrt{2\pi}\Delta R_P} \exp\left[\frac{-(x-R_P)^2}{2\Delta R_P^2}\right] \tag{8.1}$$

where R_p: projected range in μm; ΔR_p: scatter or "straggle" in μm; and Q=dose (劑量,用量) of the ion beam (atoms/cm^2). [see Table 8.2 for R_p & ΔR_p]

Table 8.2 | Ion implantation of common dopants in silicon

Ion	Range R_p, nm	Straggle ΔR_p, nm
At 30 keV energy level		
Boron (B)	106.5	39.0
Phosphorus (P)	42.0	19.5
Arsenic (As)	23.3	9.0
At 100 keV energy level		
Boron (B)	307.0	69.0
Phosphorus (P)	135.0	53.5
Arsenic (As)	67.8	26.1

Source: Ruska [1987].

8.4 Diffusion

- Diffusion
  - Slow compared to ion implantation.
  - Take place at elevated temperatures.

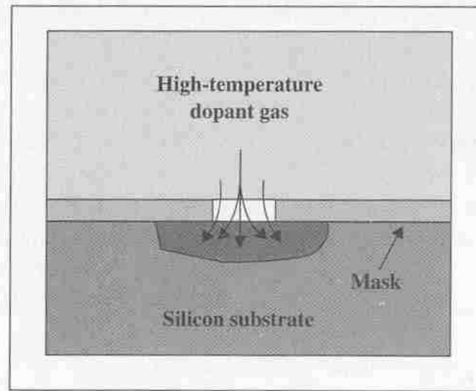


Figure 8.6 | Doping of a silicon substrate by diffusion.

- Fick's law: give the dopant flux (摻雜物通量) in the substrate in the x-direction,

$$F = -D\frac{\partial N}{\partial x} \tag{8.2}$$

where F: dopant flux in [atoms/cm^2-s]; D: diffusivity, [cm^2/s]; N: dopant concentration in the substrate [atoms/cm^3].

  - Similar to Fourier law for heat conduction.
  - Fick's 2nd law: can be derived using the continuity equation.

$$\frac{\partial N}{\partial t} = -\frac{\partial F}{\partial x}$$

$$\Rightarrow \frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2} \tag{8.3}$$

  - <Case 1> Constant-Source Diffusion (Jaeger, 1988)
    - The impurity concentration is held constant at the wafer surface (x=0).
    - Solution:

$$N(x,t) = N_0 \operatorname{erfc}\left[\frac{x}{2\sqrt{Dt}}\right] \tag{8.4}$$

where erfc(x) is the complementary error function:

$$\operatorname{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-y^2}\,dy \tag{8.5}$$

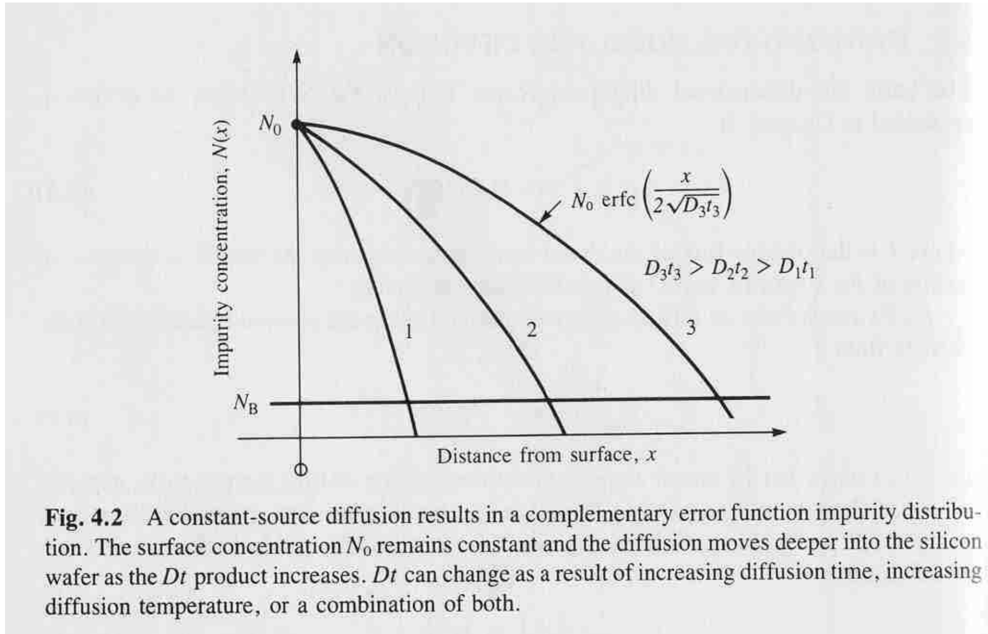


Fig. 4.2 A constant-source diffusion results in a complementary error function impurity distribution. The surface concentration N_0 remains constant and the diffusion moves deeper into the silicon wafer as the Dt product increases. Dt can change as a result of increasing diffusion time, increasing diffusion temperature, or a combination of both.

- Case 2: limited-source diffusion (Jaeger, 1988)
  - A fixed quantity of the impurity species is deposited in a thin layer on the silicon surface.
  - Use an impulse function, the dose Q (劑量), at the silicon surface as the initial boundary condition.
  - Solution:

$$N(x,t) = \frac{Q}{\sqrt{\pi D t}} \exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right]$$

