Lecture 3-1 Review of Micro Fabrication I: CMOS process, Lithography, and Oxidation

1. Overview of Monolithic Micro-fabrication Process:
   Example:

   NMOS Transistor (Metal-Oxide-Semiconductor) cross section:

4 AN OVERVIEW OF MICROELECTRONIC FABRICATION

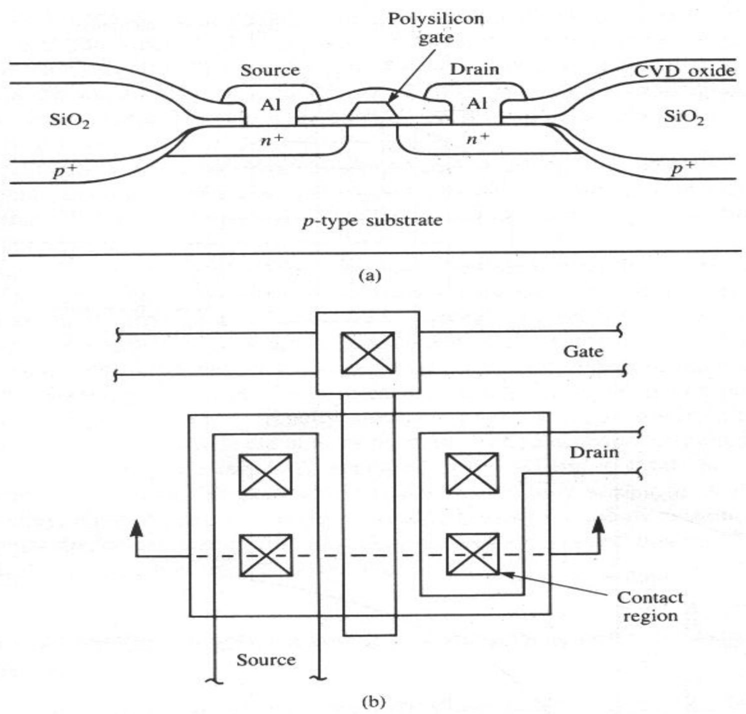


Fig. 1.2 The basic structure of an *n*-channel metal-oxide-semiconductor (NMOS) transistor structure. (a) The vertical cross section through the transistor; (b) a composite top view of the masks used to fabricate the transistor in (a).

Basic process used:

- Oxidation
- Photolithography
- Etching
- Diffusion
- Evaporation or sputtering
- Chemical Vapor Deposition (CVD)
- Ion implantation

NMOS Process:

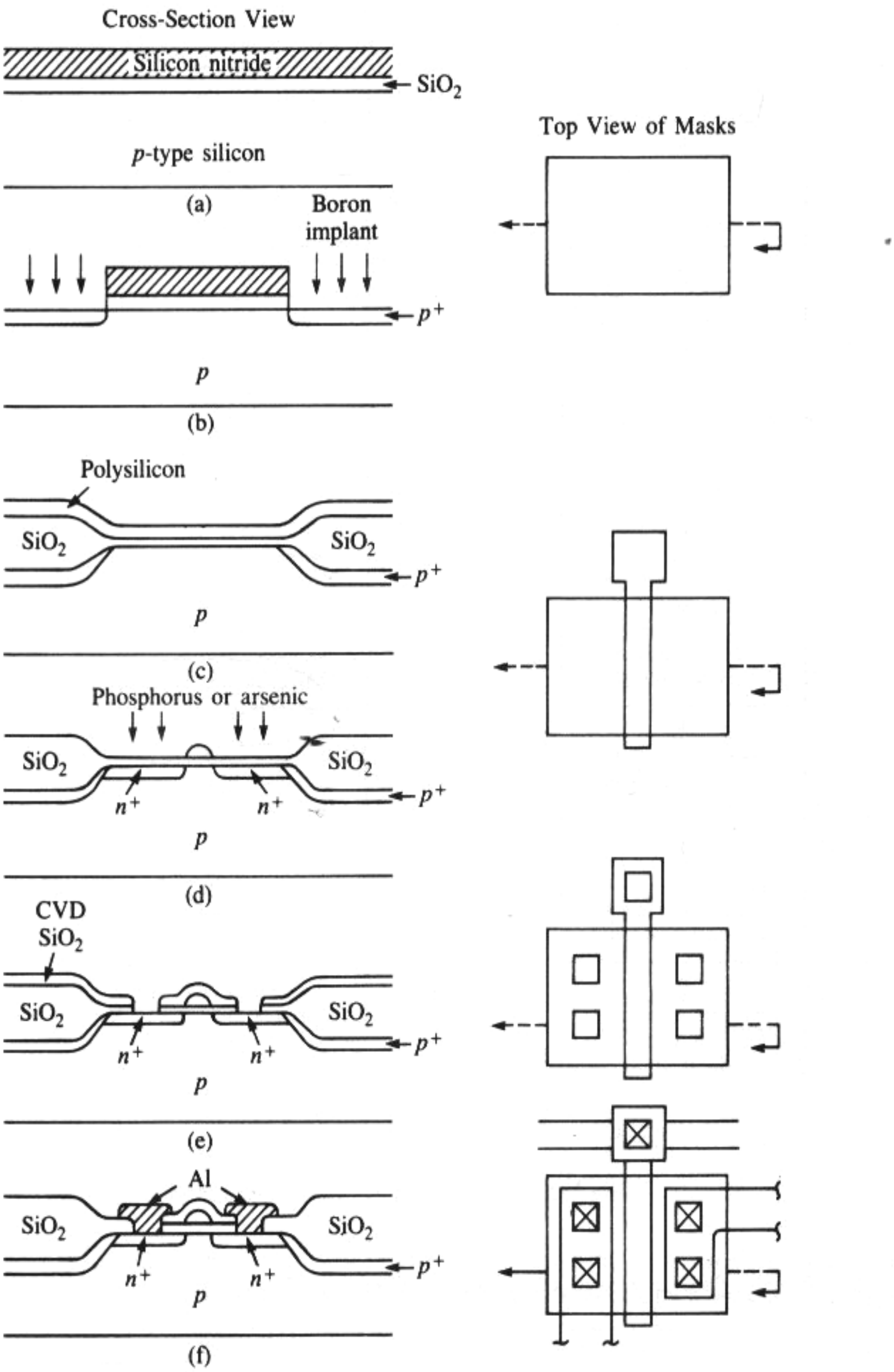


Fig. 1.4 Process sequence for a semirecessed oxide NMOS process. (a) Silicon wafer covered with silicon nitride over a thin padding layer of silicon dioxide; (b) etched wafer after first mask step. A boron implant is used to help control field oxide threshold; (c) structure following nitride removal and polysilicon deposition; (d) wafer after second mask step and etching of polysilicon; (e) the third mask has been used to open contact windows following silicon dioxide deposition; (f) final structure following metal deposition and patterning with fourth mask.

