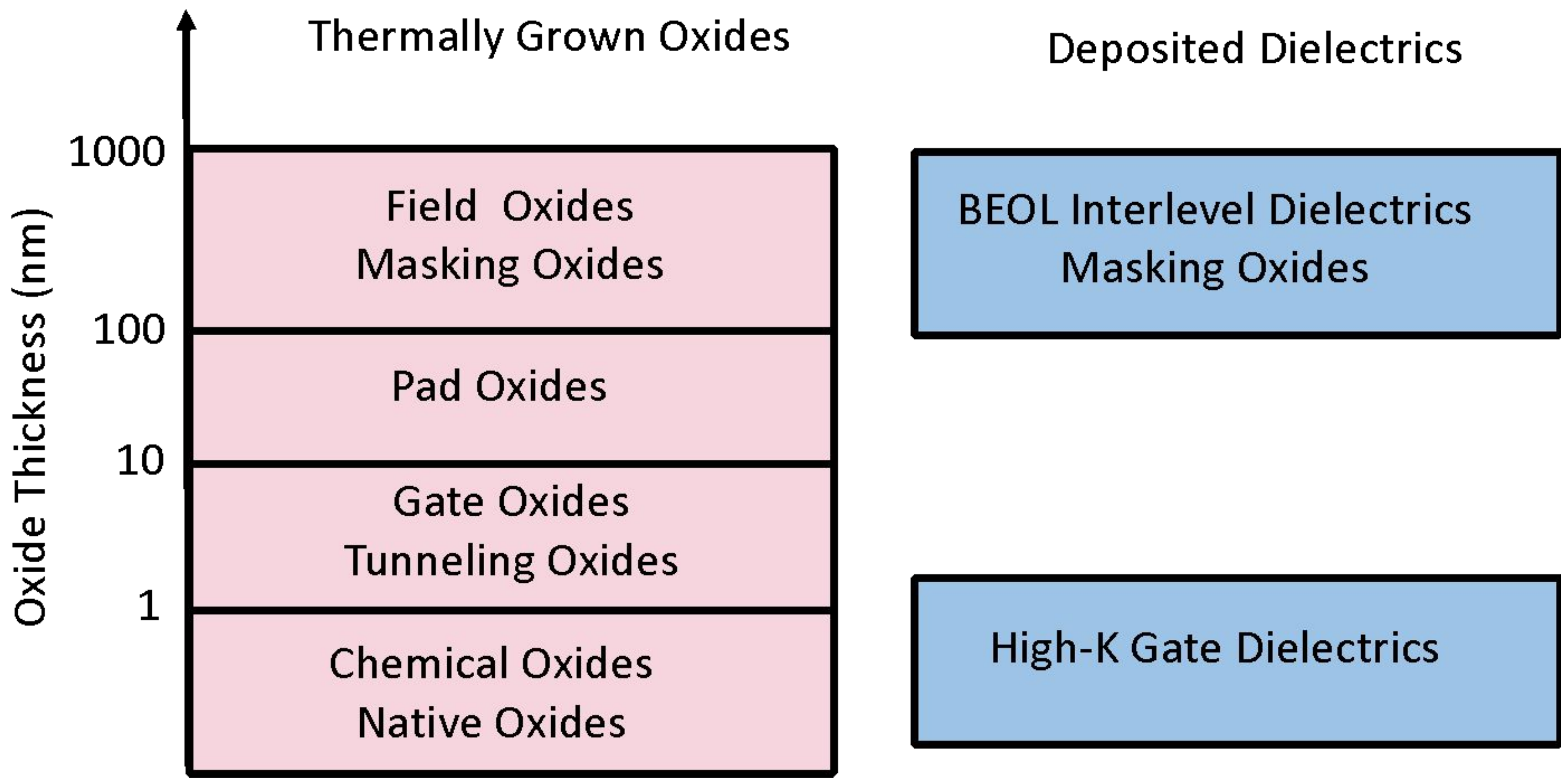
Silicon Dioxide – Growth & Characterization