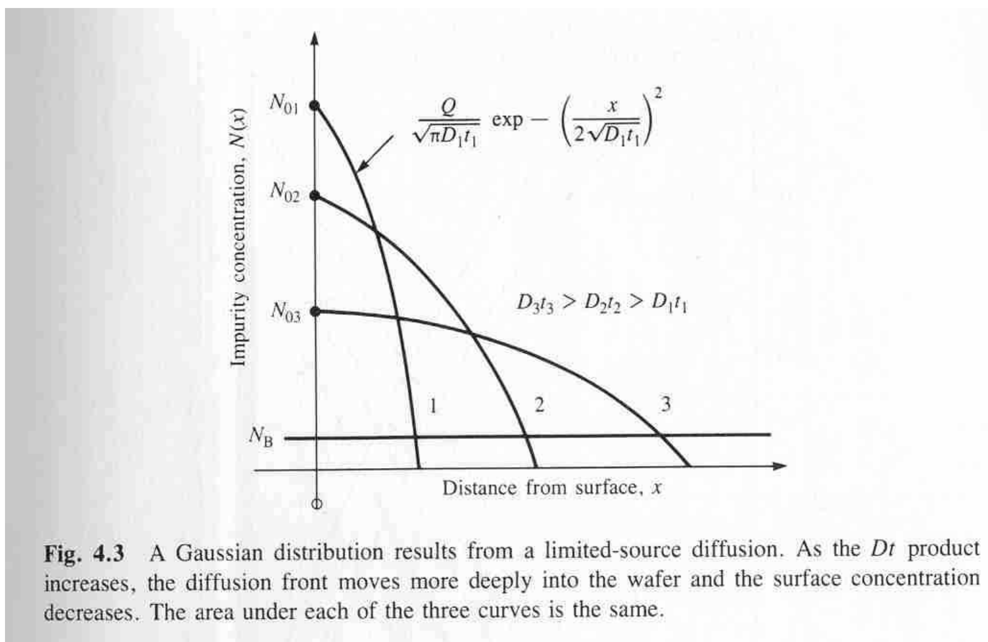


Fig. 4.3 A Gaussian distribution results from a limited-source diffusion. As the Dt product increases, the diffusion front moves more deeply into the wafer and the surface concentration decreases. The area under each of the three curves is the same.

- Diffusivity D:
  - can be estimated for the three common dopants (boron, arsenic, and phosphorus):

$$\ln(\sqrt{D}) = aT' + b \tag{8.2}$$

where $T' = 1000/T$ with T = diffusion temperature in K. See Table 8.3 for a and b.

Table 8.3 | Constants for Equation (8.6)

Dopants	Constant *a*	Constant *b*
Boron	−19.9820	13.1109
Arsenic	−26.8404	17.2250
Phosphorus ($N_s = 10^{21}/cm^3$)	−15.8456	11.1168
Phosphorus ($N_s = 10^{19}/cm^3$)	−20.4278	13.6430

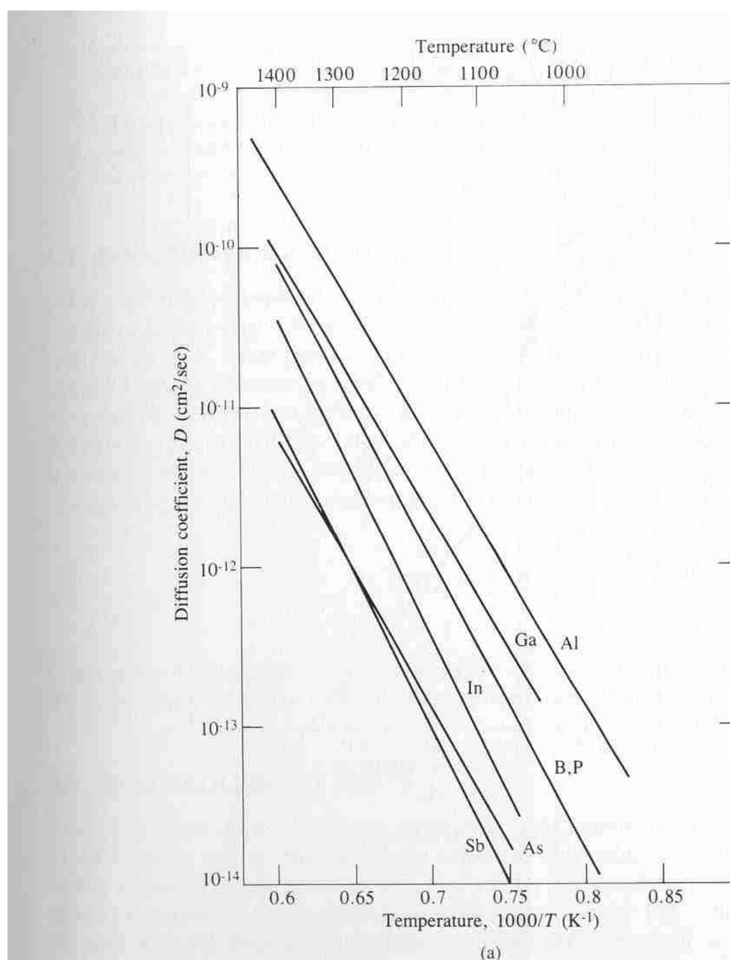


Fig. 4.5 Diffusion constants in silicon for (a) substitutional diffusers (above) and (b) interstitial diffusers (next page). Copyright John Wiley & Sons, Inc; reprinted with permission from ref. [25].

(Jaeger, 1988)

8.5 Oxidation

8.5.1 Thermal Oxidation

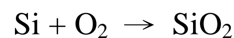
- Four types of thin films frequently used in microelectronics: (Sze, 1985)

1. Thermal oxidation
2. Dielectric layers
3. Polycrystalline silicon
4. Metal films

8.5.2 Silicon Dioxide

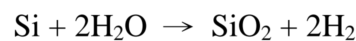
- Three principal uses of SiO_2:
  1. as a thermal and electric insulator (see Table 7.1);
  2. as a mask (遮蓋物) in the etching of silicon substrates;
  (∵SiO_2 has much stronger resistance to most etchants than silicon)
  3. as a sacrificial layer (犧牲層) in the surface micromachining.

- Oxidation: by heating silicon in an oxidant (e.g., O_2) with or without steam.
  (a) Dry oxidation:



$$Si + O_2 \rightarrow SiO_2$$

  (b) Wet oxidation in steam:



$$Si + 2H_2O \rightarrow SiO_2 + 2H_2$$

- Thermal oxidation
  - Furnace tube: preheated to 900~1200℃.
  - O_2 or $H_2O_{(steam)}$: is blown into the furnace.
  - Timing, temperature, and gas flow rate: are strictly controlled.

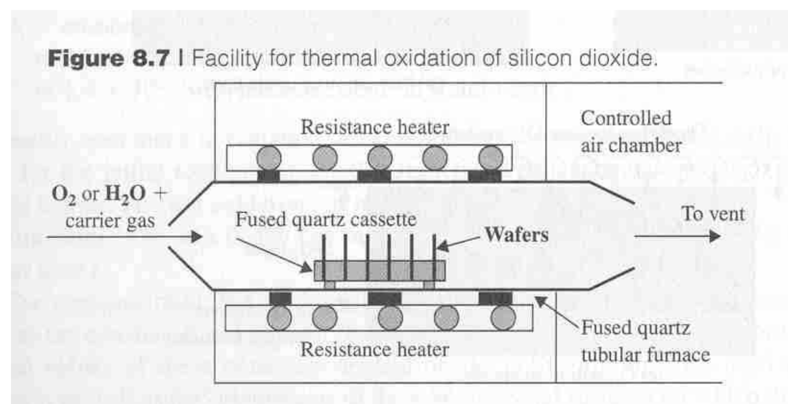


Figure 8.7 | Facility for thermal oxidation of silicon dioxide.