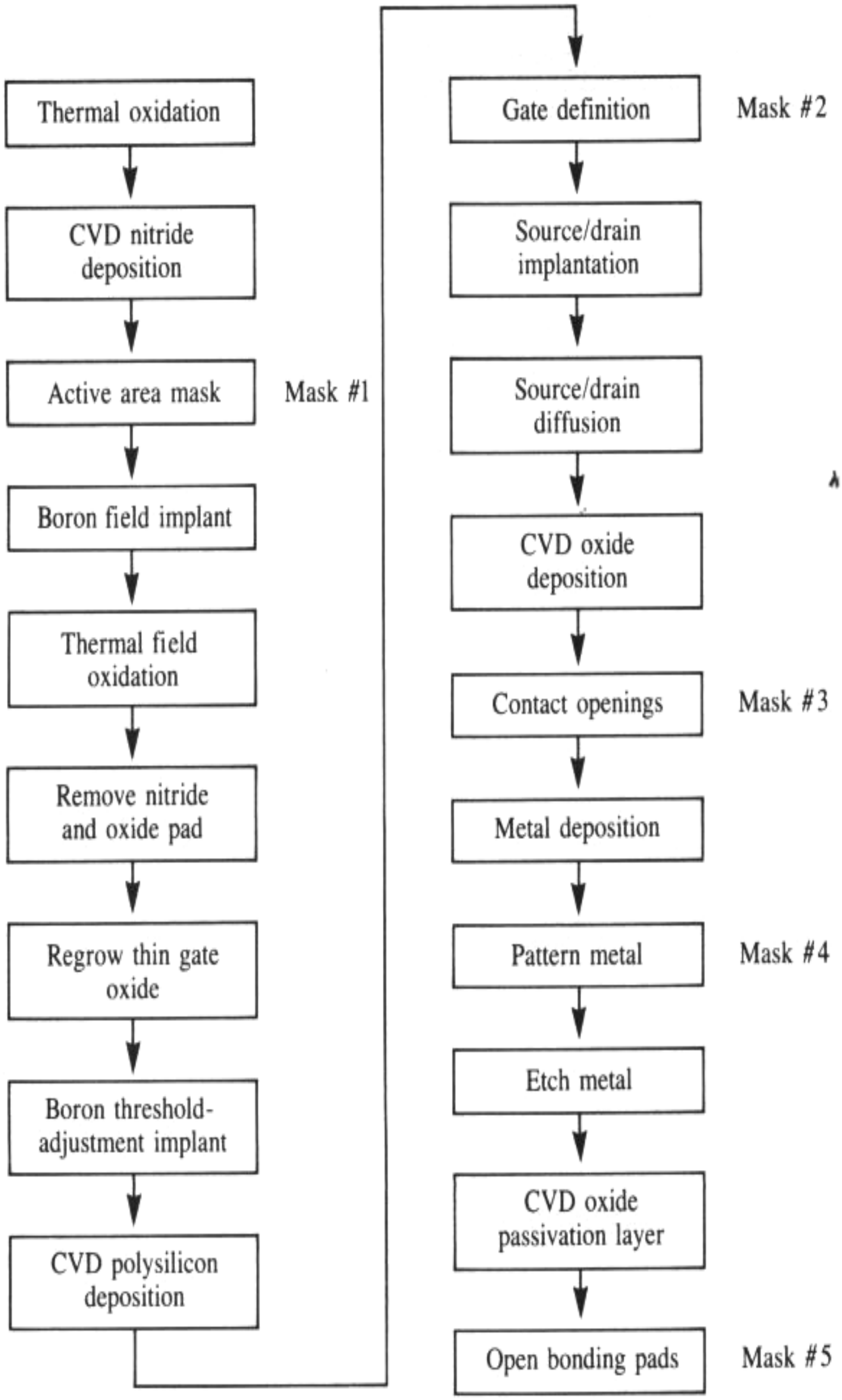


Fig. 1.5 Basic NMOS process flowchart.

CMOS Process:

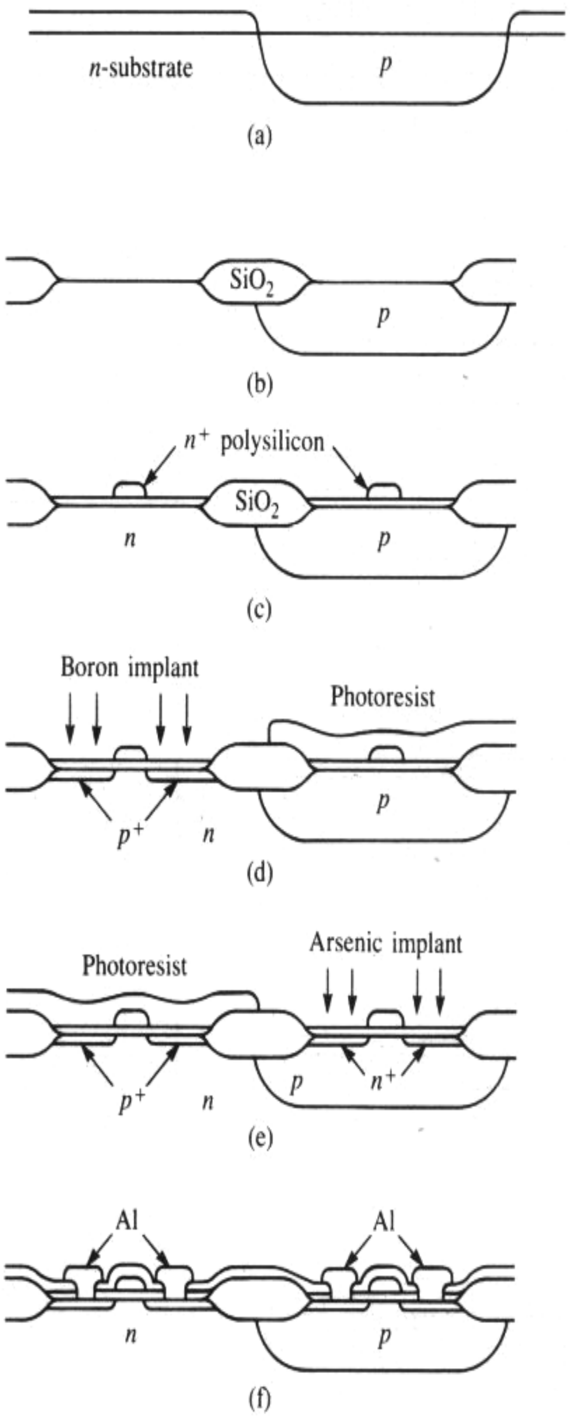


Fig. 1.6 Cross-sectional views at major steps in a basic CMOS process. (a) Following *p*-well diffusion, (b) following selective oxidation, and (c) following gate oxidation and polysilicon gate definition; (d) PMOS source/drain implantation; (e) NMOS source/drain implantation; (f) structure following contact and metal mask steps.

2. **Lithography**:

- Environment requirement:

  Clean room environment: Class 1-10,000, (0.5 μm particles/cubic foot), defects 10% each layer yield 50% functional devices after 7 mask process.

- Process:

Fig. 2.1 Steps of the photolithographic process

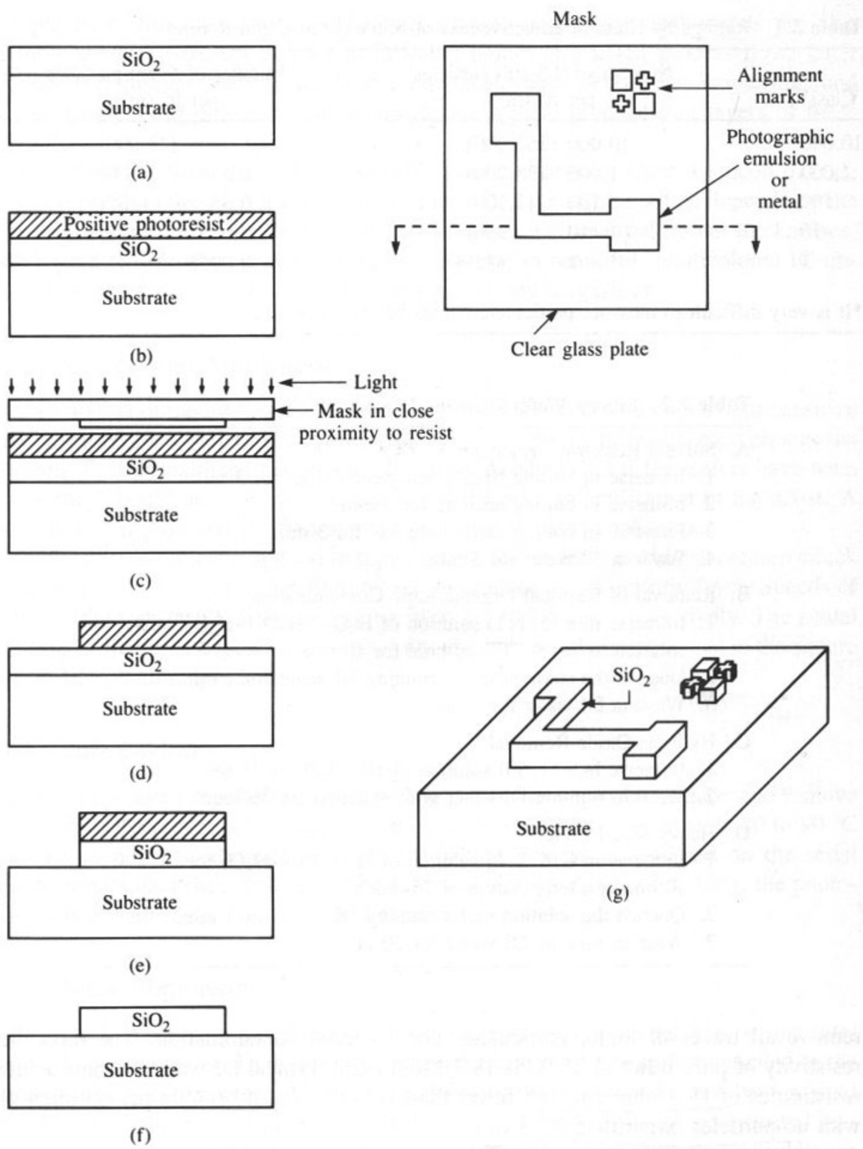


Fig. 2.2 Drawings of wafer through the various steps of the photolithographic process. (a) Substrate covered with silicon dioxide barrier layer; (b) positive photoresist applied to the surface of the wafer; (c) mask in close proximity to the surface of the resist-covered wafer; (d) substrate following resist exposure and development; (e) substrate following etching of the silicon dioxide layer; (f) oxide barrier on wafer surface after resist removal; (g) view of substrate with silicon dioxide pattern on the surface.

- **Wafer cleaning**:
  Goal: to remove
  1. Particulate matter (airborne bacteria, dust, abrasive particles: SiC, Al_2O_3, diamond power),
  2. Traces of organic (Grease, Wax from cutting oil or physical handling, finger print, plasticizers from containers and wrapping materials)
  3. Light metal ion (Na, K... from etchant impurities)
  4. Heavy metal impurities (Ca, Co, Hg, Cu, Au, Fe, Ag, Ni…electrodeposition from etchant)
  5. Native oxide (~ 50 Å)