KEY CONCLUSIONS

Silicon Dioxide

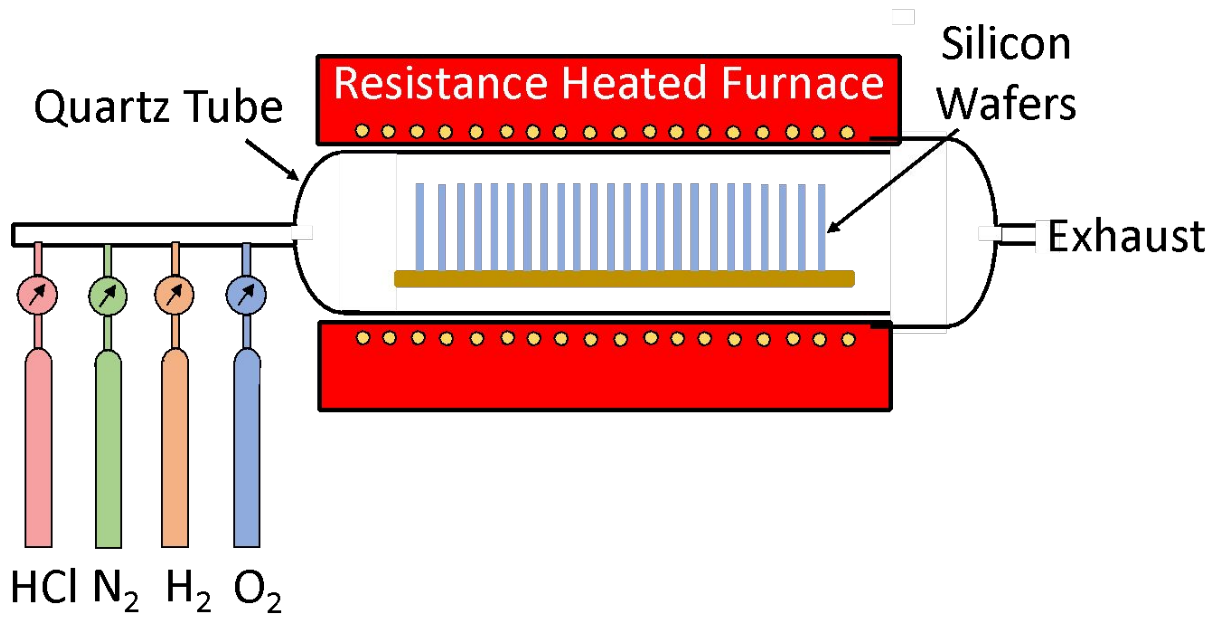


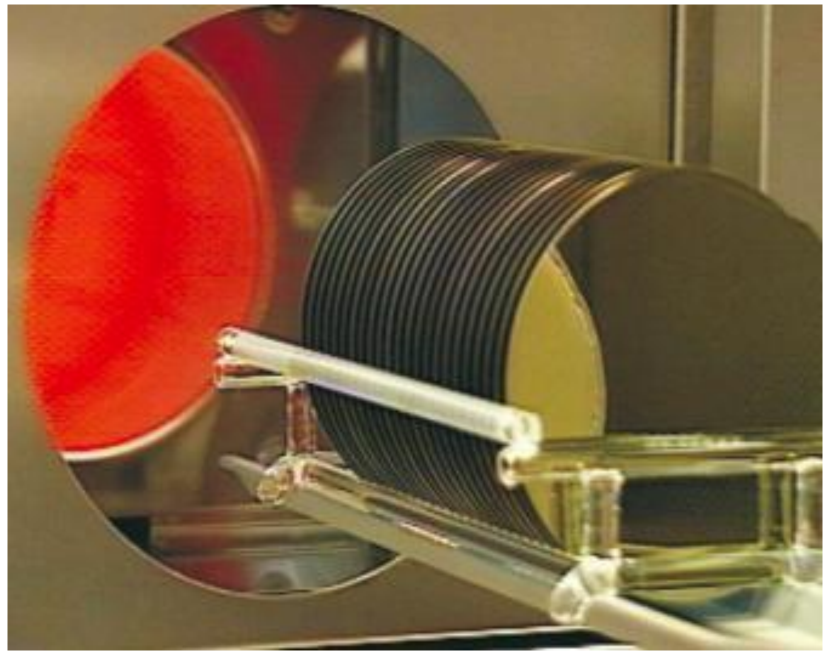
SiO_2:

- Easily selectively etched using lithography.
- Masks most common impurities (B, P, As, Sb).
    - Excellent insulator ($r > 10^{16}$ W cm, $E_g > 9$ eV).
    - High breakdown field (10^7 V/cm)
    - Excellent junction passivation.
    - Stable bulk electrical properties.
- Stable and reproducible interface with Si.

- SiO_2 and the Si/SiO_2 interface are the principal reasons for silicon's dominance in the IC industry.
- No other known semiconductor/insulator combination has properties that match the Si/SiO_2 interface.
- However high-K materials have recently been successfully introduced into manufacturing.

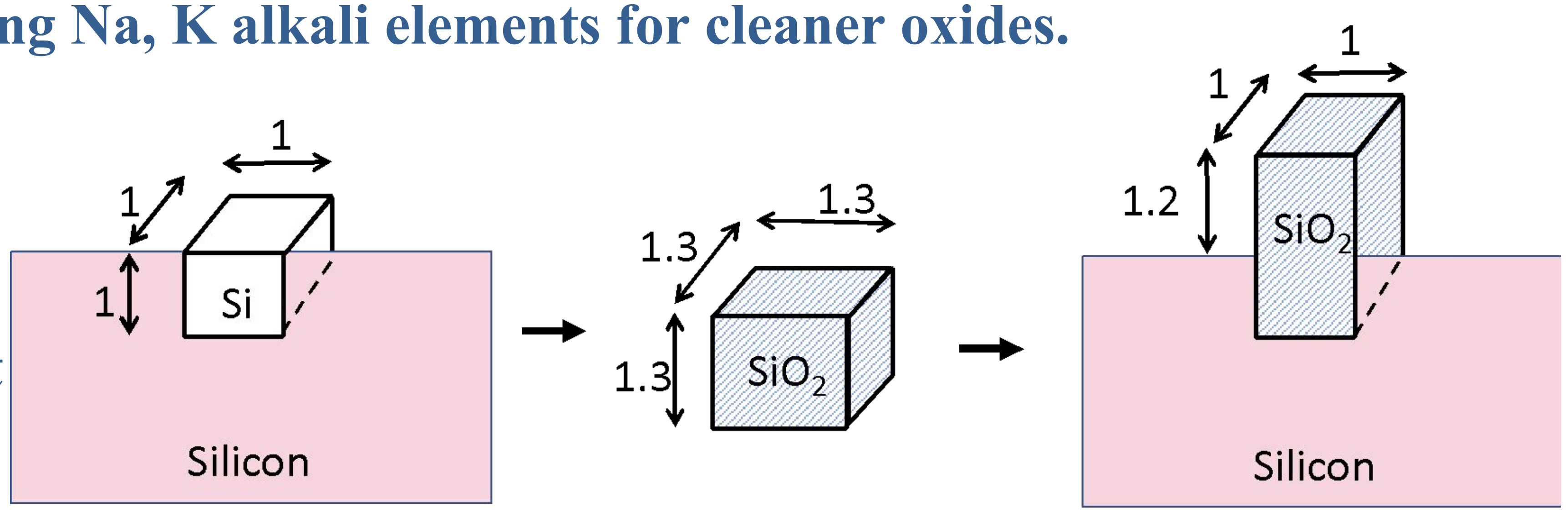
Oxidation



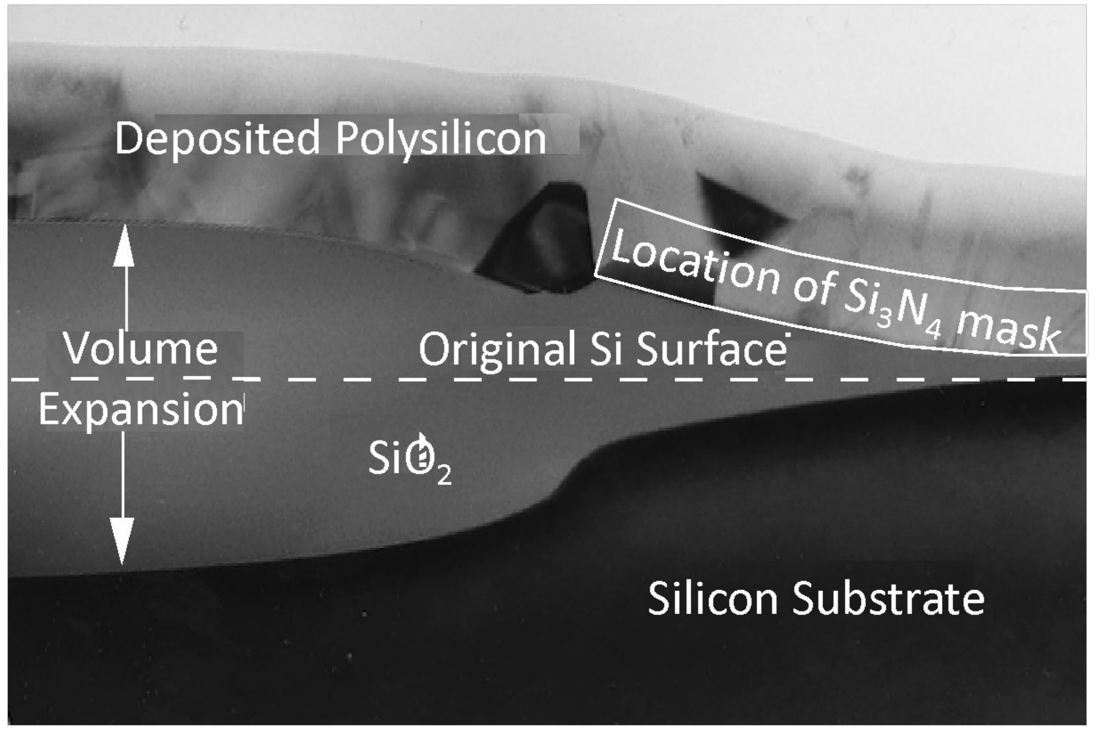


- Dry oxidation is O_2 oxidation.
- Wet oxidation uses $H_2 + O_2$ ignited in back end of furnace.
- Cl can help with gettering Na, K alkali elements for cleaner oxides.