- Thickness of oxide:

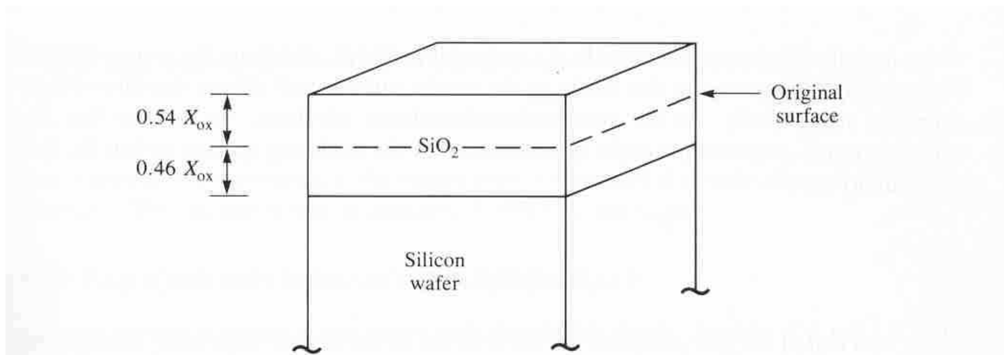


Fig. 3.2 Formation of a silicon dioxide layer on the surface of a silicon wafer consumes silicon during growth of the layer. The oxide expands to fill a region approximately 54% above and 46% below the original surface of the wafer. The exact percentages depend on the density of the oxide.

8.5.3 Thermal Oxidation Rate

- Thermal oxidation:
  - Thermal diffusion, plus chemical reaction.

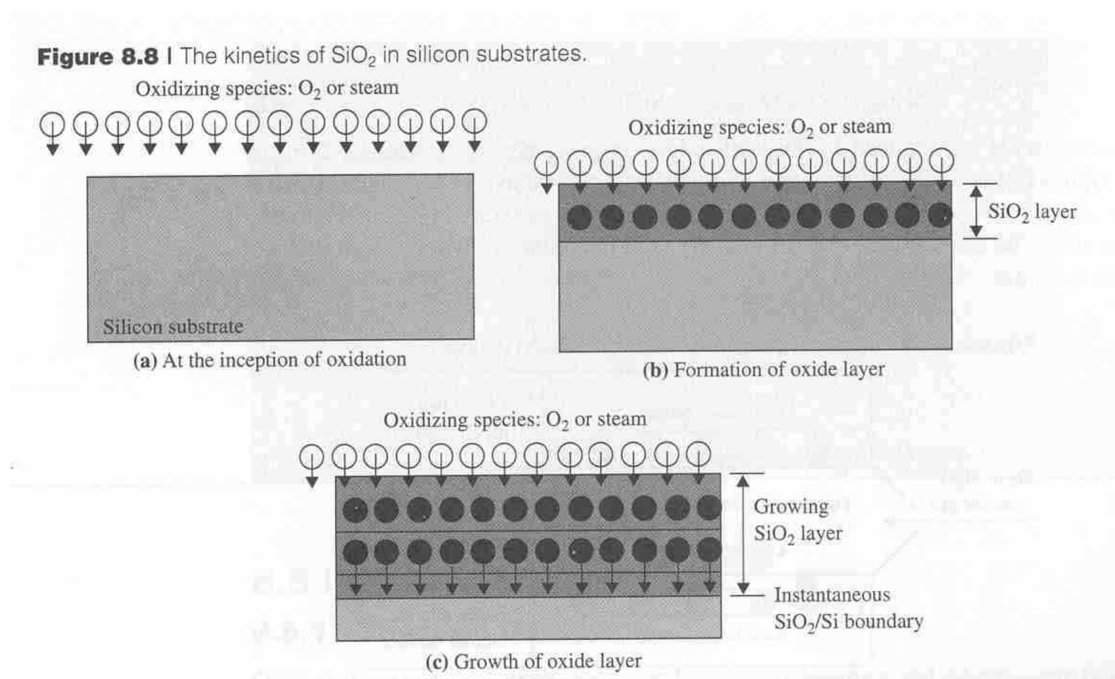


Figure 8.8 | The kinetics of SiO_2 in silicon substrates.
(a) At the inception of oxidation (b) Formation of oxide layer (c) Growth of oxide layer

  - As the oxide grows, O_2 must pass through more and more oxide, and the growth rate decreases as time goes.
  - A simple model assumes that oxygen diffuses through the existing oxide layer.

    Solution:

    (i) For small time t, $x = \frac{B}{A}(t+\tau)$ (8.9)

(ii) For large time t, $x = \sqrt{B(t+\tau)}$ (8.10)

where A and B are constants, and

$$\tau = \frac{\left(\frac{d_0^2 + 2Dd_0}{k_s}\right)N_1}{2DN_0}$$

where D=diffusivity; d_0=thickness of initial oxide layer; k_s=surface reaction rate constant; N_0=concentration of the oxidizing species at the oxide surface; N_1=number of molecules of the oxidizing species that are incorporated into a unit volume of the resulting oxide.

- In Eq. (8.9), the linear rate constant B/A:

$$\log\left(\frac{B}{A}\right) = aT' + b \quad (8.12)$$

- In Eq. (8.10), the parabolic rate constant B:

$$\log(B) = aT' + b \quad (8.13)$$

where $T' = 1000/T$, and the coefficients a and b in Eqs. (8.12) and (8.13) can be obtained from Table 8.4.