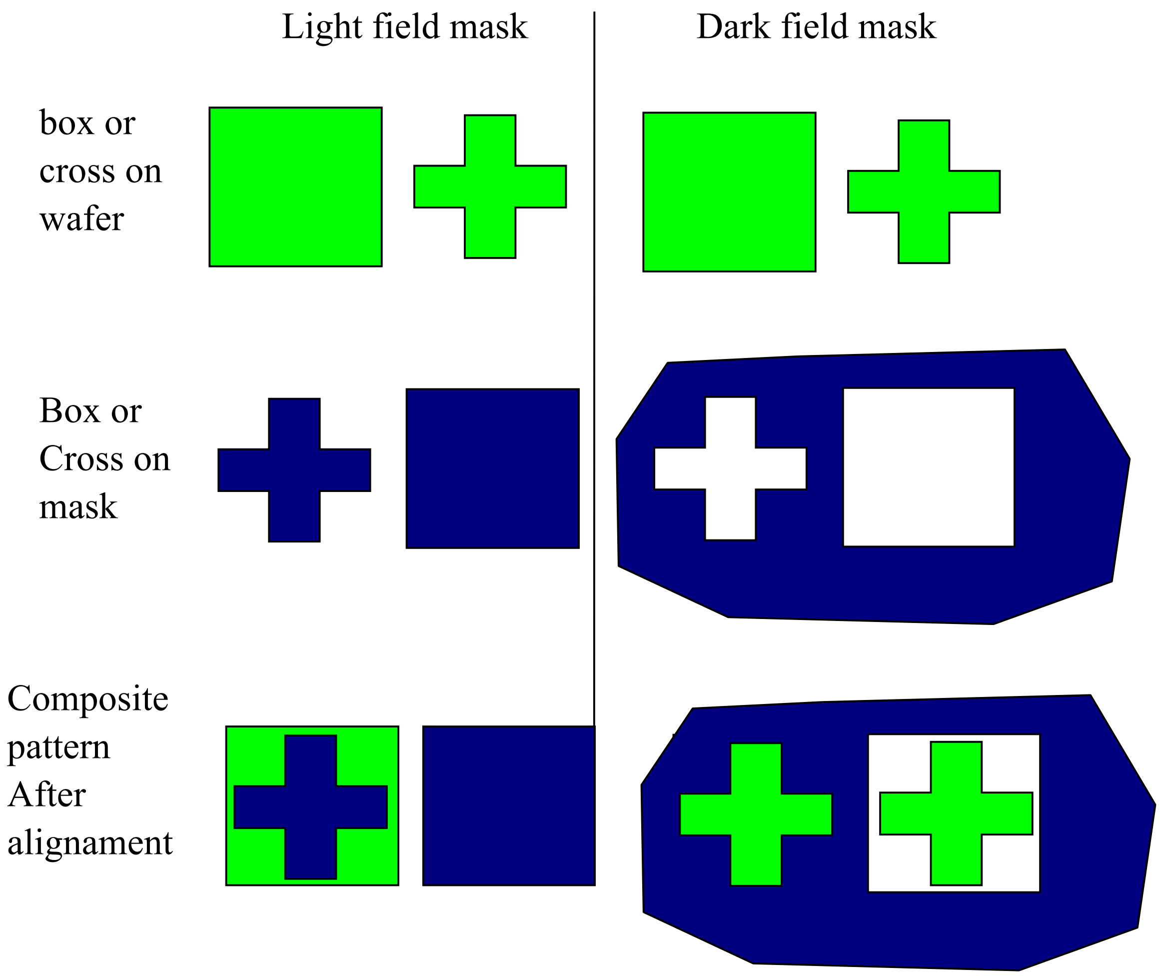
- **DI Water** (deionized water, 18 Mohm-cm at 25° C, <0.25 μm particles, <1.2 colonies of bacteria/mL)

- **Silicon wafer cleaning procedure**:
  A. Organic removal by Solvent:
     1. Immerse in boiling trichloroethylene (TCE) for 3 min
     2. Immerse in boiling acetone for 3 min
     3. Immerse in boiling methyl alcohol for 3 min
     4. Wash in DI water for 3 min
  B. Removal of Residual Organic/Heavy metal impurities
     1. Immerse in a (5:1:1) solution of H_2O-HH_4OH-H_2O_2 at 75-80° C for 10 min. (RCA I)
     2. Quench the solution under running DI water for 1 min.
     3. Wash in DI water for 5 min
  C. Hydrous Oxide removal:
     1. Immerse in a (1:50) solution of HF-H_2O for 40-60 sec
     2. Wash in running DI water with agitation for 30 sec.
  D. Light-metal-ion contamination removal:
     1. Immerse in a (6:1:1) solution of H_2O-HCl-H_2O_2 for 10 min at temp of 75-80° C
     2. Quench the solution under running DI water for 1 min.
     3. Wash in DI water for 20 min

- **Photoresist Application**:

1. Clean and dry wafer surface
2. Adhesion promoter (for example, HMDS)
3. Spin on: 1000~5000 rpm yield 2.5-0.5 μm (for AZ 5214), thickness inversely proportional to square root of spin rate.

- **Soft bake**:
  1. To improve adhesion and remove solvent
  2. 10-30 min in an oven at 80-90° C in air or nitrogen environment.
- **Mask alignment**:
  1. Alignment tolerance depends on feature size (typically 0.25-2 μm for 1.25-5 μm feature)
  2. Alignment marks:



- **Photoresist Exposure and Development:**
  1. High intensity UV light.(typically 350-450 nm)
  2. Positive and negative PR.