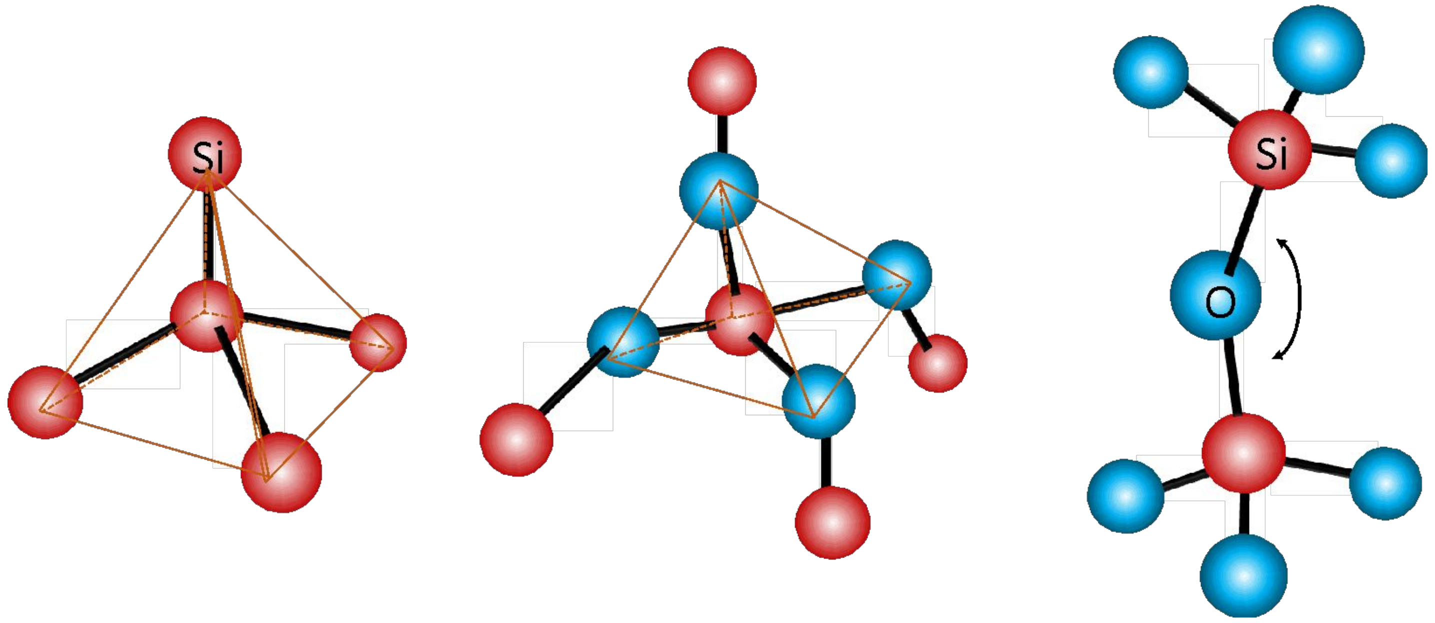
- Oxidation involves a volume expansion (≈ 2.2X).
- Especially in 2D and 3D structures, stress effects play a dominant role.



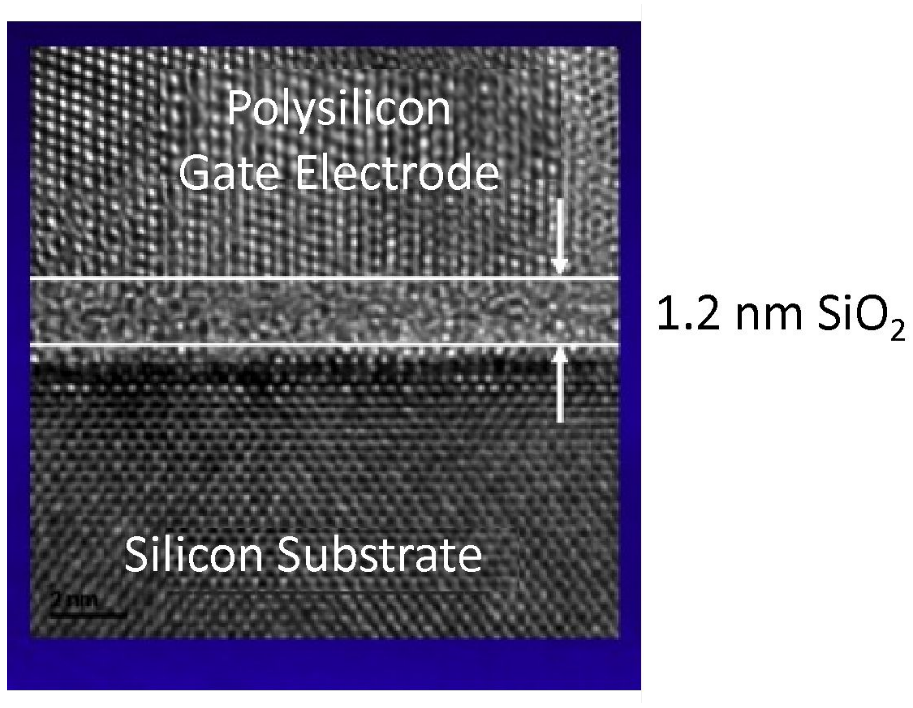
Oxidation Contd..



- LOCOS



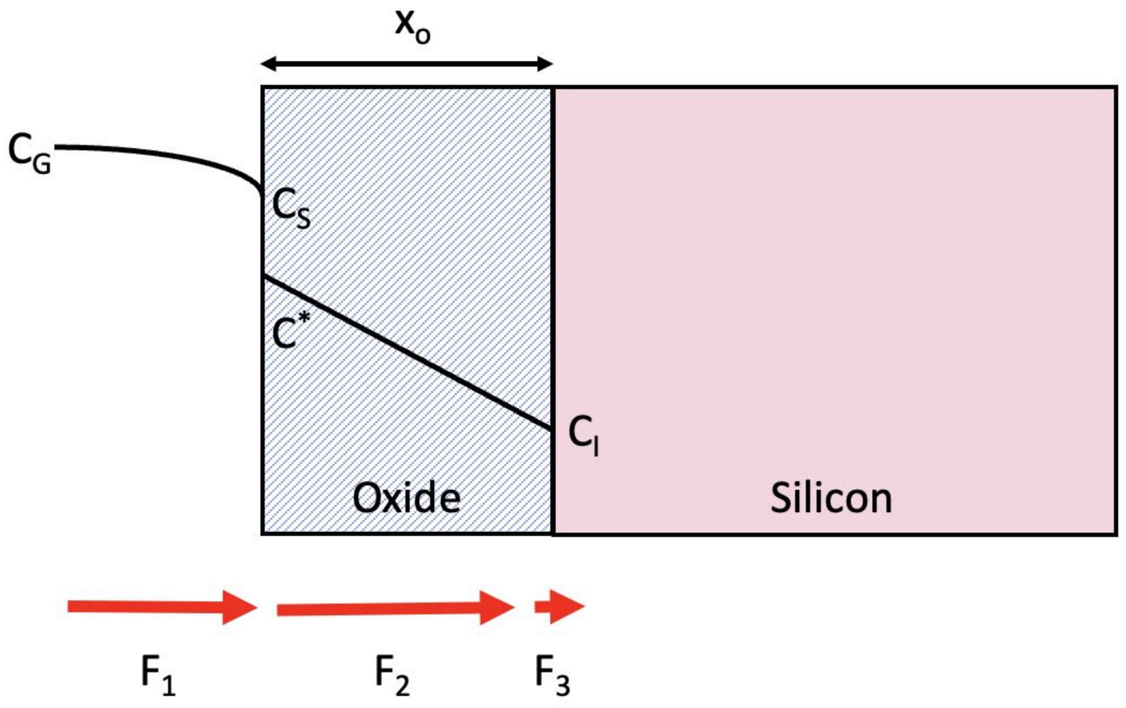
- SiO_2 is amorphous even though it grows on a crystalline substrate.