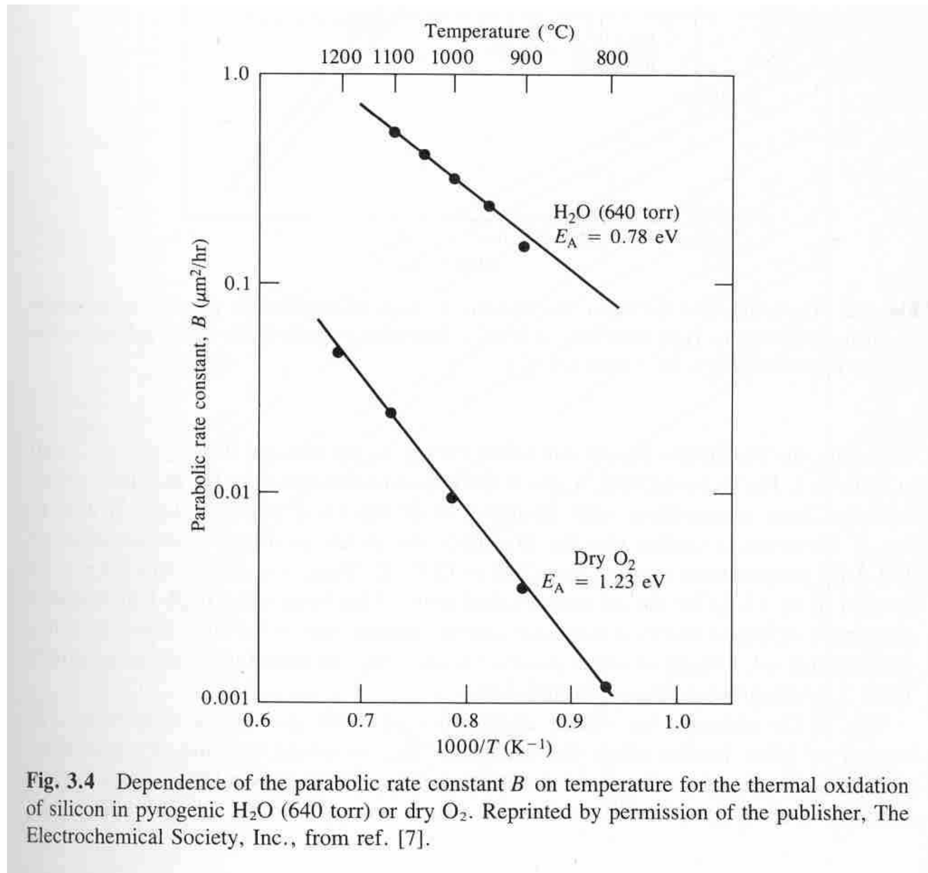


Fig. 3.4 Dependence of the parabolic rate constant B on temperature for the thermal oxidation of silicon in pyrogenic H_2O (640 torr) or dry O_2. Reprinted by permission of the publisher, The Electrochemical Society, Inc., from ref. [7].

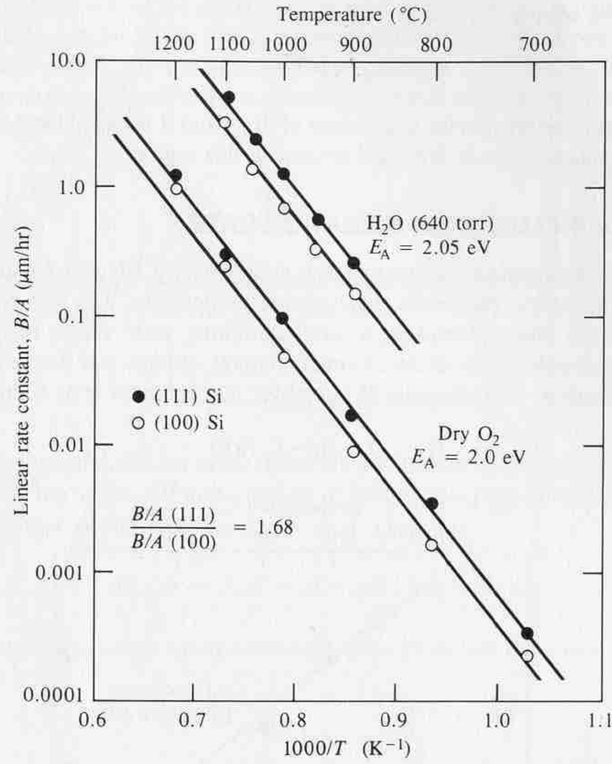


Fig. 3.5 Dependence of the linear rate constant B/A on temperature for the thermal oxidation of silicon in pyrogenic H_2O (640 torr) or dry O_2. Reprinted by permission of the publisher, The Electrochemical Society, Inc., from ref. [7].

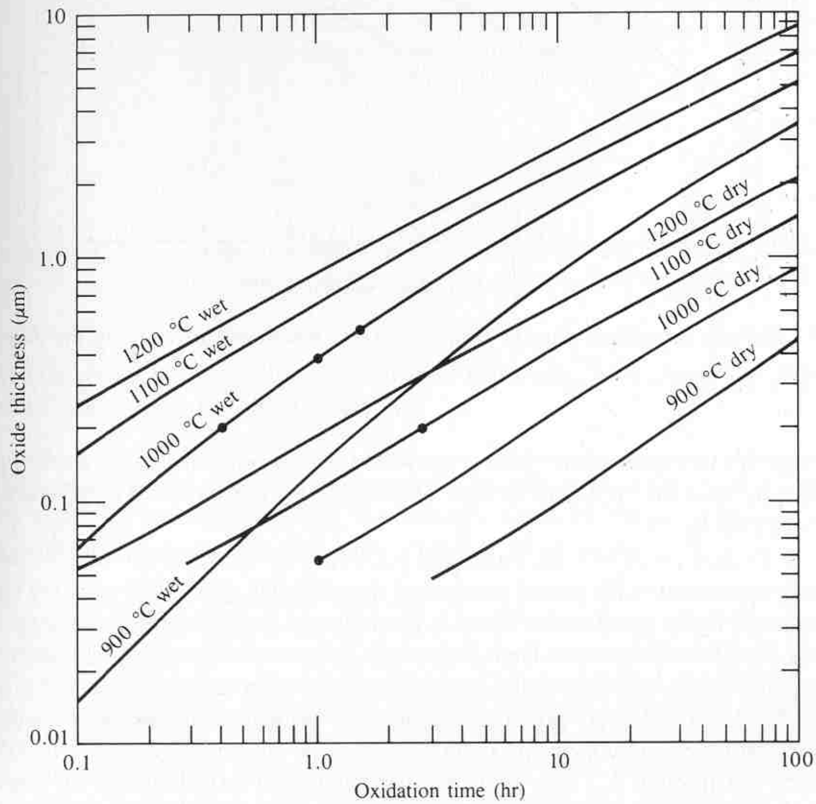


Fig. 3.6 Wet and dry silicon dioxide growth for ⟨100⟩ silicon calculated using the data from Table 3.1.

