

3 / Thermal Oxidation of Silicon

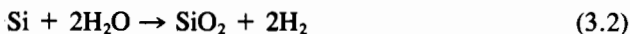
Upon exposure to oxygen, the surface of a silicon wafer oxidizes to form silicon dioxide. This native silicon dioxide film is a high-quality electrical insulator and can be used as a barrier material during impurity diffusion. These two properties of silicon dioxide were the primary process factors leading to silicon becoming the dominant material in use today for the fabrication of integrated circuits. This chapter discusses the theory of oxide growth, oxide growth processes, factors affecting oxide growth rate, impurity redistribution during oxidation, and techniques for selective oxidation of silicon. Methods for determining the thickness of the oxide film are also presented.

3.1 THE OXIDATION PROCESS

Thermal oxidation of silicon is easily achieved by heating the wafer to a high temperature, typically 900 to 1200 °C, in an atmosphere containing either pure oxygen or water vapor. Both water vapor and oxygen move (diffuse) easily through silicon dioxide at these high temperatures (see Fig. 3.1). Oxygen arriving at the silicon surface can then combine with silicon to form silicon dioxide. The chemical reaction occurring at the silicon surface is



for dry oxygen and



for water vapor. Silicon is consumed as the oxide grows, and the resulting oxide expands during growth, as shown in Fig. 3.2. The final oxide layer is approximately 54% above the original surface of the silicon and 46% below the original surface.

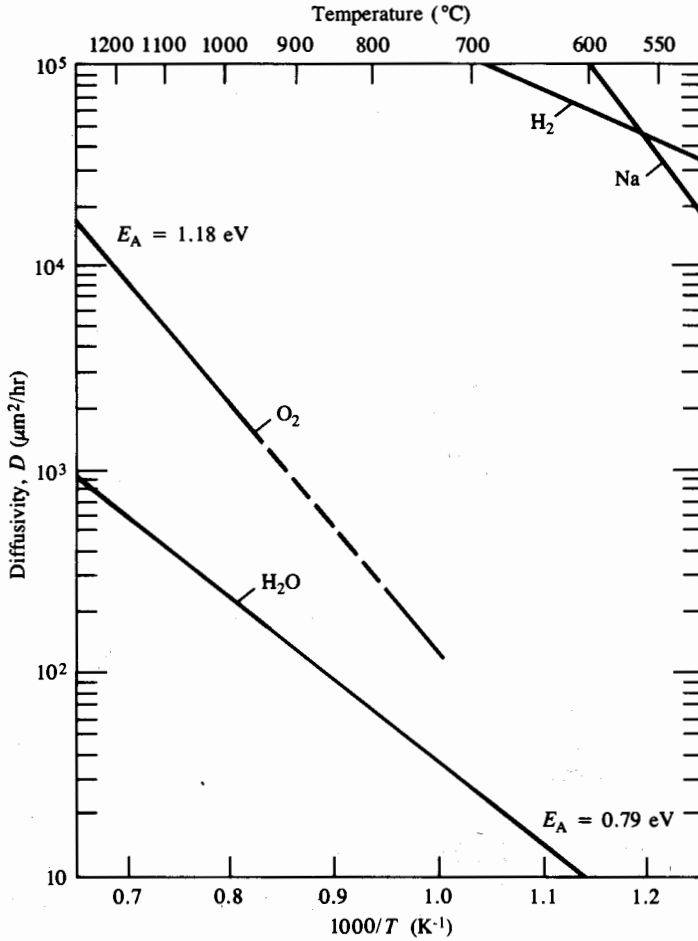


Fig. 3.1 Diffusivities of hydrogen, oxygen, sodium, and water vapor in silicon glass. Copyright John Wiley & Sons, Inc. Reprinted with permission from ref. [2].

3.2 MODELING OXIDATION

In order for oxidation to occur, oxygen must reach the silicon interface. As the oxide grows, oxygen must pass through more and more oxide, and the growth rate decreases as time goes on. A simple model for oxidation can be developed by assuming that oxygen diffuses through the existing oxide layer. *Fick's first law of diffusion* states that the particle flow per unit area, J (called *particle flux*), is directly proportional to the concentration gradient of the particle:

$$J = -D \partial N(x, t) / \partial x \quad (3.3)$$

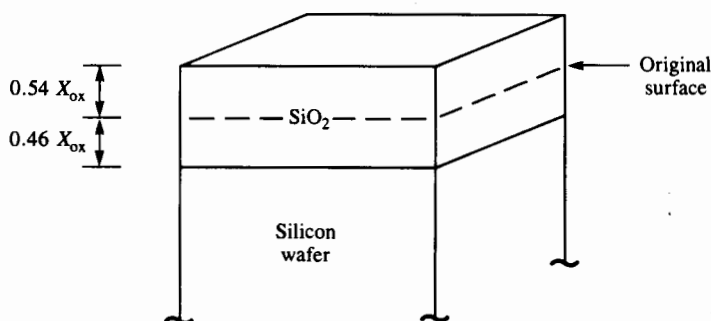


Fig. 3.2 Formation of a silicon dioxide layer on the surface of a silicon wafer consumes silicon during growth of the layer. The oxide expands to fill a region approximately 54% above and 46% below the original surface of the wafer. The exact percentages depend on the density of the oxide.

where D is the diffusion coefficient and N is the particle concentration. The negative sign indicates that particles move from a region of high concentration to a region of low concentration.