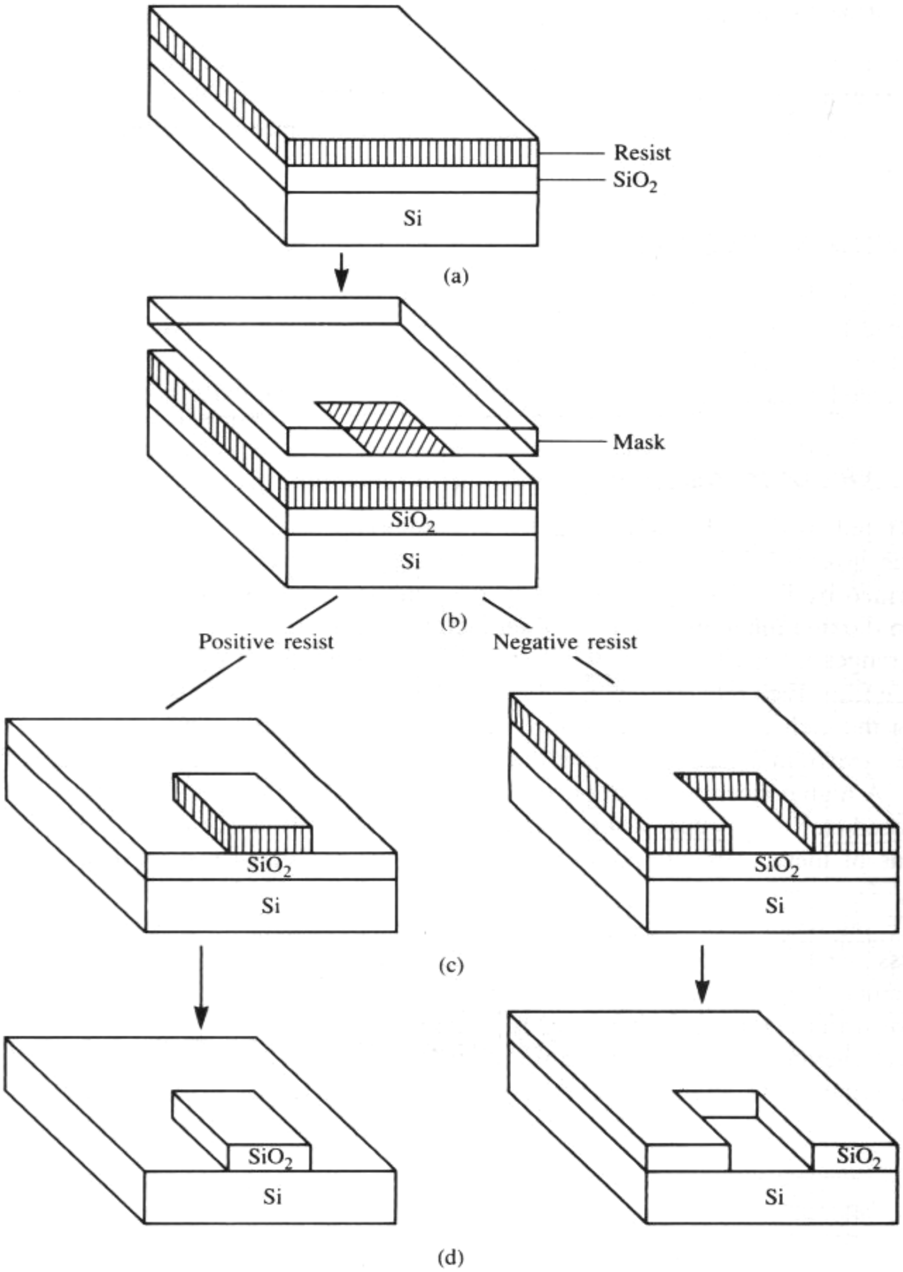
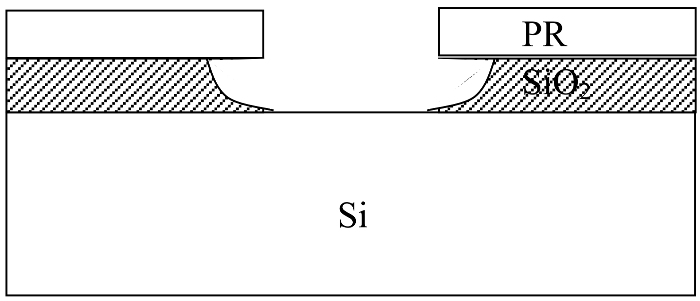


Fig. 2.4 Resist and silicon dioxide patterns following photolithography with positive and negative resists.

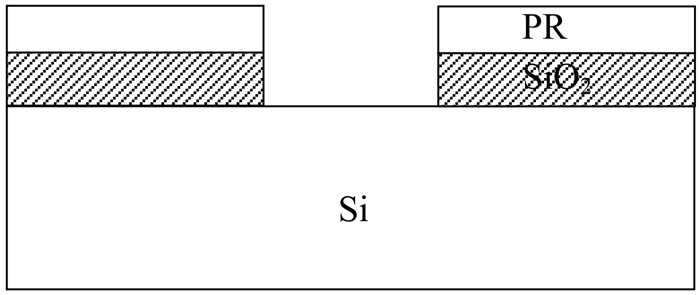
- **Hard Baking:**
  1. Harden the photoresist and improve adhesion to the substrate.
  2. typically 20-30 min at 120-180 C.

- **Etching Techniques:**
  1. wet chemical etching: SiO_2: BOE or BHF (contain HF), Si_3N_4: Hot H_3PO_4, Al: H_3PO_4+CH_3COOH+HNO_3, etc…, PR adhesion to substrate surface is important. Undercutting may be as large as the etching depth.
  2. Dry Etching:
     a. Plasma etching: immerses the wafers in a gaseous plasma created by RF excitation in vacuum. The plasma contains fluorine or chlorine ions. Etching occurs chemically.
     b. Sputter etching: uses energetic noble gas such as Ar^+ to bombard the wafer surface. Etching occurs by physically knocking atoms off the surface of the wafer. High anisotropic, but poor selectivity.
     c. Reactive-ion etching (RIE): combines the plasma and sputter etching process. Plasma systems are used to ionize reactive gases, and the ions are accelerated to bombard the surface. Etching occurs through a combination of the chemical reaction and momentum transfer from the etching species.

Typically Etching profile for wet etching:



- Typically Etching profile for dry etching：



- Photoresist removal: Liquid stripper or oxidizing (burning) in an Oxygen plasma system—*resist ashing.*
- Photomask fabrication and printing methods:

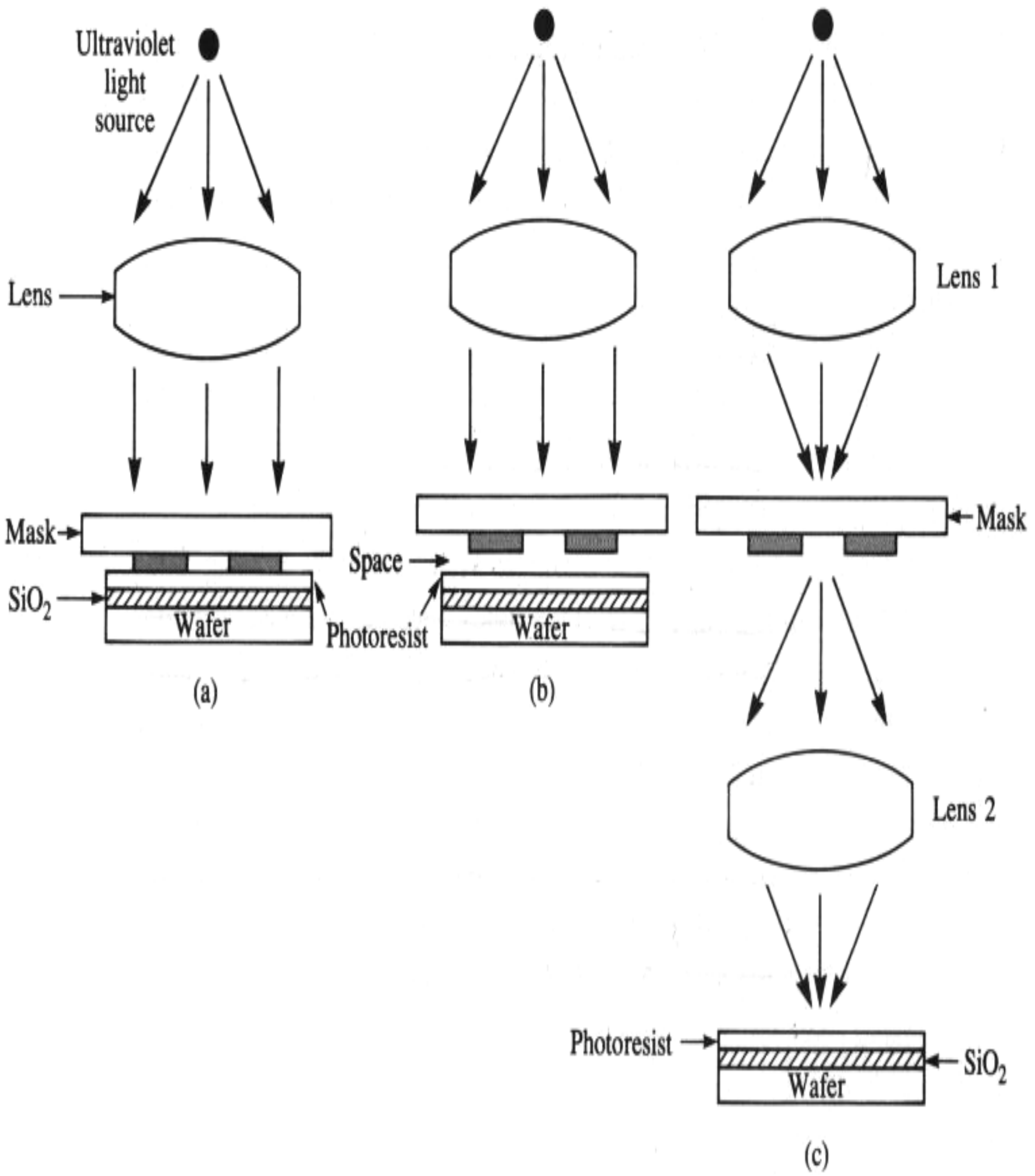


Fig. 2.8 Artist's conception of various printing techniques. (a) Contact printing, in which wafer is in intimate contact with mask; (b) proximity printing, in which wafer and mask are in close proximity; (c) projection printing, in which light source is scanned across the mask and focused on the wafer. Copyright, 1983, Bell Telephone Laboratories, Incorporated. Reprinted by permission from ref. [2].

3. Thermal Oxidation:

1. SiO_2 melting point: 1732 C, growth 1 μm SiO_2 Consume 0.44 μm Silicon. It is a high quality insulator and good barrier material during impurity diffusion.
2. Diffusivity:

$$D = D_0 e^{-E_A / kT}$$

D_0=Diffusion constant, E_A=activation energy of the diffusion species in eV/Molecule. K=Boltzmann's constant, 8.62e^{-5} eV/K, T= temperature.

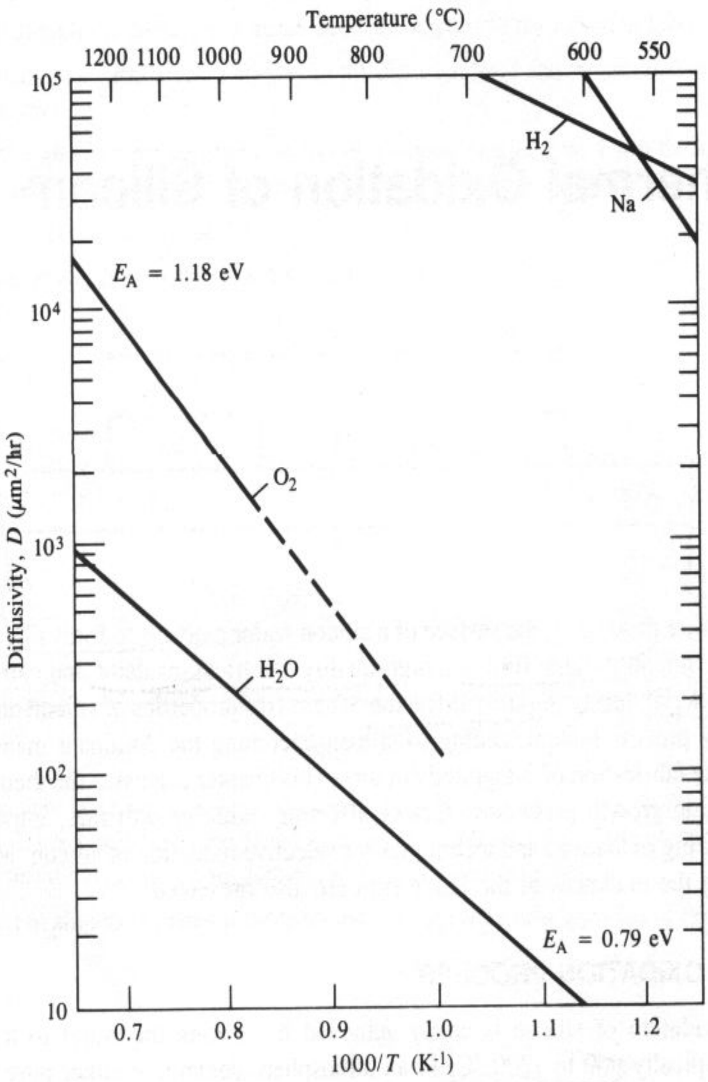


Fig. 3.1 Diffusivities of hydrogen, oxygen, sodium, and water vapor in silicon glass. Copyright John Wiley & Sons, Inc. Reprinted with permission from ref. [2].