- Basic structure of SiO_4 tetrahedra that are the basic building block of SiO_2.
- At the Si/SiO_2 interface there are a few defects (broken bonds, strained bonds etc.).

Deal Grove Model

- The basic model for oxidation was developed in 1965 by Deal and Grove.



$$\mathrm{Si} + O_2 \rightarrow \mathrm{Si}O_2 \qquad (1)$$

$$\mathrm{Si} + 2H_2\mathrm{O} \rightarrow \mathrm{Si}O_2 + 2H_2 \qquad (2)$$

- Many experiments have shown that F_1 is not rate limiting. It can be neglected

$$F_2 = -D\frac{dC}{dx} = D\left(\frac{C^* - C_i}{x_0}\right) \qquad (3)$$

$$F_3 = k_s C_i \qquad (4)$$

Under steady state conditions, $F_2 = F_3$

Deal Grove model Contd..

$$D\left(\frac{C^* - C_i}{x_0}\right) = k_s C_i \qquad (5)$$

$$C_i = \frac{C^*}{k_s \frac{x_0}{D} + 1} \qquad (6)$$

- The growth rate is F_3/N_1

$$\frac{dx_0}{dt} = \frac{F_3}{N_1} = \frac{k_s C^*/N_1}{k_s\, x_0/D + 1} \qquad (7)$$

$$\frac{dx_0}{dt} = \frac{B}{2x_0 + A} \qquad (8)$$

where $B/A = k_s C^*/N_1$

$B = 2DC^*/N_1$

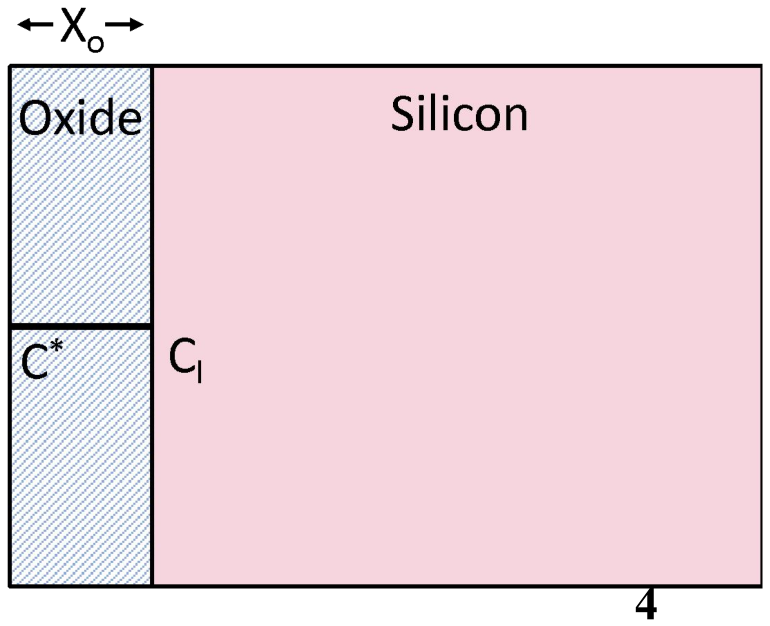
- Integrating

$$\frac{x_0^2}{B} + \frac{x_0}{B/A} = t + \tau \quad \text{where} \quad \tau = \frac{x_i^2}{B} + \frac{x_i}{B/A} \qquad (9)$$

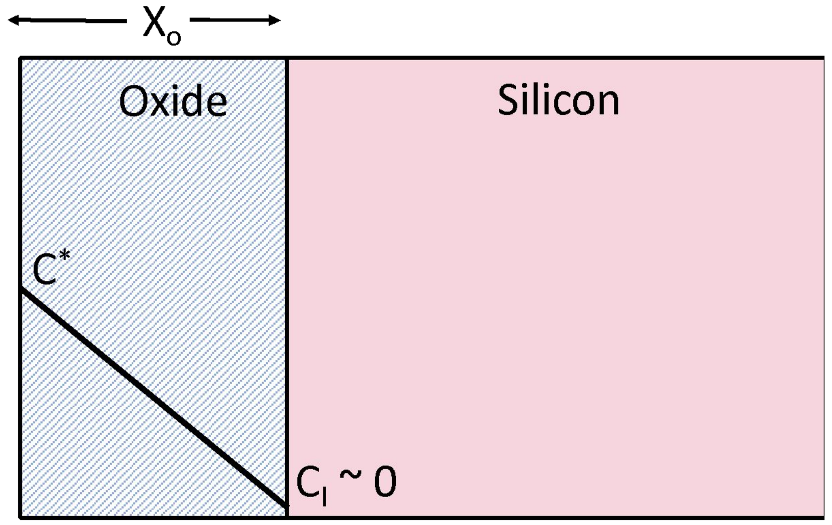
$$x_0 = \frac{A}{2}\left\{\sqrt{1 + \frac{t + \tau}{A^2/4B}} - 1\right\} \qquad (10)$$

Deal Grove Model Contd..