For our case of silicon oxidation, we will make the approximation that the oxygen flux passing through the oxide in Fig. 3.3 is constant everywhere in the oxide (oxygen does not accumulate in the oxide). The oxygen flux J is then given by

$$J = -D(N_0 - N_i)/X_0 \quad (\text{number of particles/cm}^2\text{-sec}) \quad (3.4)$$

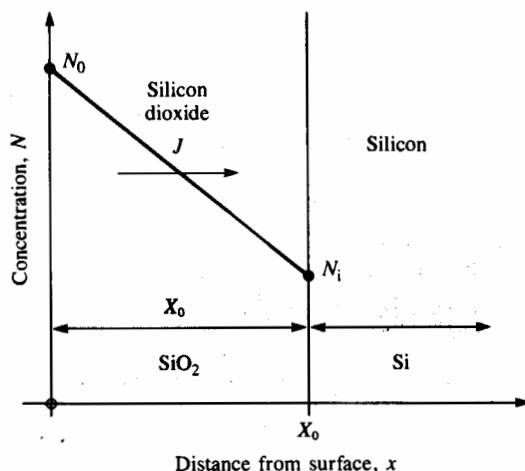


Fig. 3.3 Model for thermal oxidation of silicon. X_0 is the thickness of the silicon dioxide layer at any time t . J is the constant flux of oxygen diffusing through the layer, and N_0 and N_i represent the oxygen concentration at the oxide surface and silicon dioxide-silicon interface, respectively.

where X_0 is the thickness of the oxide at a given time, and N_0 and N_i are the concentrations of the oxidizing species in the oxide at the oxide surface and silicon dioxide-silicon interface, respectively. At the silicon dioxide-silicon interface, we assume that the oxidation rate is proportional to the concentration of the oxidizing species so that the flux at the interface is

$$J = k_s N_i \quad (3.5)$$

where k_s is called the *rate constant* for the reaction at the Si-SiO₂ interface. Eliminating N_i using eqs. (3.4) and (3.5), the flux J becomes

$$J = DN_0/(X_0 + D/k_s) \quad (3.6)$$

The rate of change of thickness of the oxide layer with time is then given by the oxidizing flux divided by the number of molecules M of the oxidizing species that are incorporated into a unit volume of the resulting oxide:

$$dX_0/dt = J/M = (DN_0/M)/(X_0 + D/k_s) \quad (3.7)$$

This differential equation is easily solved using the boundary condition $X_0(t = 0) = X_i$, which yields

$$X_i^2 + AX_i = B\tau$$

or

$$t = X_0^2/B + X_0/(B/A) - \tau \quad (3.8)$$

where $A = 2D/k_s$, $B = 2DN_0/M$, and $\tau = X_i^2/B + X_i/(B/A)$. X_i is the initial thickness of oxide on the wafer. A thin native oxide layer (10 to 20 Å) is always present on silicon due to atmospheric oxidation, or X_i may represent a thicker oxide grown during previous oxidation steps. Solving eq. (3.8) for $X_0(t)$ yields

$$X_0(t) = 0.5A \left[\left\{ 1 + \frac{4B}{A^2}(t + \tau) \right\}^{1/2} - 1 \right] \quad (3.9)$$

For short times with $(t + \tau) \ll A^2/4B$,

$$X_0(t) = (B/A)(t + \tau) \quad (3.10)$$

Oxide growth is proportional to time, and the ratio B/A is called the *linear (growth) rate constant*. In this region, growth rate is limited by the reaction at the silicon interface.

For long times with $(t + \tau) \gg A^2/4B, t \gg \tau$,

$$X_0 = \sqrt{Bt} \quad (3.11)$$

Oxide growth is proportional to the square root of time, and B is called the *parabolic rate constant*. The oxidation rate is diffusion-limited in this region.

3.3 FACTORS INFLUENCING OXIDATION RATE

There is good experimental agreement with this simple theory. Figures 3.4 and 3.5 show experimental data for the parabolic and linear rate constants. The rate-constant data follow straight lines when plotted on a semilogarithmic scale versus reciprocal temperature. This type of behavior occurs in many natural systems and is referred to as an *Arrhenius relationship*. A mathematical model for this behavior is as follows:

$$D = D_0 \exp(-E_A/kT) \quad (3.12)$$

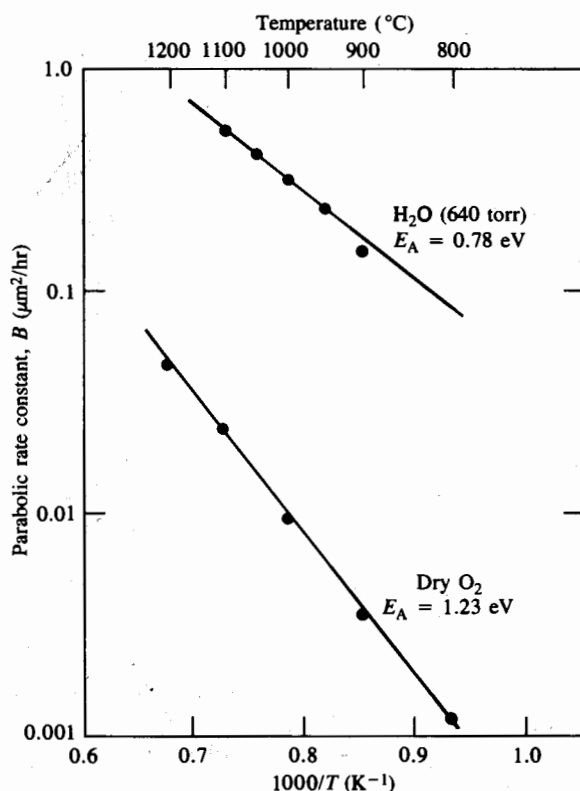


Fig. 3.4 Dependence of the parabolic rate constant B on temperature for the thermal oxidation of silicon in pyrogenic H_2O (640 torr) or dry O_2 . Reprinted by permission of the publisher, The Electrochemical Society, Inc., from ref. [7].