3. Oxide formation:

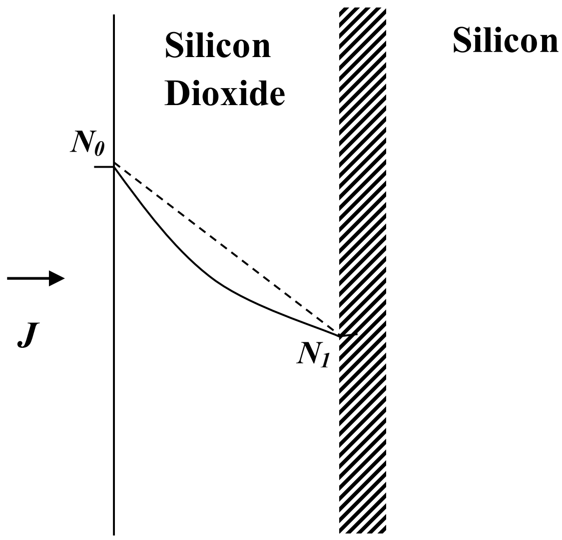
Dry Oxide:

$$Si + O_2 \longrightarrow SiO_2$$

Wet Oxide:

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

4. Kinetics of Oxide Growth:



Assume a silicon slice is brought in contact with the oxidant, with concentration N_g in the gas phase, resulting in surface concentration of N_0 molecules/cm^3 for this species. N_0: solid solubility of the species at the oxidation temperature. (at 1000 C, 5.2e^{16} for dry oxygen and 3e^{19} for water vapor). Transport of specie may occur by both drift and diffusion, here we neglect drift. The flux density ***J*** of oxidizing species arriving at the gas-oxide interface is :

$$J = -D\frac{\partial N}{\partial x} \cong \frac{D(N_0 - N_1)}{x} \qquad (2\text{-}1)$$

where x is thickness of the oxide at a given time. This is *Henry's law.*

On arrival at the silicon surface the species enters into chemical reaction with it. If it is assumed that this reaction proceeds at the rate proportional to the concentration of the oxidizing species, then

$$J = kN_1 \qquad (2\text{-}2)$$

Where k is the interfacial reaction rate constant.
These two flux must be equal under steady-state diffusion conditions. Combining Eqs. (2-1) and (2-2) gives:

$$J \cong \frac{DN_0}{x + D/k} \qquad (2\text{-}3)$$

The rate of change of the oxide layer thickness is given by:

$$\frac{dx}{dt} = \frac{J}{n} = \frac{DN_0/n}{x + D/k} \qquad (2\text{-}4)$$

Were n is the number of molecules of the oxidizing impurity that are incorporated into unit volume of the oxide. Solving this equation to the boundary condition that x=0 at t=0, gives

$$x^2 + \frac{2D}{k}x = \frac{2DN_0}{n}t \qquad (2\text{-}5)$$

So that

$$x = \frac{D}{k}[(1 + \frac{2N_0k^2t}{Dn})^{1/2} - 1] \qquad (2\text{-}6)$$

Define $A=2D/k$, $B=2DN_0/n$, when t is small (<<1, thickness <500), equation (2-6) can be reduced to:

$$x = \frac{B}{A}t \qquad \text{(reaction limit)} \qquad (2\text{-}7)$$

and for large t:

$$x = \sqrt{Bt} \qquad \text{(diffusion limit)} \qquad (2\text{-}8)$$

5. Thickness vs. Time and Temp:

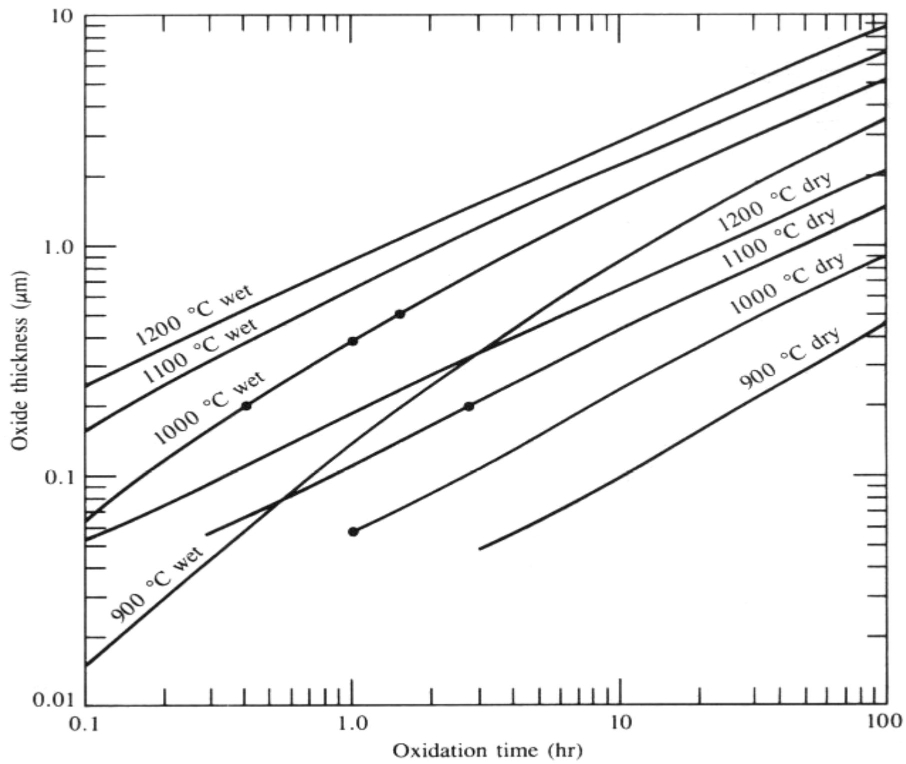


Fig. 3.6 Wet and dry silicon dioxide growth for ⟨100⟩ silicon calculated using the data from Table 3.1.