- **Two Limiting Conditions**

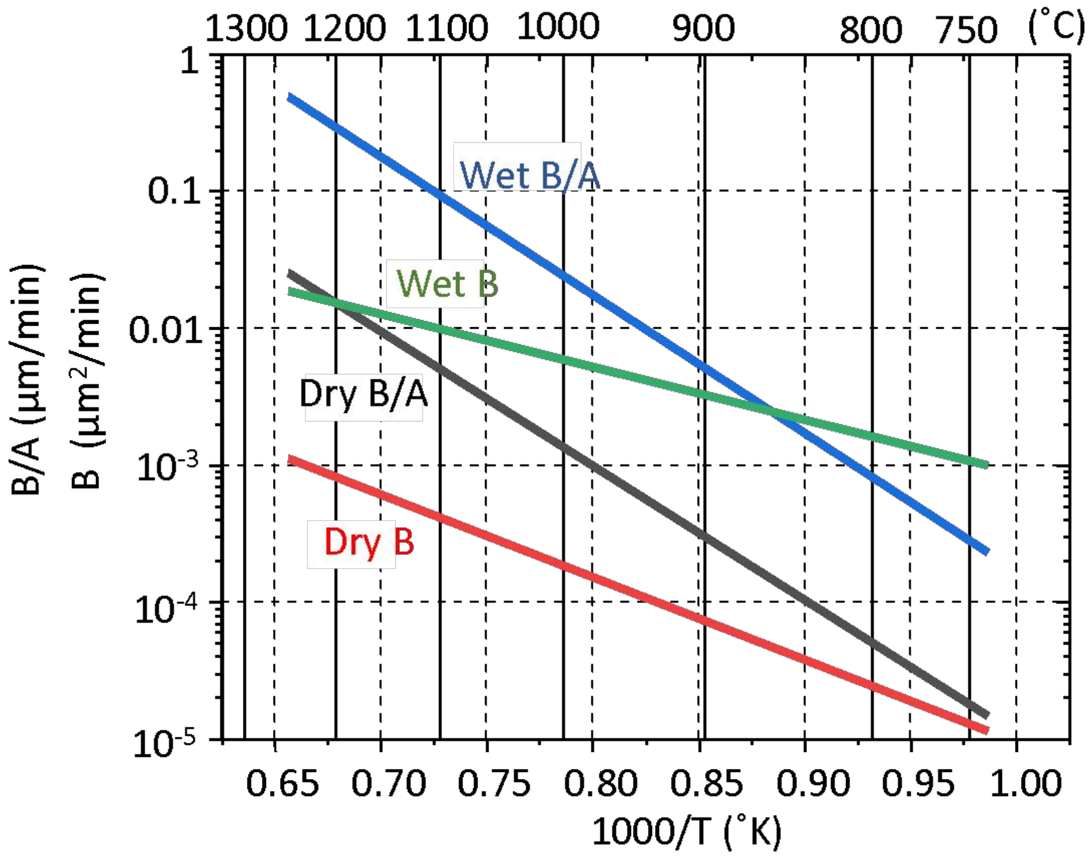


$$x_0 = B/A\ (t + \tau)$$



$$x_0^2 = B\ (t + \tau)$$

- **For thin oxides, growth is limited by chemistry at the Si/SiO_2 interface. Growth is linear with time.**
- **For thick oxides growth is limited by oxidant diffusion. Growth is parabolic with time.**