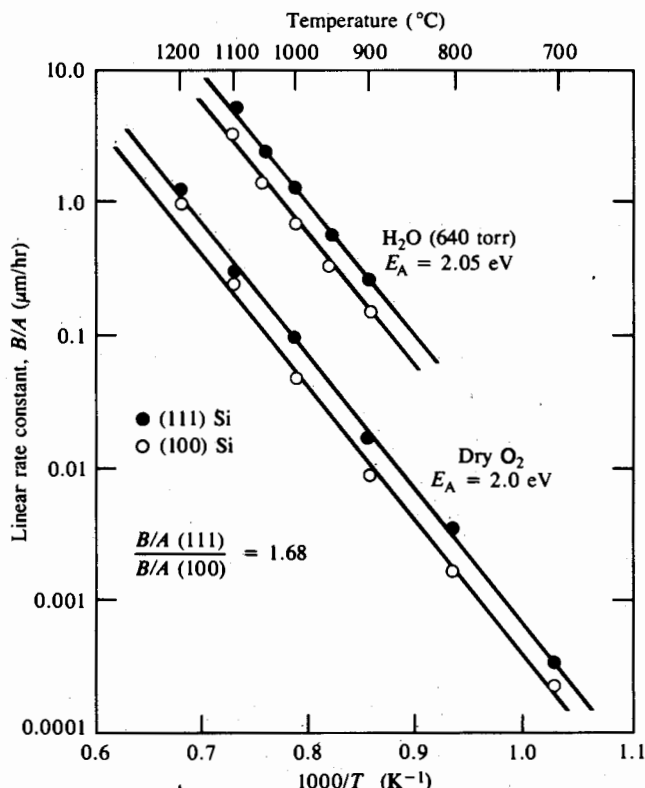


Fig. 3.5 Dependence of the linear rate constant B/A on temperature for the thermal oxidation of silicon in pyrogenic H_2O (640 torr) or dry O_2 . Reprinted by permission of the publisher, The Electrochemical Society, Inc., from ref. [7].

Values for the coefficient D_0 and activation energy E_A for wet and dry oxygen are given in Table 3.1. For wet oxidation, a plot of the experimental data of oxide thickness versus oxidation time is consistent with an initial oxide thickness of approximately zero at $t = 0$. However, a similar plot for dry oxidation yields an initial oxide thickness of 250 Å for temperatures ranging from 800 to 1200 °C. Thus, a nonzero value for τ must be used in eq. (3.8) for dry oxidation calculations. This large value of X_i indicates that our simple oxidation theory is not quite correct, and the reason for this value of X_i is not well understood. Graphs of oxide growth versus time, calculated using the values from Table 3.1, are given in Figs. 3.6 and 3.7.

Eq. (3.12) indicates the strong dependence of oxide growth on temperature. A number of other factors affect the oxidation rate, including wet and dry oxidation, pressure, crystal orientation, and impurity doping. Water vapor has a much higher solubility than oxygen in silicon dioxide, which accounts for the much higher oxide

Table 3.1 Values for Coefficient D_0 and Activation Energy E_A for Wet and Dry Oxygen.*

	Wet O ₂ ($X_i = 0$ nm)		Dry O ₂ ($X_i = 25$ nm)	
	D_0	E_A	D_0	E_A
<100> Silicon				
Linear (B/A)	$9.70 \times 10^7 \mu\text{m/hr}$	2.05 eV	$3.71 \times 10^6 \mu\text{m/hr}$	2.00 eV
Parabolic (B)	$386 \mu\text{m}^2/\text{hr}$	0.78 eV	$772 \mu\text{m}^2/\text{hr}$	1.23 eV
<111> Silicon				
Linear (B/A)	$1.63 \times 10^8 \mu\text{m/hr}$	2.05 eV	$6.23 \times 10^6 \mu\text{m/hr}$	2.00 eV
Parabolic (B)	$386 \mu\text{m}^2/\text{hr}$	0.78 eV	$772 \mu\text{m}^2/\text{hr}$	1.23 eV

*Data from ref. [7].

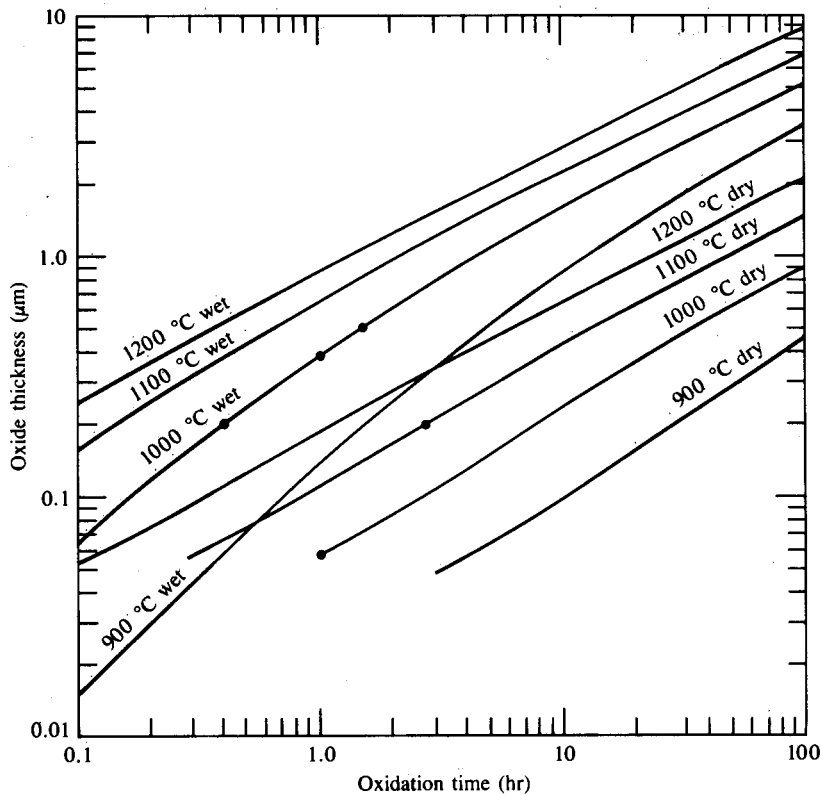


Fig. 3.6 Wet and dry silicon dioxide growth for <100> silicon calculated using the data from Table 3.1.