Table 8.4 | Coefficients for determining the rates of oxidation in silicon

Constants	Coefficient *a*	Coefficient *b*	Conditions
Linear rate constant, Eq. (8.12)	−10.4422	6.96426	Dry O_2, E_a = 2 eV, (100) silicon
	−10.1257	6.93576	Dry O_2, E_a = 2 eV, (111) silicon
	−9.905525	7.82039	H_2O vapor, E_a = 2.05 eV, (110) silicon
	−9.92655	7.948585	H_2O vapor, E_a = 2.05 eV, (111) silicon
Parabolic rate constant, Eq. (8.13)	−14.40273	6.74356	Dry O_2, E_a = 1.24 eV, 760 torr vacuum
	−10.615	7.1040	H_2O vapor, E_a = 0.71 eV, 760 torr vacuum

8.5.4 Oxide Thickness by Color

- Both SiO_2 and Si_3N_4 layers have a color distinct from that of the silicon substrate.

- SiO_2: transparent, but with a different light refraction index from that of the silicon substrate.
  → Different colors on the surface corresponding to the layer's thickness when illuminated by white light.

- The color of a SiO_2 layer's surface is the result of the interference of the reflected light rays.

Table 8.5 | Color of silicon dioxide layers of selected thickness

SiO_2 layer thickness, μm	0.050	0.075	0.275 0.465	0.310 0.493	0.50	0.375	0.390
Color	Tan	Brown	Red–violet	Blue	Green to yellow–green	Green–yellow	Yellow

8.6 Chemical Vapor Deposition

- Deposition vs. diffusion and thermal oxidation processes:
  - Deposition adds thin films to, instead of consuming, the substrate.
  - Wide range of materials: can be organic (有機的) or inorganic.
    (a) Metals: e.g., Al, Ag, Au, Ti, W, Cu, Pt, Sn.
    (b) Compounds: NiTi (the common shape-memory alloy) and the piezoelectric ZnO.
    (c) Others.

- Two classes of deposition:
  (1) *Physical vapor deposition* (PVD)
    - direct impingement (衝擊;撞擊) of particles on the hot substrate surfaces.
  (2) *Chemical vapor deposition* (CVS)
    - Involves chemical reactions of the reactants and carrier gas at the hot substrate surface.
    - More effective in terms of growth rate and quality.
    - Most CVD processes involve low gas pressures, and some in high vacuum.

8.6.1 Working Principle of CVD

- Working Principle:
  - Involve the flow of a gas (called *carrier gas*) with diffused reactants (擴散的反應物).
  - While the gas flows over the hot solid surface, the energy supplied by the surface temperature provokes chemical reactions of the reactants that form films.
  - The by-products of the chemical reactions are then vented (排出).

- In the reactor, resistance heaters either surround the chamber (Fig. 8.9a) or lie directly under the susceptor that holds the substrates (Fig. 8.9b).

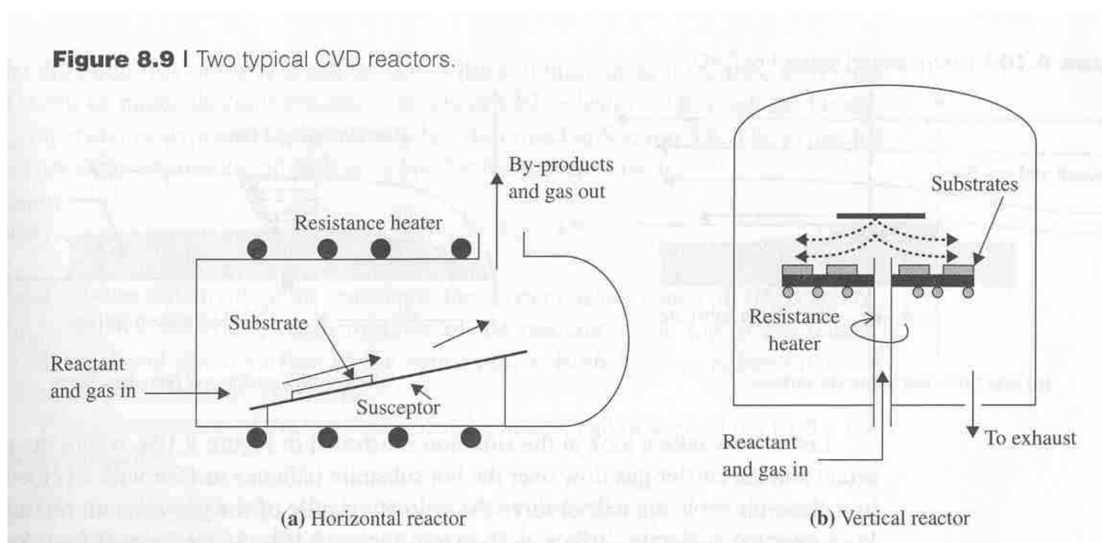


Figure 8.9 I Two typical CVD reactors.

8.6.2 Chemical Reaction in CVD

- 3 common thin films by CVD:
  (1) Silicon dioxide;

(2) Silicon nitride;

(3) Polycrystalline silicon.

- Silicon dioxide
  - SiO_2 thin films can be produced by either the diffusion process (Sec. 8.4) or CVD.
  - Reactants and carrier gases for SiO_2 by CVD:
    - Reactants: $SiCl_4$, $SiBr_4$, or SiH_2Cl_2.
    - Carrier gases: O_2, NO, NO_2, and CO_2 with H_2.
  - Chemical reaction:

$$SiH_4 + O_2 \rightarrow SiO_2 + 2H_2 \quad (8.14)$$

  - Reaction temperature: 400~500℃.
  - Activation energy Ea=0.4eV.

(Note: 1 eV = $1.6\text{x}10^{-19}$ J)

- Silicon nitride
  - Common carrier gas: ammonia (氨).
  - Chemical reaction:

$$3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2 \quad (8.15a)$$

$$3SiCl_4 + 4NH_3 \rightarrow Si_3N_4 + 12HCl \quad (8.15b)$$

$$3SiH_2Cl_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2 \quad (8.15c)$$

  - Reaction temperature: 700~900℃ for silane (矽烷) in Eq.8.15a; 850℃ for silicon tetrachloride (四氯化矽) in Eq.8.15b; and 650~750℃ for dichlorosilane in Eq.8.15c.
  - Activation energy Ea=1.8eV.