Ambient

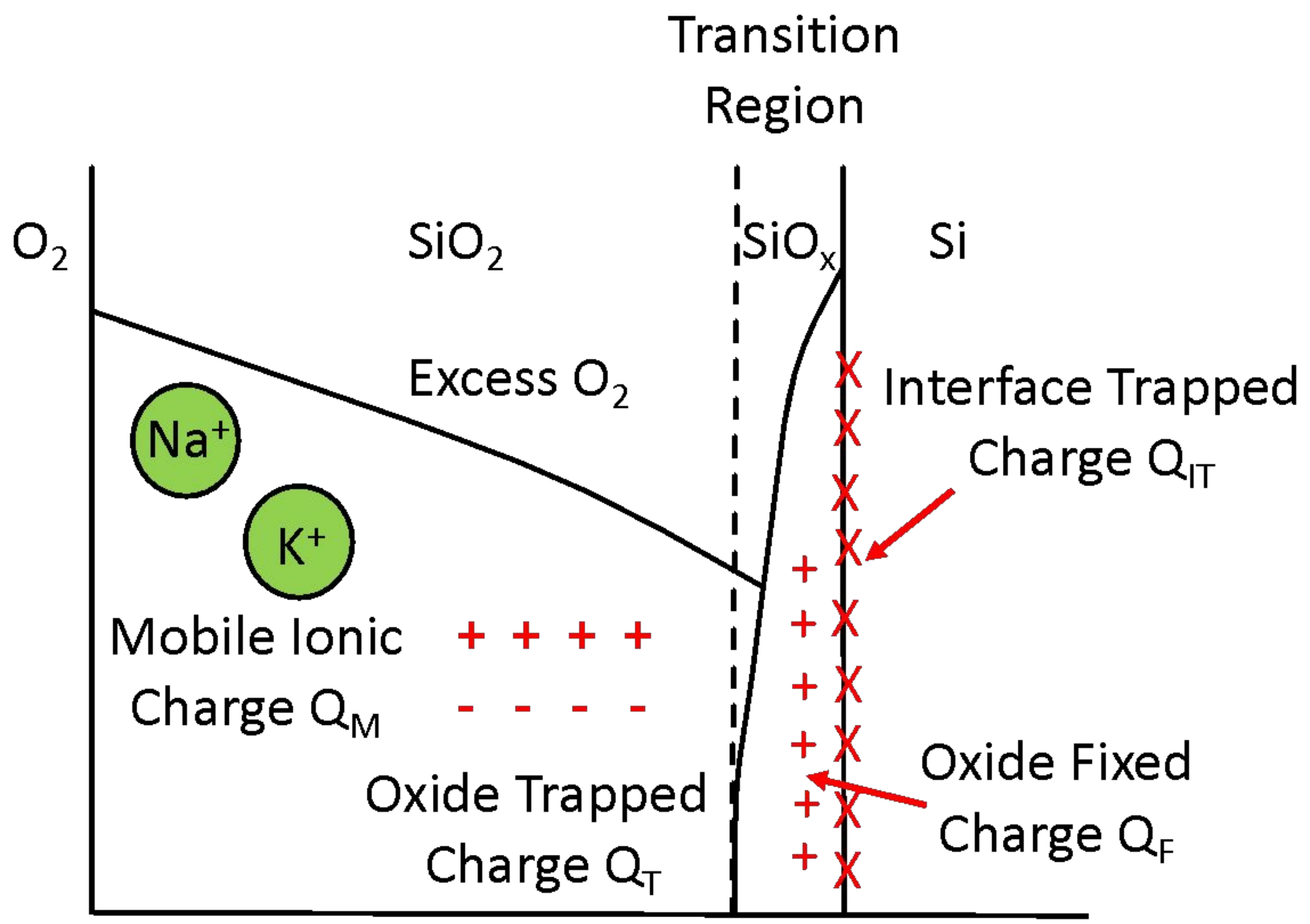
Dry O_2

H_2O

$$B = C_1 \exp^{(-E_1/kT)} \qquad (11)$$

$$\frac{B}{A} = C_2 \exp^{(-E_2/kT)} \qquad (12)$$

Defects in Oxide

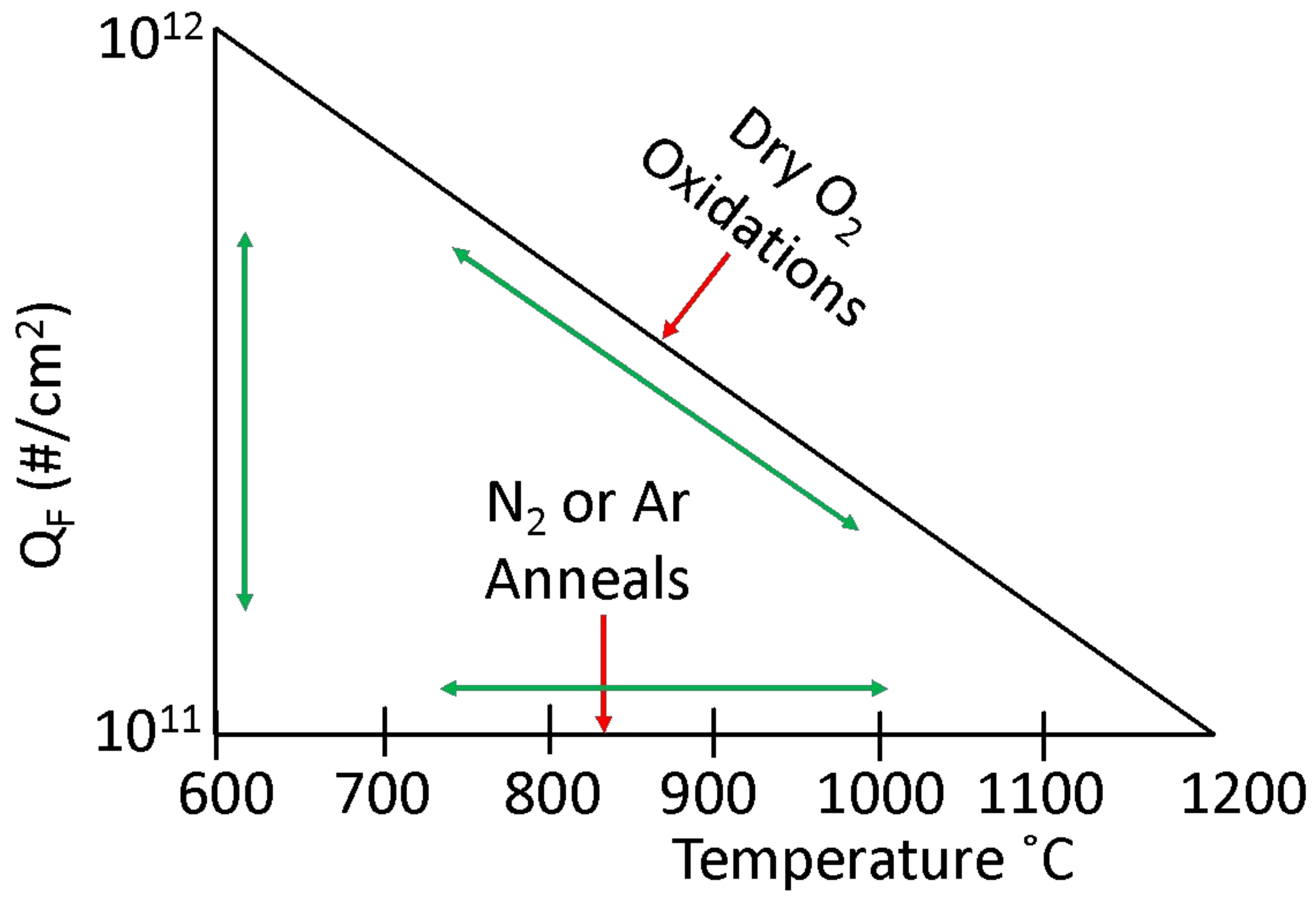


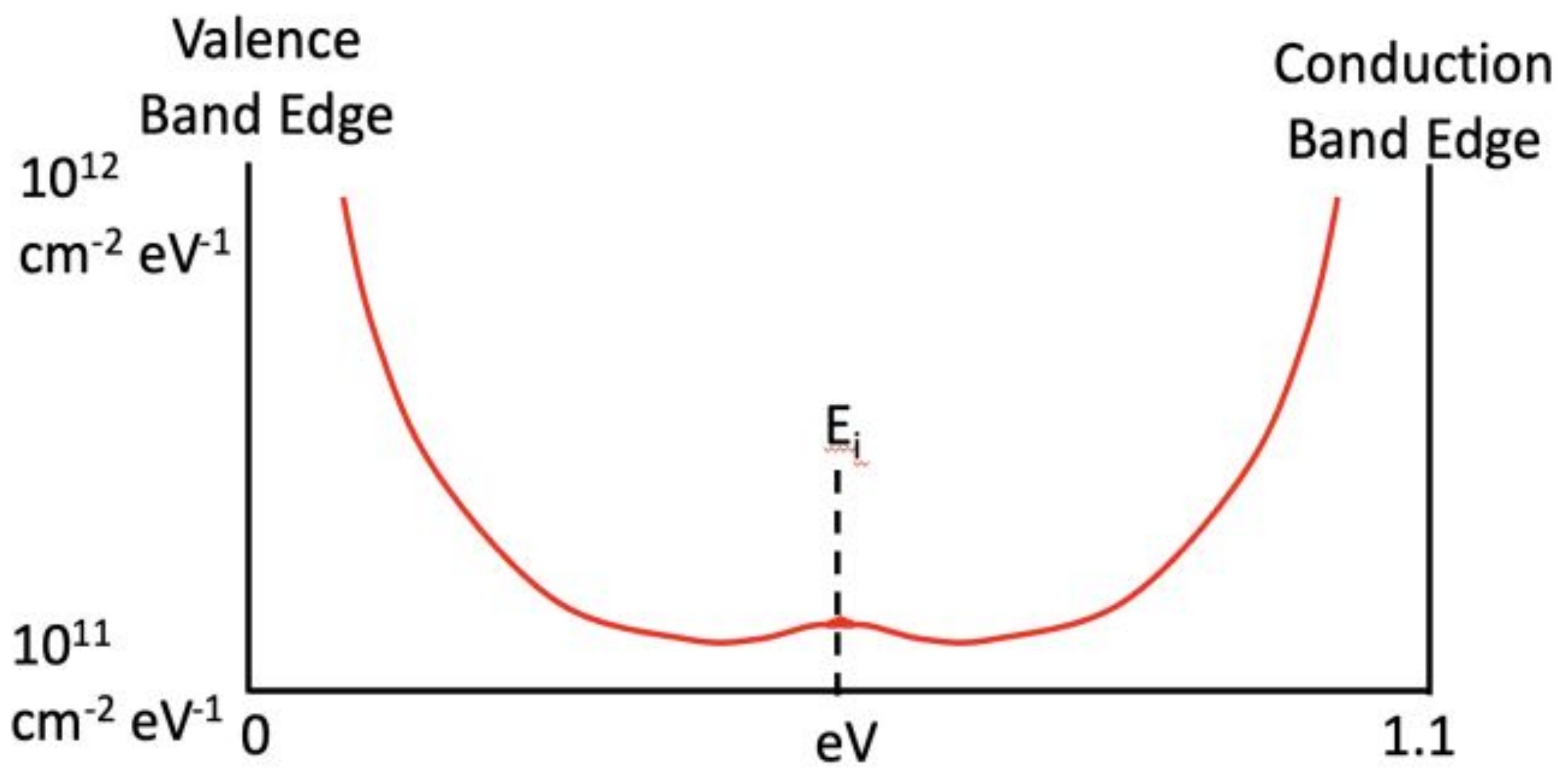
- **Four charges are associated with insulators and insulator/semiconductor interfaces.**
  - **Q_f - fixed oxide charge #/cm^2**
  - **Q_{it} - interface trapped charge**
  - **Q_m - mobile oxide charge #/cm^2**
  - **Q_{ot} - oxide trapped charge #/cm^2**
- **Q_f is fixed and positive.**
- **Q_{it} can trap carriers, many energy levels in bandgap.**

- **For Si/SiO_2 interfaces, $Q_f < 10^{11}$ cm^{-2} and $Q_{it} < 10^{11}$ cm^{-2}eV$^{-1.}$**
- **For SiC/SiO_2 interfaces, $Q_f \approx 10^{12}$ cm^{-2} and $Q_{it} \approx 10^{12} - 10^{13}$ cm^{-2}eV^{-1}**

High interface charge densities can have detrimental effects on MOSFETs
- MOSFET channel mobility is reduced significantly.
- MOSFET subthreshold slope is increased dramatically.