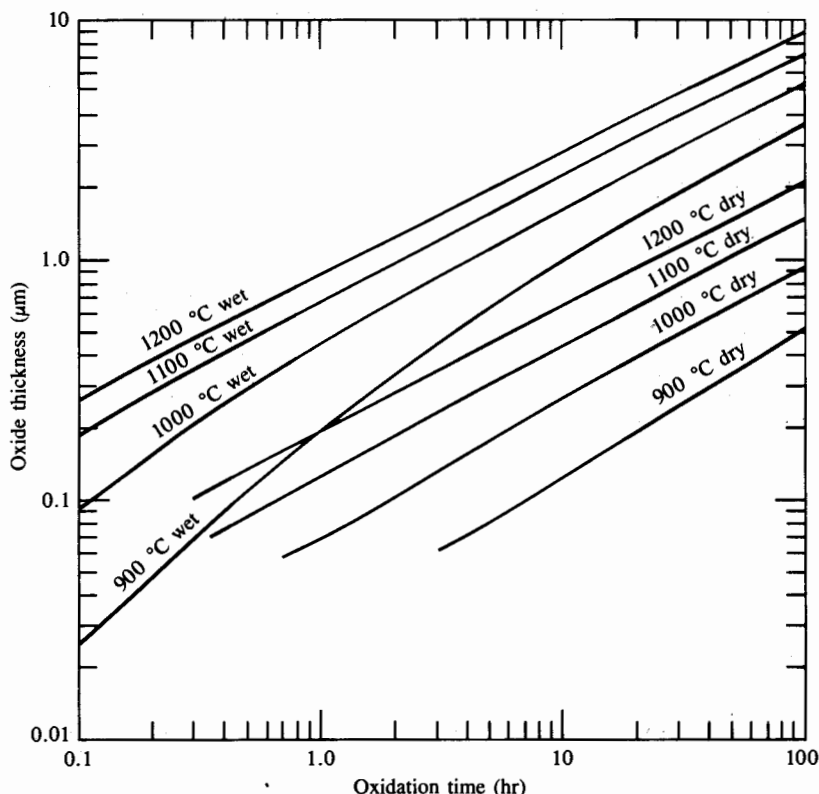


Fig. 3.7 Wet and dry silicon dioxide growth for $\langle 111 \rangle$ silicon calculated using the data from Table 3.1.

growth rate in a wet atmosphere. Slower growth results in a denser, higher-quality oxide and is usually used for MOS gate oxides. More-rapid growth in wet oxygen is used for thicker masking layers.

Eq. (3.8) shows that both the linear and parabolic rate constants are proportional to N_0 . N_0 is proportional to the partial pressure of the oxidizing species, so pressure can be used to control oxide growth rate. There is great interest in developing low-temperature processes for VLSI fabrication. High pressure is being used to increase oxidation rates at low temperatures (see Fig. 3.8). In addition, very thin oxides (50 to 200 Å) are required for VLSI, and low-pressure oxidation is being investigated as a means of achieving controlled growth of thin oxides.

Figures 3.4 through 3.7 also show the dependence of oxidation rate on substrate crystal orientation for the $\langle 111 \rangle$ and $\langle 100 \rangle$ materials most commonly used in bipolar and MOS processes, respectively. The crystal orientation changes the number of silicon

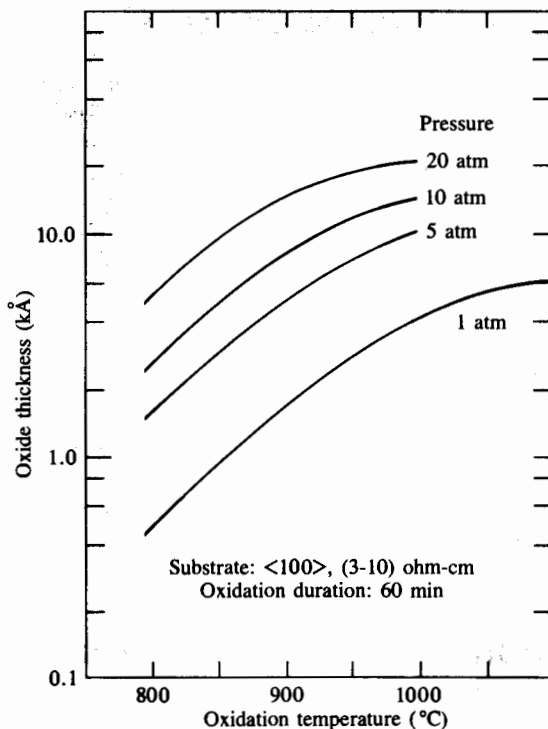


Fig. 3.8 Wet oxide growth at increased pressures. Reprinted with permission of Solid State Technology, published by Technical Publishing, a company of Dun and Bradstreet, from ref. [10].

bonds available at the silicon surface, which influences the oxide growth rate and quality of the silicon-silicon dioxide interface.

Example 3.1: Using Fig. 3.6, a 1-hr oxidation of $\langle 100 \rangle$ silicon at 1000°C in dry oxygen will produce a silicon dioxide film approximately 580 \AA ($0.058 \mu\text{m}$) thick. The same oxidation in wet oxygen will yield a film 3900 \AA ($0.39 \mu\text{m}$) thick.

Example 3.2: A $\langle 100 \rangle$ wafer has a 2000-\AA oxide on its surface. (a) How long did it take to grow this oxide at 1100°C in dry oxygen? (b) The wafer is put back in the furnace in wet oxygen at 1000°C . How long will it take to grow an additional 3000 \AA of oxide? Solve this problem graphically using Fig. 3.6 and 3.7 as appropriate. (c) Repeat part (b) using the oxidation theory presented in eqs. (3.3) through (3.12).

Solution: (a) Using Fig. 3.6, it would take 2.75 hr to grow a $0.2\text{-}\mu\text{m}$ oxide in dry oxygen at 1100°C .

(b) We can solve part (b) graphically using Fig. 3.6. The total oxide at the end of the oxidation would be $0.5 \mu\text{m}$. If there were no oxide on the surface, it would take 1.5 hr to grow $0.5 \mu\text{m}$. However, there is already a $0.2\text{-}\mu\text{m}$ oxide on the surface, and the furnace "thinks" that the wafer has already been in the furnace for 0.4 hr. The time required to grow the additional $0.3 \mu\text{m}$ of oxide is the difference in these two times: $\Delta t = (1.5 - 0.4) \text{ hr} = 1.1 \text{ hr}$.