- Polycrystalline silicon
  - Pyrolysis process (a decomposition process using heat):

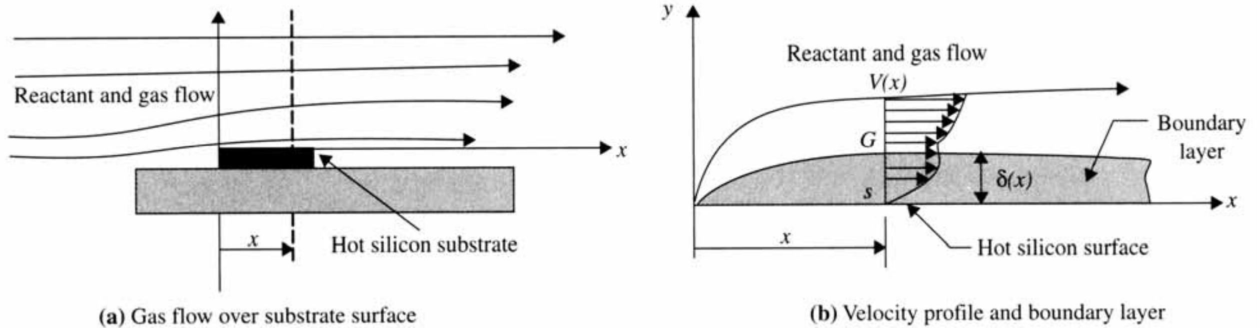
$$SiH_4 \rightarrow Si + 2H_2 \quad (8.16)$$

  - Reaction temperature: 600~650℃.
  - Activation energy Ea=1.7eV.

8.6.3 Rate of Deposition

- Boundary layer δ(x) for laminar (層流的) flow in Fig. 10:
  - The reactant (反應物) needs to diffuse across this layer
  - → The retarding (妨礙) factor to the chemical reaction

Figure 8.10 | Thermal/fluid aspect of CVD.



- $$\delta(x) = \frac{x}{\sqrt{\mathrm{Re}(x)}} \tag{8.17}$$

where Re(x) is the Reynolds number of the gas mixture,

$$\mathrm{Re}(x) = \frac{\rho L V(x)}{\mu} \tag{8.18}$$

where ρ: mass density of the gas mixture, L: characteristic length of the flow, and μ: dynamic viscosity of gases (see Table 8.6)

- Note that CVD takes place at low gas velocity about Re=100.

Table 8.6 | Dynamic viscosity of gases used in CVD processes

	Viscosity, μP			
Gas	**0°C**	**490°C**	**600°C**	**825°C**
Hydrogen, H_2	83	167	183	214
Nitrogen, N_2	153	337	–	419
Oxygen, O_2	189	400	–	501
Argon, Ar	210	448	–	563

1 poise (P) = 1 dyne-s/cm^2 = 0.1 N-s/m^2 = 0.1 kg/m-s
Source: Ruska [1987].

- The diffusion flux of the reactant, $\vec{N}$, across the boundary layer thickness in [atoms or molecules/m^2-s] can be expressed by the Fick's law:

$$\vec{N} = \frac{D}{\delta}(N_G - N_S) \tag{8.19}$$

where D: diffusivity in [cm^2/s], and N_G and N_S: concentration of the reactant

at the top of the boundary layer, G, and at the surface of the substrates, s, in [molecules/m^3], which can be obtained from *PV=nRT*.

- The reactant diffuses through the boundary layer, and forms the film by chemical reaction at the hot surface of the substrate. The reaction rate at the substrate surface:

$$\dot{N} = k_s N_S \tag{8.20}$$

where k_s, the surface reaction rate constant (as shown in Eq. 8.11), can be shown as:

$$k_s = k' \exp\left(-\frac{E_a}{kT}\right) \tag{8.21}$$

where *k'*: constant depending on the reaction and the reactant concentration; E_a: activation energy; *k*: Boltzmann constant, and *T*: absolute temperature.

- At equilibrium, Eq. (20) = Eq. (21)

$$\dot{N} = \frac{DN_G k_s}{D + \delta k_s} \tag{8.22}$$

- The rate of the growth of the thin film over the substrate surface, *r*, in [m/s]:

$$r = \frac{DN_G}{\gamma\delta} \tag{8.23a}$$

for $\delta k_s \geq D$, or

$$r = \frac{N_G k_s}{\gamma} \tag{8.23b}$$

where γ is the number of atoms or molecules per unit volume of thin film:

$$\gamma = \frac{1}{v} = \frac{1}{\frac{4}{3}\pi a^3} \tag{8.24}$$

where *a*: atom radius (see Table 8.7).

Table 8.7 | Atomic radius of selected materials

Reactant materials	Atomic radius, nm	Ionic radius, nm
Hydrogen	0.046	0.154
Helium	0.046	0.154
Boron	0.097	0.02
Nitrogen	0.071	0.02
Oxygen	0.060	0.132
Aluminum	0.143	0.057
Silicon	0.117	0.198
Phosphorus	0.109	0.039
Argon	0.192	
Iron	0.124	0.067
Nickel	0.125	0.078
Copper	0.128	0.072
Gallium	0.135	0.062
Germanium	0.122	0.044
Arsenic	0.125	0.04

Source: Kwok [1997].

8.6.4 Enhanced CVD

- Previous subsections:
  - *APCVD* (*atmospheric pressure CVD*) involves elevated temperature, but near atmospheric pressure.

- This subsection:
  - Other CVD for better results either for higher rate of growth or for better quality of the deposited film.
  - LPCVD (low-pressure CVD) and PECVD (plasma-enhanced CVD)

- LPCVD:
  - The reduction of gas pressure will increase the deposition rate.
  - More uniform
  - Allow stacked wafers: good for mass production.

- PECVD:
  - Use radio-frequency (RF) plasma to transfer energy into reactant gases.
    → allow substrates to maintain at lower temperature than that in APCVD and LPCVD.
    → reduce the chances of substrate damage by elevated tempearture.

Figure 8.12 | A PECVD reactor.