6. Dopant Redistribution during Oxidation:

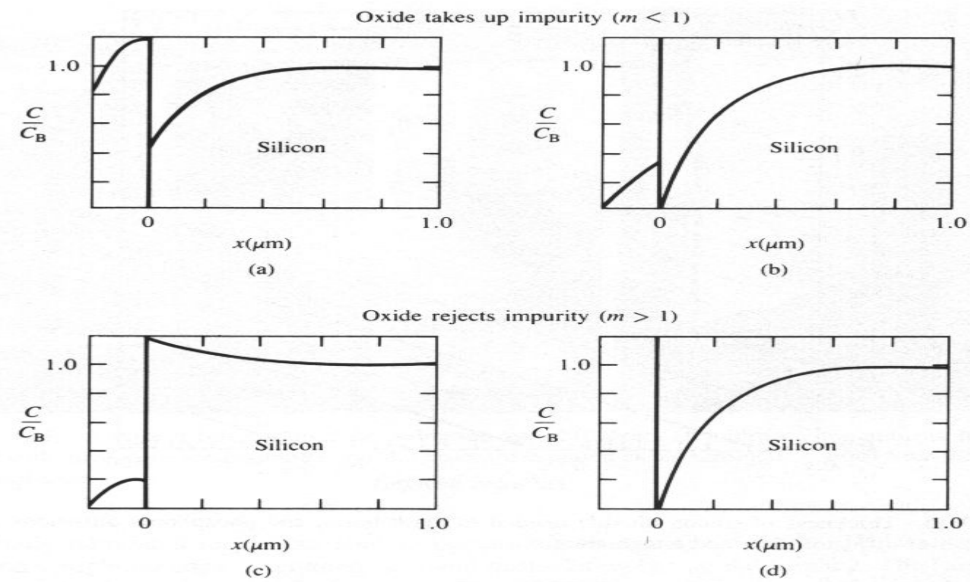


Fig. 3.9 The effects of oxidation on impurity profiles. (a) Slow diffusion in oxide (boron); (b) fast diffusion in oxide (boron with hydrogen ambient); (c) slow diffusion in oxide (phosphorus); (d) fast diffusion in oxide (gallium). Copyright John Wiley & Sons, Inc. Reprinted with permission from ref. [3].

7. Selective Oxidation:

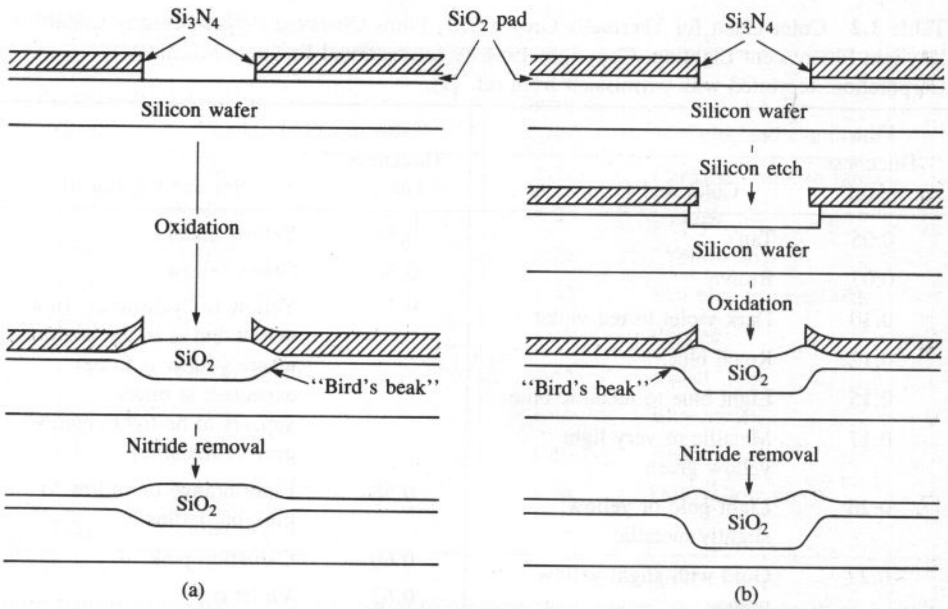


Fig. 3.12 Cross section depicting process sequence for (a) semirecessed and (b) fully recessed oxidations of silicon.

8. Color:

Table 3.2 Color Chart for Thermally Grown SiO_2 Films Observed Perpendicularly Under Daylight Fluorescent Lighting. Copyright 1964 by International Business Machines Corporation; reprinted with permission from ref. [9].

Film Thickness (μm)	Color and Comments	Film Thickness (μm)	Color and Comments
0.05	Tan	0.54	Yellow green
0.07	Brown	0.56	Green yellow
0.10	Dark violet to red violet	0.57	Yellow to "yellowish" (not yellow but is in the position where yellow is to be expected; at times appears to be light creamy gray or metallic)
0.12	Royal blue	0.58	Light orange or yellow to pink borderline
0.15	Light blue to metallic blue	0.60	Carnation pink
0.17	Metallic to very light yellow green	0.63	Violet red
0.20	Light gold or yellow; slightly metallic	0.68	"Bluish" (not blue but borderline between violet and blue green; appears more like a mixture between violet red and blue green and looks grayish)
0.22	Gold with slight yellow orange	0.72	Blue green to green (quite broad)
0.25	Orange to melon	0.77	"Yellowish"
0.27	Red violet	0.80	Orange (rather broad for orange)
0.30	Blue to violet blue	0.82	Salmon
0.31	Blue	0.85	Dull, light red violet
0.32	Blue to blue green	0.86	Violet
0.34	Light green	0.87	Blue violet
0.35	Green to yellow green	0.89	Blue
0.36	Yellow green	0.92	Blue green
0.37	Green yellow	0.95	Dull yellow green
0.39	Yellow	0.97	Yellow to "yellowish"
0.41	Light orange	0.99	Orange
0.42	Carnation pink	1.00	Carnation pink
0.44	Violet red		
0.46	Red violet		
0.47	Violet		
0.48	Blue violet		
0.49	Blue		
0.50	Blue green		
0.52	Green (broad)		

Reference:

1. Introduction to Microelectronic Fabrication, Gerold W. Neudeck, Robert F. Pierret, Addison-Wesley Publishing Company, 1993.
2. Fundamentals of Microfabrication, Marc Madou, CRC Press, 1997