(c) From Table 3.1, $B = 3.86 \times 10^2 \exp(-0.78/kT) \mu\text{m}^2/\text{hr}$ and $(B/A) = 0.97 \times 10^8 \exp(-2.05/kT) \mu\text{m}/\text{hr}$. Using $T = 1273 \text{ K}$, $B = 0.314 \mu\text{m}^2/\text{hr}$ and $(B/A) = 0.738 \mu\text{m}/\text{hr}$. Using these values and an initial oxide thickness of $0.2 \mu\text{m}$ yields a value of 0.398 hr for the effective initial oxidation time τ . Using τ and a final oxide thickness of $0.5 \mu\text{m}$ yields an oxidation time of 1.08 hr. Note that both the values of t and τ are close to those found in part (b). Of course, our results depend on our ability to interpolate logarithmic scales!

Heavy doping of silicon also changes its oxidation characteristics. Phosphorus doping increases the linear rate constant without altering the parabolic rate constant. Boron doping, on the other hand, increases the parabolic rate constant but has little effect on the linear rate constant. These effects are related to impurity redistribution during oxidation, which is discussed in the next section.

3.4 DOPANT REDISTRIBUTION DURING OXIDATION

During oxidation, the impurity concentration changes in the silicon near the silicon-silicon dioxide interface. Boron and gallium tend to be depleted from the surface, whereas phosphorus, arsenic, and antimony pile up at the surface.

Impurity depletion and pileup depend on both the diffusion coefficient and the *segregation coefficient* of the impurity in the oxide. The segregation coefficient m is equal to the ratio of the equilibrium concentration of the impurity in silicon to that of the impurity in the oxide. Various possibilities are depicted in Fig. 3.9. The value of m for boron is temperature-dependent and is less than 0.3 at normal diffusion temperatures. Boron also diffuses slowly through SiO_2 . Thus, boron is depleted from the silicon surface and remains in the oxide (Fig. 3.9a). The presence of hydrogen during oxide growth or impurity diffusion greatly enhances the diffusion of boron through oxide, resulting in enhanced depletion of boron at the silicon surface (Fig. 3.9b).

The value of m is approximately ten for phosphorus, antimony, and arsenic. These elements are rejected by the oxide, and they diffuse slowly in the oxide, resulting in pileup at the silicon surface (Fig. 3.9c).

Gallium has a segregation coefficient of 20. However, it diffuses very rapidly through silicon dioxide. This combination causes depletion of gallium at the surface, as shown in Fig. 3.9d.

The effects of boron depletion and phosphorus pileup are particularly important in both bipolar and MOS processing. Process design must take both problems into account, and it may be necessary to add or change processing steps to overcome the effects of these phenomena.

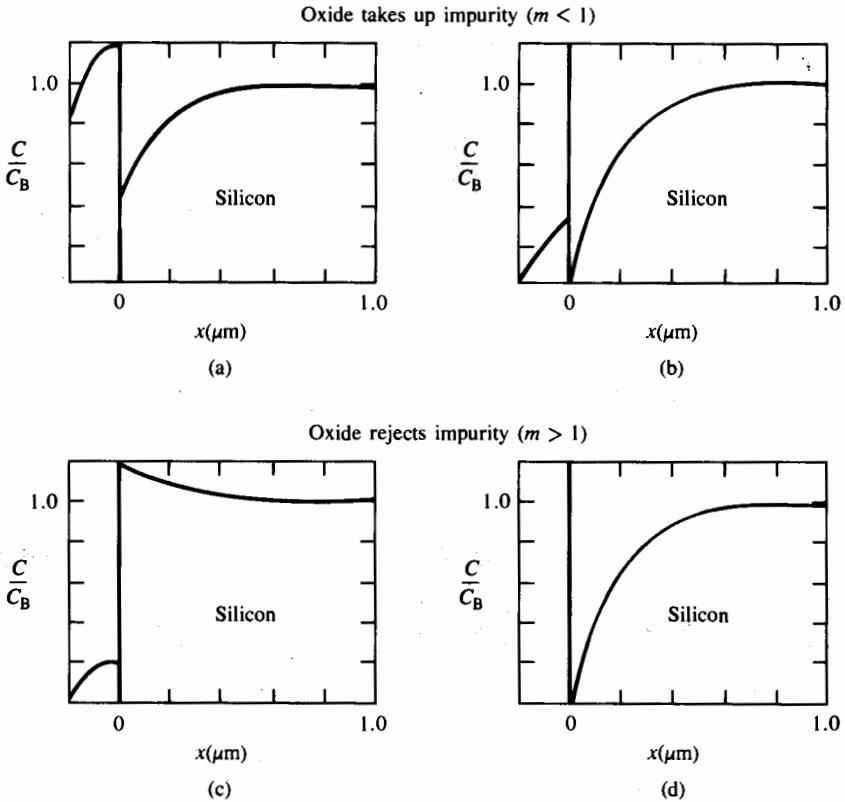


Fig. 3.9 The effects of oxidation on impurity profiles. (a) Slow diffusion in oxide (boron); (b) fast diffusion in oxide (boron with hydrogen ambient); (c) slow diffusion in oxide (phosphorus); (d) fast diffusion in oxide (gallium). Copyright John Wiley & Sons, Inc. Reprinted with permission from ref.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

3.5 MASKING PROPERTIES OF SILICON DIOXIDE

One of the most important properties of silicon dioxide is its ability to mask impurities during high-temperature diffusion. The diffusivities of antimony, arsenic, boron, and phosphorus in silicon dioxide are all orders of magnitude smaller than their corresponding values in silicon. Thus SiO_2 films can be used effectively to mask these elements. Relatively deep diffusion can take place in unprotected regions of silicon, whereas no significant impurity penetration will occur in regions covered by silicon dioxide.