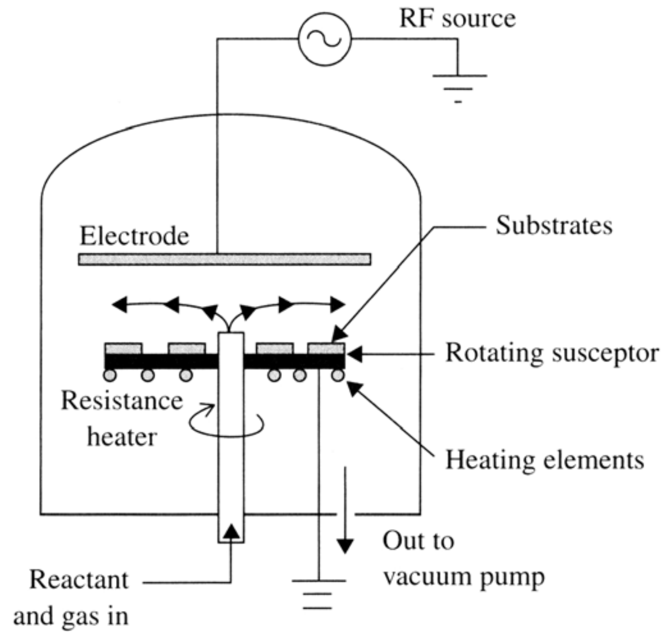


Table 8.8 | Summary and comparison of three principal CVD processes

CVD process	Pressure/ temperature	Normal deposition rates, 10^{-10} m/min	Advantages	Disadvantages	Applications
APCVD	100–10 kPa/ 350–400°C	700 for SiO_2	Simple, high rate, low temperature	Poor step coverage, particle contamination	Doped and undoped oxides
LPCVD	1–8 torr/ 550-900°C	50–180 for SiO_2 30–80 for Si_3N_4 100–200 for polysilicon	Excellent purity and uniformity, large wafer capacity	High temperature and high deposition rates	Doped and undoped oxides, silicon nitride, polysilicon, and tungsten
PECVD	0.2–5 torr/ 300–400°C	300–350 for Si_3N_4	Lower substrate temperature; fast, good adhesion	Vulnerable to chemical contamination	Low-temperature insulators over metals, and passivation

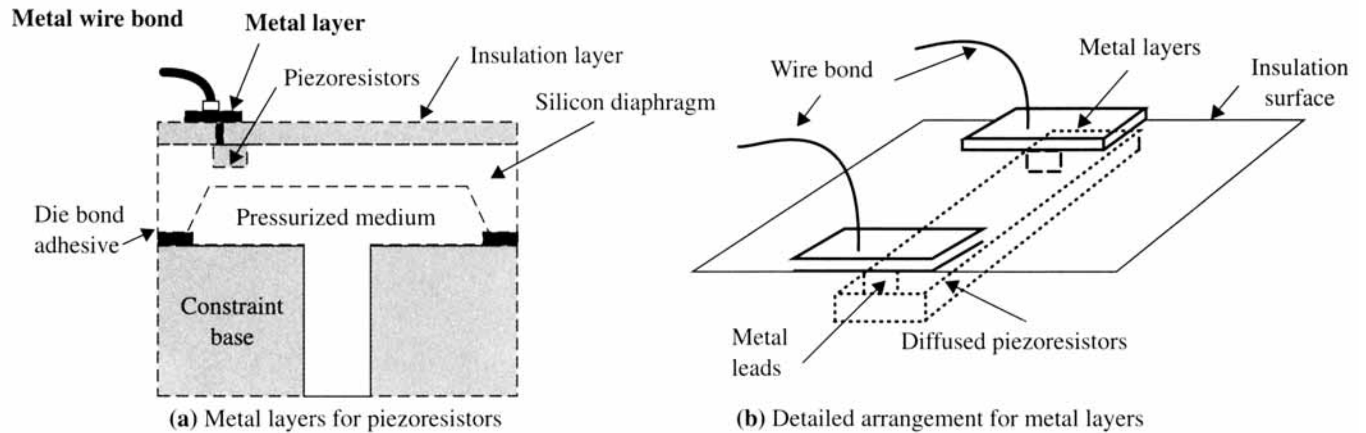
Source: Madou [1997].

8.7 Physical Vapor Deposition – Sputtering

- Sputtering

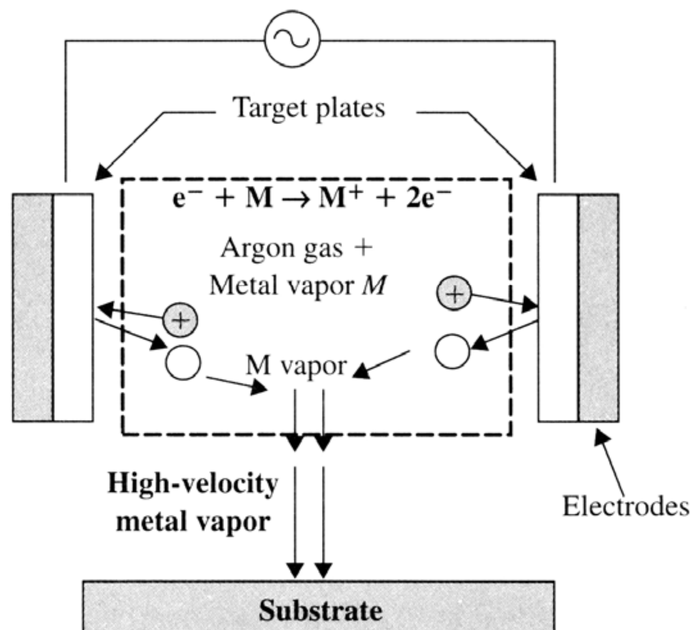
  - Often used to deposit thin metallic films in the order of 100 Å thick.
  - Metallic films: required to supply electricity, or transmit the signals (e.g., in a piezoresistor in Fig. 8.13), etc.

Figure 8.13 I Metallic layers for signal transmission in a micropressure sensor.



- Involve very low pressure: high vacuum around 5×10^{-7} torr (1 torr = 1 mm of Hg).
- Involve low temperature (which is contrary to CVD): little chemical reaction takes place.
  → Physical deposition
- The positively charged gas ions of the metal in the plasma bombard the metal atoms out of the target surface, which would be adsorbed onto the substrate.

Figure 8.14 I Graphical illustration of sputtering process.