Defects in Oxide



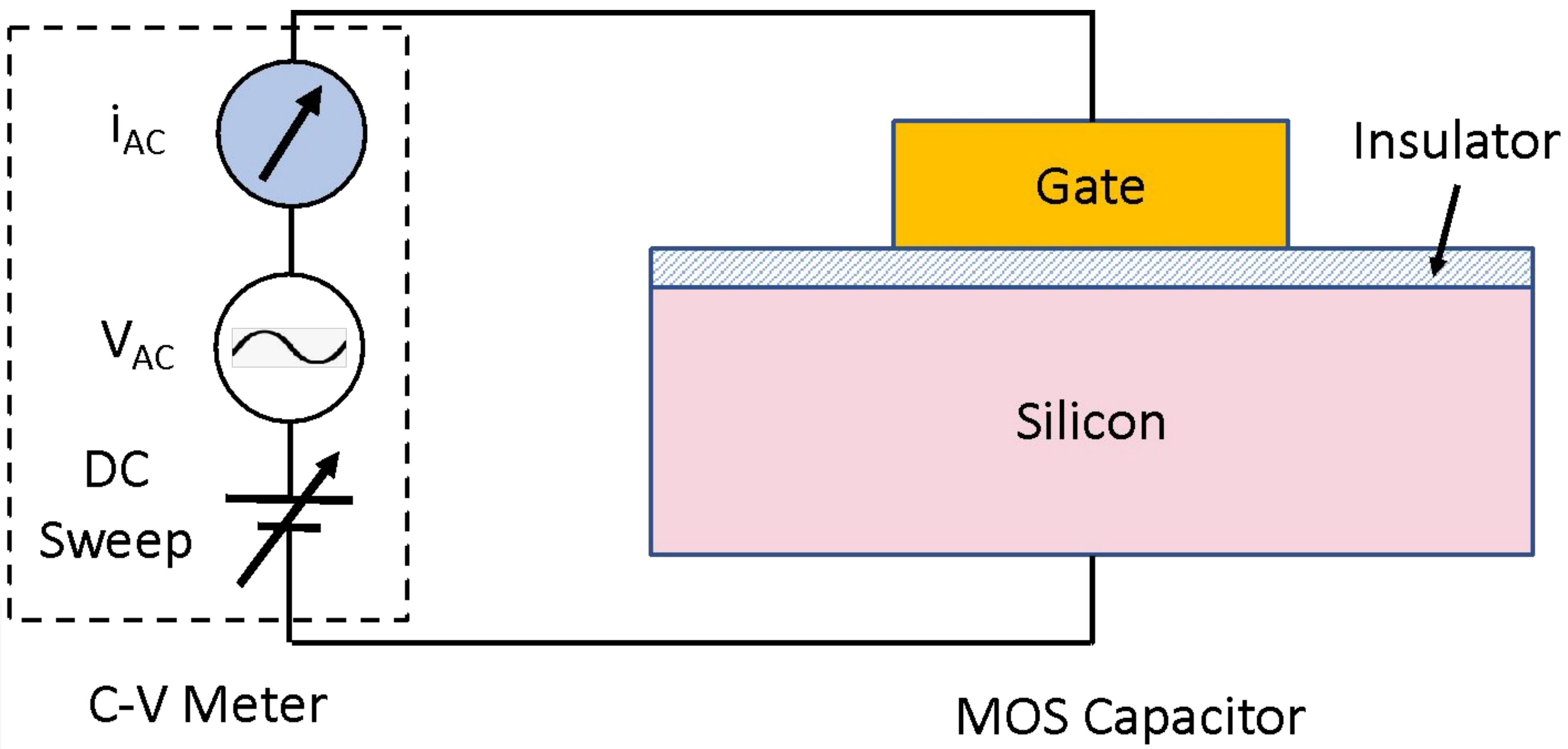


- Q_f is a sheet of positive charge very close to the Si/SiO_2 interface.
- Magnitude depends on oxidation T and ambient.
- Inert anneals lower Q_f so are usually used at the end of an oxidation.
- (100) are ≈ 3X lower. Values above for (111).

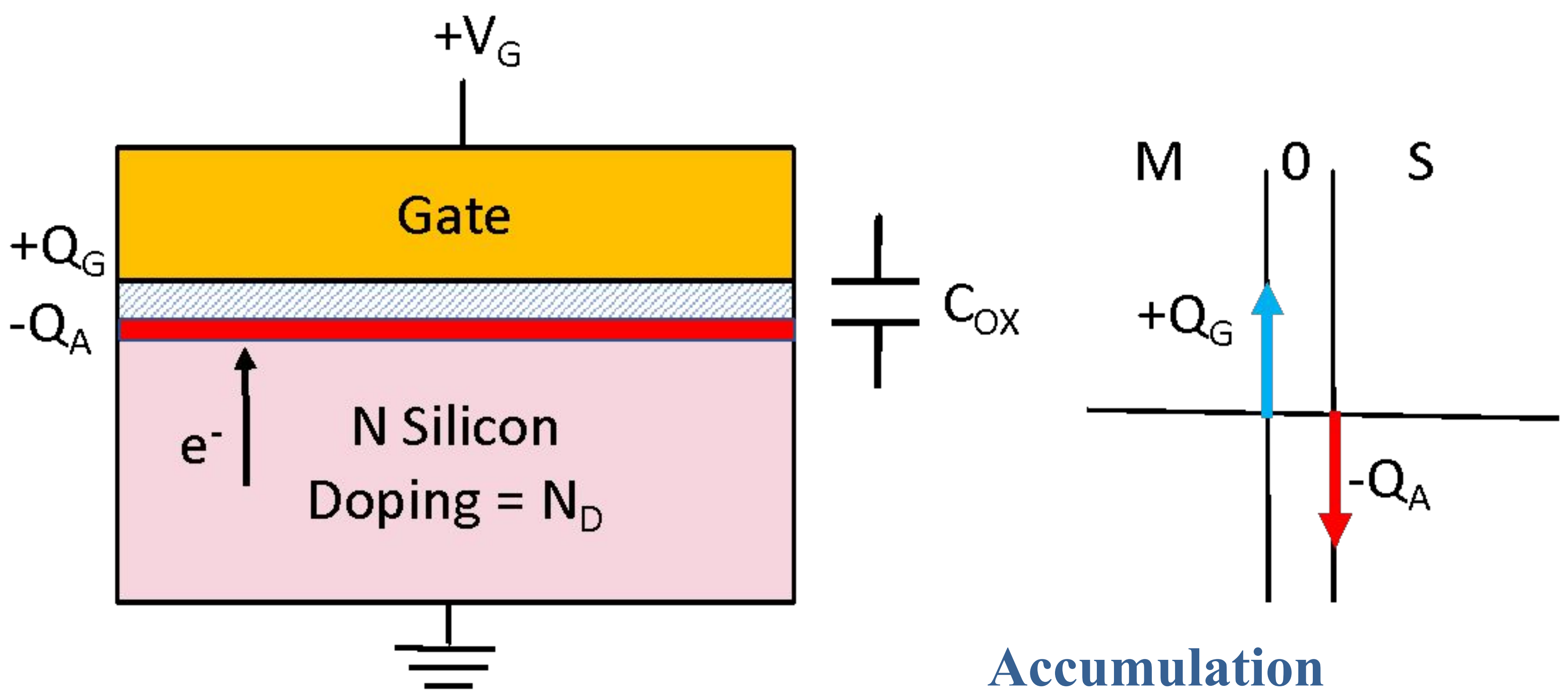
- Q_{it} is also very close to the Si/SiO_2 interface.
- These are traps that can capture h^+ and e^-.
- Traps have energy levels across the silicon bandgap, peaking near the band edges.
- H can passivate these traps