Figure 3.10 gives the SiO_2 thickness required to mask boron and phosphorus diffusions as a function of diffusion time and temperature. Note that silicon dioxide is four to five times more effective in masking boron than in masking phosphorus. Arsenic and antimony diffuse more slowly than phosphorus, so an oxide thick enough to mask

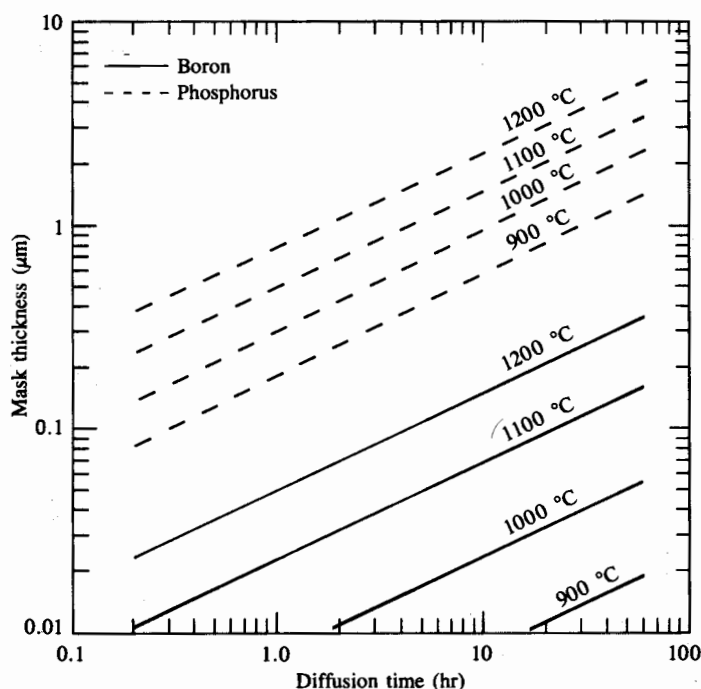


Fig. 3.10 Thickness of silicon dioxide needed to mask boron and phosphorus diffusions as a function of diffusion time and temperature.

phosphorus is also sufficient to mask arsenic and antimony. Masking oxide thicknesses of 0.5 to 1.0 μm are typical in integrated-circuit processes. The masking oxide would be considered to have failed if the impurity level under the mask were to reach a significant fraction (10%) of the background concentration in the silicon.

The graph for boron is valid for an environment which contains no hydrogen! As mentioned earlier, the presence of hydrogen greatly enhances the boron diffusivity. Wet oxidation releases hydrogen, and care must be taken to avoid boron diffusion in the presence of water vapor.

As mentioned in Section 3.4, gallium diffuses rapidly through SiO_2 , as does aluminum, and silicon dioxide cannot be used as a mask for these elements. However, silicon nitride can be used effectively as a mask for these impurities.

3.6 TECHNOLOGY OF OXIDATION

Thermal oxidation of silicon is typically carried out in a high-temperature furnace tube. The tubes may be made of quartz, polycrystalline silicon, or silicon carbide and are

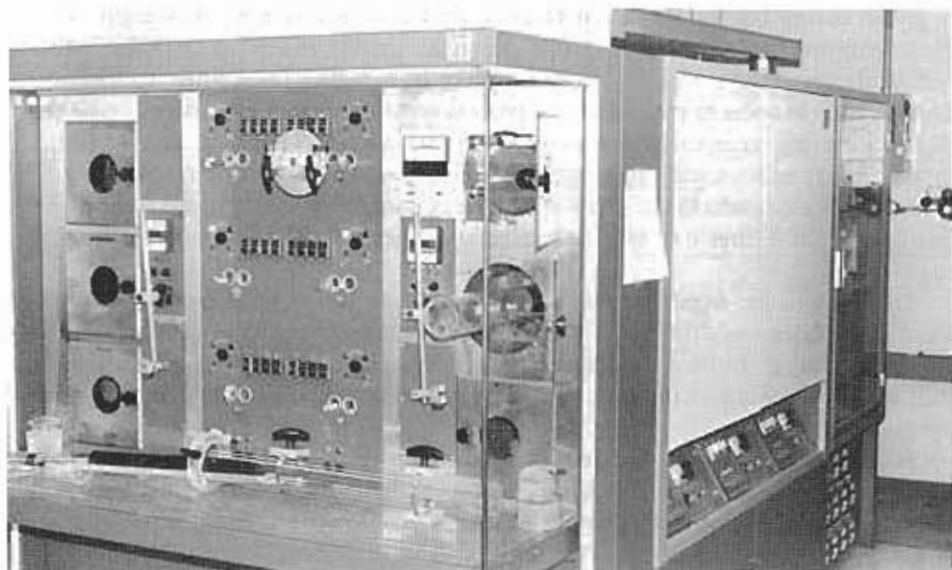


Fig. 3.11 A typical furnace used for oxidation and diffusion. This furnace contains six tubes, each with three-zone temperature control. Gases are supplied under automatic control from the rear of each tube.

specially fabricated to prevent sodium contamination during oxidation. The wafers are placed upright on edge in a quartz boat and pushed slowly into the furnace. The furnace is maintained at a temperature between 800 and 1200 °C. Three-zone resistance-heated furnaces maintain the temperature within a fraction of a degree over a distance of 0.5 m in the center zone. A photograph of a typical six-tube furnace used for oxidation and diffusion appears in Fig. 3.11.

The furnace is continually purged with an inert gas such as nitrogen prior to oxidation. Oxidation begins by introducing the oxidizing species into the furnace in gaseous form. Extremely high-purity oxygen is available and is used for dry oxidation. Water vapor may be introduced by passing oxygen through a bubbler containing deionized water heated to 95 °C. The oxygen serves as a transport gas to carry the water vapor into the furnace. High-purity water vapor can also be obtained by burning hydrogen and oxygen in the furnace tube. Steam is not often used because it tends to pit the silicon surface.

3.7 OXIDE QUALITY

Wet oxidation is used to grow relatively thick oxides used for masking. An oxidation growth cycle usually consists of a sequence of dry/wet/dry oxidations. Most of the oxide

is grown during the wet oxidation phase since the growth rate is much higher in the presence of water. Dry oxidation results in a higher-density oxide than that achieved with wet oxidation. Higher density in turn results in a higher breakdown voltage (5 to 10 MV/cm). In order to maintain good process control, the thin gate oxides ($<1000 \text{ \AA}$) of MOS devices are usually formed using dry oxidation.