8.8 Deposition by Epitaxy

(Epitaxy: 晶體定向生長，指晶體附著於其他晶體表面,往一定方向生長)

- Epitaxy Deposition:
  - The process to grow a film of the same single-crystal material onto the single-crystal substrate.
  - Used to build 3-dimensional geometry of the devices in MEMS.
  - Used in production of silicon diodes and transistors in the IC industry.
  - Similar to CVD in the way of using carrier gases with reactants.
  - Can deposit Si, or GaAs (a compound), etc.
  - Several methods for Si epitaxy:
    1. Vapor-phase epitaxy (VPE)
       - Most popular one in the IC industry.
       - Use reactant vapors containing silicon (see Table 8.9).
    2. Molecular-beam epitaxy (MBE)
    3. Metal-organic CVD (MOCVD)
    4. Complementary metal oxidation of semiconductors (CMOS) epitaxy
       - Frequently used in MEMS fabrication.

Table 8.9 | Reactant vapors for epitaxial deposition

Reactant vapors	Normal process temperature, °C	Normal deposition rate, μm/min	Required energy supply, eV	Remarks
Silane (SiH_4)	1000	0.1–0.5	1.6–1.7	No pattern shift
Dichlorosilane (SiH_2Cl_2)	1100	0.1–0.8	0.3–0.6	Some pattern shift
Trichlorosilane ($SiHCl_3$)	1175	0.2–0.8	0.8–1.0	Large pattern shift
Silicon tetrachloride ($SiCl_4$)	1225	0.2–1.0	1.6–1.7	Very large pattern shift

Source: Ruska [1987].

- Use silane as the reactant:

$$SiH_4 \rightarrow Si_{(solid)} + 2H_{2\,(gas)} \tag{8.25}$$

- By-product of the reactions such as $SiCl_2$ and HCl:
  - HCl is highly erosive (腐蝕性的): etch the newly produced silicon film.
  - Dedicate control of the process such that the rate of silicon production exceeds the rate of silicon etching.

- Reactors similar to some of those used in CVD: Fig. 8.15.
  - Has a high risk of explosion as a result of using H_2 as the carrier gas at a high temperature.
    → need to use N_2 to purge (清除): drive out O_2.
  -

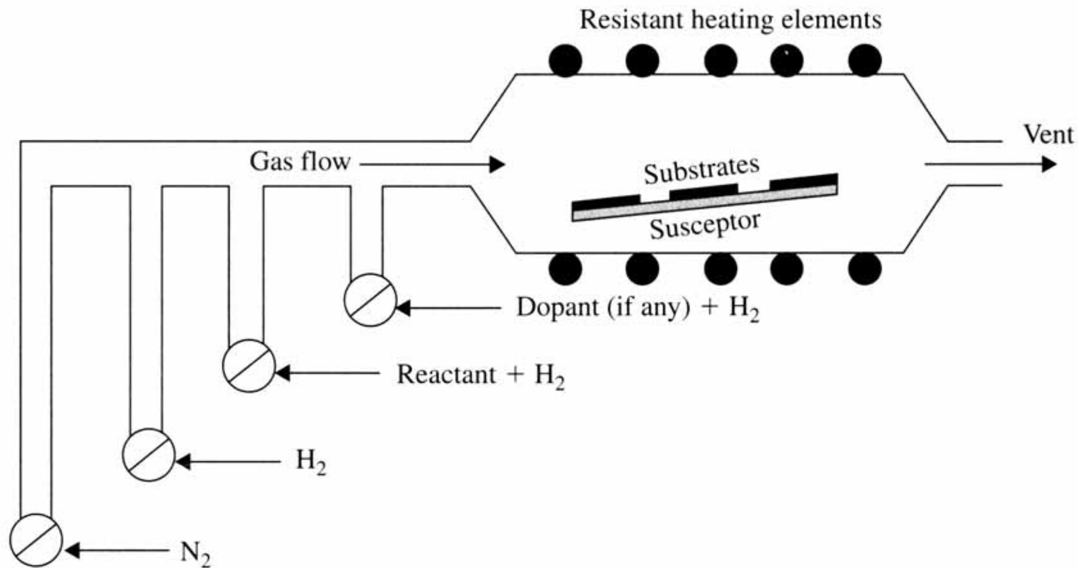


Figure 8.15 | Horizontal epitaxial deposition reactor.

8.9 Etching

- Etching
  - Involve the removal of materials in desired areas.
  - Chemical and physical etching:
    - Chemical etching: wet etching
    - Physical etching: dry etching or plasma etching

8.9.1 Chemical etching

- Chemical etching:
  - Use solutions with diluted chemicals to dissolve (溶解) substrates.
    - HF: to dissolve SiO_2, Si_3N_4, and polycrystalline silicon.
    - KOH: to etch the silicon substrates.
    - Etching rate: depends on the substrate materials to be etched, the chemical concentration, and the solution temperature.

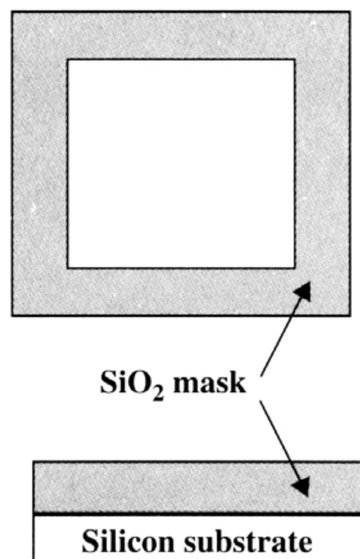
- Two types of etching:
  1. Isotropic etching (等向性蝕刻)
     - The etching of substrate takes place uniformly in all directions at the same rate.
  2. Anisotropic etching (非等向性蝕刻)
     - Etch away the substrate material at a faster rate in preferred directions.

- Advantages
  - Inexpensive
  - Faster etching rate(e.g., a few microns to several tens of microns per minute for isotropic etchants and about 1 μm/min for anisotropic etchants) compared to dry etching (e.g., 0.1 μm/min).

- Disadvantages
  - Poor quality
  - No effective wet etching for some substrates (e.g., Si_3N_4).

- Etching mask (遮蓋物):
  - To protect the underneath materials.

Figure 8.17 | SiO_2 masking for etching cavity in micropressure sensors.



8.9.2 Plasma Etching

- Plasma Etching:
  - Plasma: positive-charged ions with a large number of electrons, an diluted inert (惰性的) carrier gas such as argon.
  - Low temperature: 50~100℃.
  - High vacuum.

Figure 8.18 | Plasma assisted etching.