Ideal Scaling of MOSFET

Gate length ($L_g$) $\rightarrow 1/K$
Gate width ($L_w$) $\rightarrow 1/K$
Gate oxide thickness ($T_{ox}$) $\rightarrow 1/K$
Junction depth ($D$) $\rightarrow 1/K$
Threshold voltage ($V_{th}$) $\rightarrow 1/K$

Grow Dielectric Layers on Semiconductors

Oxide: easy to grow, insulating (SiO$_2$ band gap $\sim$8 eV), mask for diffusion, etch

Nitride: Si$_3$N$_4$, insulating, membrane, mask for selective oxidation

Oxinitride: Si$_x$O$_y$N$_z$ increase dielectric constant, prevent boron penetration

High k materials: ZrO$_2$, HfO$_2$, low leakage at same thickness $C \propto \varepsilon / t_{ox}$

- compatible with CVD poly Si
- thermal stability up to 1000 °C
- low interface state density
- low diffusivity of B and P
- high breakdown voltage
- chemical stability on Si
- can be etched
- low ionic impurity

Ref: Campbell: 4.8
Crystal Structure of Quartz

- SiO$_4$ tetrahedra
- 2.27 Å
- 1.62 Å
Silica Glass

Density: 2.65 g/cm$^3$

- Softening point: 1665 °C
- Porous- diffusive $D = D_0 e^{-E_A/kt}$

Dry oxidation $Si + O_2 \rightarrow SiO_2$

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

Ref: Campbell: 4.4
**Kinetics of Oxide Growth- Deal-Grove Model**

O₂ diffuses from gas flow to sample surface

\[
J = D \left( \frac{C_o - C_i}{x} \right) \\
J = kC_i
\]

\[
\frac{dx}{dt} = \frac{j}{n} = \frac{DC_0/n}{x + D/k} \\
\rightarrow x^2 + \frac{2D}{k}x = \frac{2DC_0}{n}t
\]

At 1000 °C, 1 atm

O₂ solubility in SiO₂: \(5.2 \times 10^{16}\) cm\(^{-3}\)

H₂O solubility in SiO₂: \(3 \times 10^{19}\) cm\(^{-3}\)

Ref: Campbell: 4.1
Initial Oxidation Rate Enhancement

• Deal-Grove Model works well for dry oxidation > 300 Å

\[ \lim_{t \to 0} \frac{dx}{dt} = \frac{B}{A} \]

• Deal-Grove Model works well for wet oxidation.

Diffusion of defects such as O vacancies from Si-SiO₂ interface to the surface.

Ref: Campbell: 4.3
• $E_A$ of linear region is close to the energy required to break Si-Si bonds (1.83 eV).

• $E_A$ of parabolic region is close to that of $O_2$ (1.18 eV) and $H_2O$ (0.78 eV) diffusion in silica.

• The parabolic growth rate is independent of crystal orientation during oxidation.

• The linear growth rate is related to the rate of incorporation of Si atoms into the silica network, so it is a function of the atom concentration on the Si surface.

$$\sigma_{100} = 6.78 \times 10^{14} \text{ cm}^{-2} \quad \sigma_{111} = 7.83 \times 10^{14} \text{ cm}^{-2} \quad \sigma_{111}/\sigma_{100} = 1.15$$
Oxide Growth

- Freshly cleaved Si grows 15-20Å of oxide in air at RT and gradually to 40 Å.
- For every micron of SiO₂ grown, 0.44 µm of Si is consumed– 2.27 x volume expansion of the consumed layer upon oxidation. \( \frac{1}{0.44} = 2.27 \)
- The oxidizing species must diffuse through the growing oxide layer to reach Si surface. The diffusion-controlled regime is observed for layers > 40 Å for dry oxidation and 1000 Å for wet oxidation.
- Wet oxidation processes are quite rapid but result in relatively porous silica films.
- Dry oxidation leads to denser and relatively low concentration of traps and interface states.
- Heavily doped Si oxidizes at a faster rate than lightly doped material.

P doping, dry oxidation, 900 °C

P piles up at Si-SiO₂ interface, increasing the linear rate but not parabolic rate.

B prefers to be incorporated in silica, weakening the bonds in silica and enhance oxidant diffusion – increasing parabolic rate but not linear rate.
Dopant Segregation

Segregation coefficient:

\[ m = \frac{\text{Concentration of impurity in Si}}{\text{Concentration of impurity in SiO}_2} \]

Ref: Campbell: 4.6

Case 1: Oxide takes up impurity (m < 1)

Case 2: Oxide rejects impurity (m > 1)

\[ m_{100} \approx 33e^{-0.52/kT} \]
\[ m_{111} \approx 20e^{-0.52/kT} \]
Growth or Etch?

\[ 2Si(s) + O_2(g) \rightarrow 2SiO(g) \]

Oxide Thickness Measurement

SEM (scanning electron microscope): need to look at Si-SiO₂ cross-section. Oxide is brighter than conducting Si. Resolution and sample size is SEM specific. ~10 nm and 1” for NDL SEM.

AFM (atomic force microscope): need to etch oxide off to measure at the Si-SiO₂ boundary. Resolution < 1nm but field of view is <100 µm for most AFM.

Nanospec: use the interference of the reflection of a monochromatic light between air/SiO₂ and SiO₂/Si to get a maximum \( d = m\lambda_1/2n \) or a minimum \( d = (m + \frac{1}{2})\lambda_2/2n \). The measured thickness range can be 10-4000 nm and localized in a diameter of 35 µm.

Ellipsometry: If linearly polarized light of a known orientation is reflected at oblique incidence from a surface then the reflected light is elliptically polarized. The shape and orientation of the ellipse depend on the angle of incidence, the direction of the polarization of the incident light, and the reflection properties of the surface. By measuring the relative phase change and amplitude change of the reflected wave, optical properties of the thin film and thickness can be deduced. With microattachment an ellipsometer can also measure localized area ~100 µm.