MOS devices are usually fabricated on wafers having a $\langle 100 \rangle$ surface orientation. The $\langle 100 \rangle$ orientation results in the smallest number of unsatisfied silicon bonds at the Si-SiO₂ interface, and the choice of the $\langle 100 \rangle$ orientation yields the lowest number of interface traps.*

Sodium ions are highly mobile in SiO₂ films (see Fig. 3.1), and contamination of MOS gate oxides was a difficult problem to overcome in the early days of the integrated-circuit industry.* Bipolar devices are much more tolerant of oxide contamination than MOS devices, and this was a primary factor in the early dominance of bipolar integrated circuits.

Sodium-ion contamination results in mobile positive charge in the oxide. In addition, a substantial level of positive fixed oxide exists at the Si-SiO₂ interface.* These charge centers attract electrons to the surface of MOS transistors, resulting in a negative shift in the threshold voltage of the MOS devices. NMOS devices become depletion-mode devices. PMOS devices remain enhancement-mode devices but have more negative threshold voltages. The first successful MOS processes were therefore PMOS processes. As the industry was able to improve overall oxide quality, NMOS processes became dominant because of the mobility advantage of electrons over holes.

It was discovered that the effects of sodium contamination can be greatly reduced by adding chlorine during oxidation. Chlorine is incorporated into the oxide and immobilizes the sodium ions. A small amount (6% or less) of anhydrous HCl can be added to the oxidizing gas. Gaseous chlorine, oxygen, or nitrogen can also be bubbled through trichloroethylene (C₂HCl₃). It should also be noted that the presence of chlorine during dry oxidation results in an increase in both the linear and parabolic rate constants.

3.8 SELECTIVE OXIDATION

The oxidation processes described above generally form an oxide film over the complete surface of the silicon wafer. The ability to selectively oxidize the silicon surface has become very important in high-density bipolar and MOS processes. Selective oxidation processes result in improved device packing density and more planar final structures.

Oxygen and water vapor do not diffuse well through silicon nitride. Figure 3.12 shows an MOS process using selective oxidation in which silicon nitride is used as an oxidation mask. A thin layer (10 to 20 nm) of silicon dioxide is first grown on the wafer to protect the silicon surface. Next, a layer of silicon nitride is deposited over the surface and patterned using photolithography. The wafer then goes through a thermal oxidation

*See Volume IV in the Modular Series on Solid State Devices, *Field Effect Devices*, Section 4.2, for an excellent discussion of oxide quality.

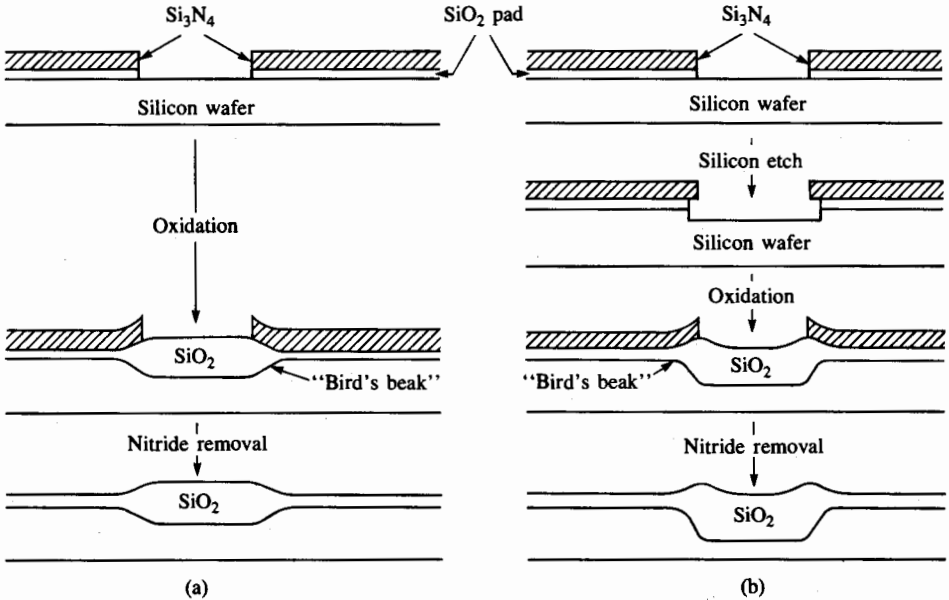


Fig. 3.12 Cross section depicting process sequence for (a) semirecessed and (b) fully recessed oxidations of silicon.

step. Oxide grows wherever the wafer is not protected by silicon nitride. This process results in the so-called *semirecessed oxide structure*.

Some oxide growth occurs under the edges of the nitride and causes the nitride to bend up at the edges of the masked area. The penetration of the oxide underneath the nitride results in a "bird's beak" structure. Formation of the bird's beak in Fig. 3.12 leads to loss of geometry control in VLSI structures, so minimization of the bird's beak phenomenon is an important goal in VLSI process design.

A *fully recessed oxide* can be formed by etching the silicon prior to oxidation. This process can yield a very planar surface after the removal of the nitride mask. Subsequent processing reduces the advantage of this process over the semirecessed version, and most processes today use some form of semirecessed oxidation.

3.9 OXIDE THICKNESS CHARACTERIZATION

One of the simplest methods for determining the thickness of an oxide is to compare the color of the wafer with the reference color chart in Table 3.2. When a wafer is illuminated with white light perpendicular to the surface, the light penetrates the oxide film and is reflected by the underlying silicon wafer. Constructive interference causes enhancement of a certain wavelength in the reflected light, and the color of the wafer corresponds to the enhanced wavelength. Constructive interference occurs when the

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		
0.15	Light blue to metallic blue	0.58	Light orange or yellow to pink borderline
0.17	Metallic to very light yellow green	0.60	Carnation pink
0.20	Light gold or yellow; slightly metallic	0.63	Violet red
0.22	Gold with slight yellow orange	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)
0.25	Orange to melon		
0.27	Red violet	0.72	Blue green to green (quite broad)
0.30	Blue to violet blue	0.77	"Yellowish"
0.31	Blue	0.80	Orange (rather broad for orange)
0.32	Blue to blue green	0.82	Salmon
0.34	Light green	0.85	Dull, light red violet
0.35	Green to yellow green	0.86	Violet
0.36	Yellow green	0.87	Blue violet
0.37	Green yellow	0.89	Blue
0.39	Yellow	0.92	Blue green
0.41	Light orange	0.95	Dull yellow green
0.42	Carnation pink	0.97	Yellow to "yellowish"
0.44	Violet red	0.99	Orange
0.46	Red violet	1.00	Carnation pink
0.47	Violet		
0.48	Blue violet		
0.49	Blue		
0.50	Blue green		
0.52	Green (broad)		

Table 3.2 (continued)

Film Thickness (μm)	Color and Comments	Film Thickness (μm)	Color and Comments
1.02	Violet red	1.24	Carnation pink to salmon
1.05	Red violet	1.25	Orange
1.06	Violet	1.28	"Yellowish"
1.07	Blue violet	1.32	Sky blue to green blue
1.10	Green	1.40	Orange
1.11	Yellow green	1.45	Violet
1.12	Green	1.46	Blue violet
1.18	Violet	1.50	Blue
1.19	Red violet	1.54	Dull yellow green
1.21	Violet red		

path length in the oxide ($2X_0$) is equal to an even multiple of one wavelength of light in the oxide.

$$2X_0 = k\lambda/n \quad (3.13)$$

where the number k is any integer greater than zero, and n is the refractive index of the oxide ($n = 1.46$ for SiO_2).

As an example, a wafer with a 5000-Å silicon dioxide layer will appear blue green. Color-chart comparisons are quite subjective, and the colors vary periodically with thickness. In addition, care must be exercised to determine the color from a position perpendicular to the wafer. The color chart (Table 3.2) is only valid for vertical illumination with fluorescent light.

Accurate thickness measurement can be achieved with an instrument called an *ellipsometer*, and this instrument is often used to make an accurate reference color chart. Polarized monochromatic light is used to illuminate the wafer at an angle to the surface. Light is reflected from both the oxide and silicon surfaces. The differences in polarization are measured, and the oxide thickness can then be calculated.^[15]

A mechanical surface profiler can also be used to measure film thickness. The oxide is partially etched from the surface of a test wafer to expose a step between the wafer and oxide surfaces. A stylus is mechanically scanned over the surface of the wafer, and thickness variations are recorded on a strip-chart recorder. Films ranging from less than 0.01 μm to more than 5 μm can be measured with this instrument.

Accurate film thickness measurements can also be achieved using light-interference effects in microscopy, and automated interference-based equipment is commercially available for thin-film characterization.

3.10 SUMMARY

Silicon dioxide provides a high-quality insulating barrier on the surface of the silicon wafer. In addition, this layer can serve as a barrier layer during subsequent impurity-diffusion process steps. These two factors have allowed silicon to become the dominant semiconductor material in use today.

A native oxide layer several tens of angstroms thick forms on the surface of silicon immediately upon exposure to oxygen even at room temperature. The thickness of this oxide layer may be readily measured from the accumulation-region capacitance of a MOS test capacitor. Thicker layers of silicon dioxide are conveniently grown in high-temperature oxidation furnaces using both wet and dry oxygen. Oxidation occurs much more rapidly in wet oxygen than in dry oxygen. However, the dry-oxygen environment produces a higher-quality oxide and is usually used for the growth of MOS gate oxides. Oxide cleanliness is extremely important for MOS processes, and great care is exercised to prevent sodium contamination of the oxide. The addition of chlorine during oxidation improves oxide quality. Finally, oxidation alters the impurity distribution at the surface of the silicon wafer. Boron tends to be depleted from the silicon surface, whereas phosphorus tends to pile up at the silicon surface.

Oxidation thickness can be accurately measured using ellipsometers, interference microscopes, and mechanical surface profilers or can be estimated from the apparent color of the oxide under vertical illumination with white light.

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PROBLEMS

- 3.1 How long does it take to grow 100 nm of oxide in wet oxygen at 1000 °C (assume $\langle 100 \rangle$ silicon)? In dry oxygen? Which process would be preferred?
- 3.2 A 1.2- μm silicon dioxide film is grown on a $\langle 100 \rangle$ silicon wafer in wet oxygen at 1100 °C. How long does it take to grow the first 0.4 μm ? The second 0.4 μm ? The final 0.4 μm ?
- 3.3 Derive eq. (3.8) by solving differential eq. (3.7).
- 3.4 How much oxide is needed to mask a 4-hr boron diffusion at 1150 °C? A 1-hr phosphorus diffusion at 1050 °C?
- 3.5 A square window is etched through 200 nm of oxide prior to a second oxidation as in Example 3.2. The second oxidation grows 300 nm of oxide in the thick oxide region. Make a scale drawing of the cross section of the wafer after the second oxidation. What are the colors of the various regions under vertical illumination by white light?
- 3.6 Write a computer program to calculate the linear and parabolic rate constants for wet and dry oxidation for temperatures of 950, 1000, 1050, 1100, 1150, and 1200 °C. Assume $\langle 100 \rangle$ silicon.
- 3.7 A $\langle 100 \rangle$ silicon wafer has 400 nm of oxide on its surface. How long will it take to grow an additional 1 μm of oxide in wet oxygen at 1100 °C? Compare graphical and mathematical results. What is the color of the final oxide under vertical illumination by white light?
- 3.8 Yellow light has a wavelength of approximately 0.57 μm . Calculate the thicknesses of silicon dioxide which will appear yellow under vertical illumination by white light. Consider oxide thicknesses less than 1.5 μm . Compare with the color chart (Table 3.2).
- 3.9 Write a computer program to calculate the time required to grow a given thickness of oxide based on the theory of Section 3.2. The user should be able to specify desired oxide thickness, wet or dry oxidation conditions, temperature, and orientation of the silicon wafer.