CV Measurements – Characterizing Oxide

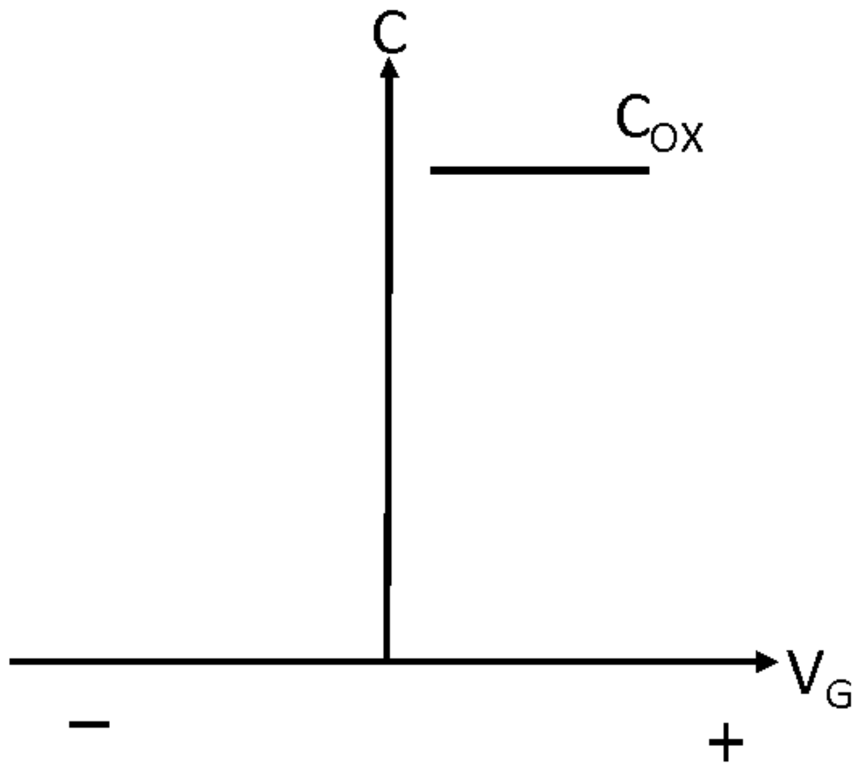
- MOS Capacitor – Characterization of quality of oxide
- Three mode of operation
  - Accumulation
  - Depletion
  - Inversion



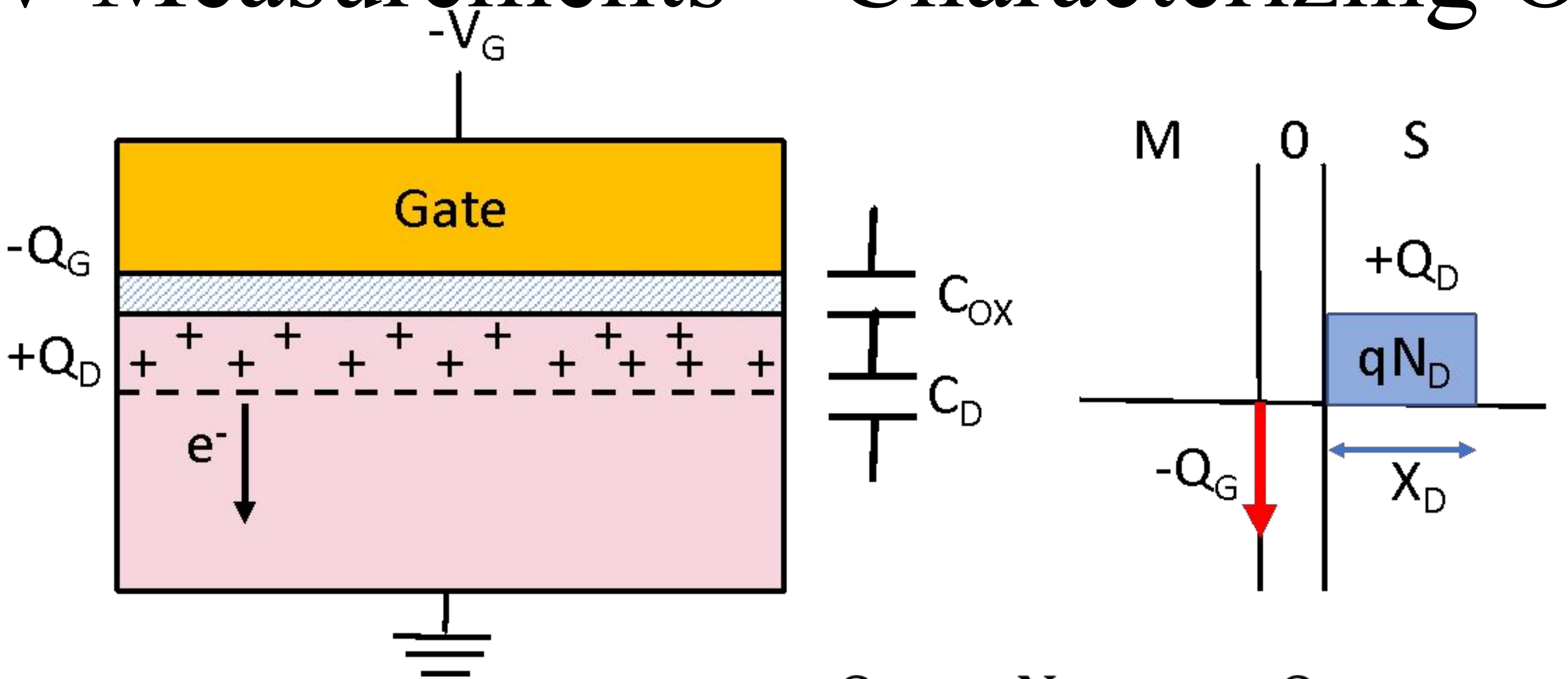
$$i_{AC} = C\,\frac{dv_{AC}}{dt} \qquad (21)$$

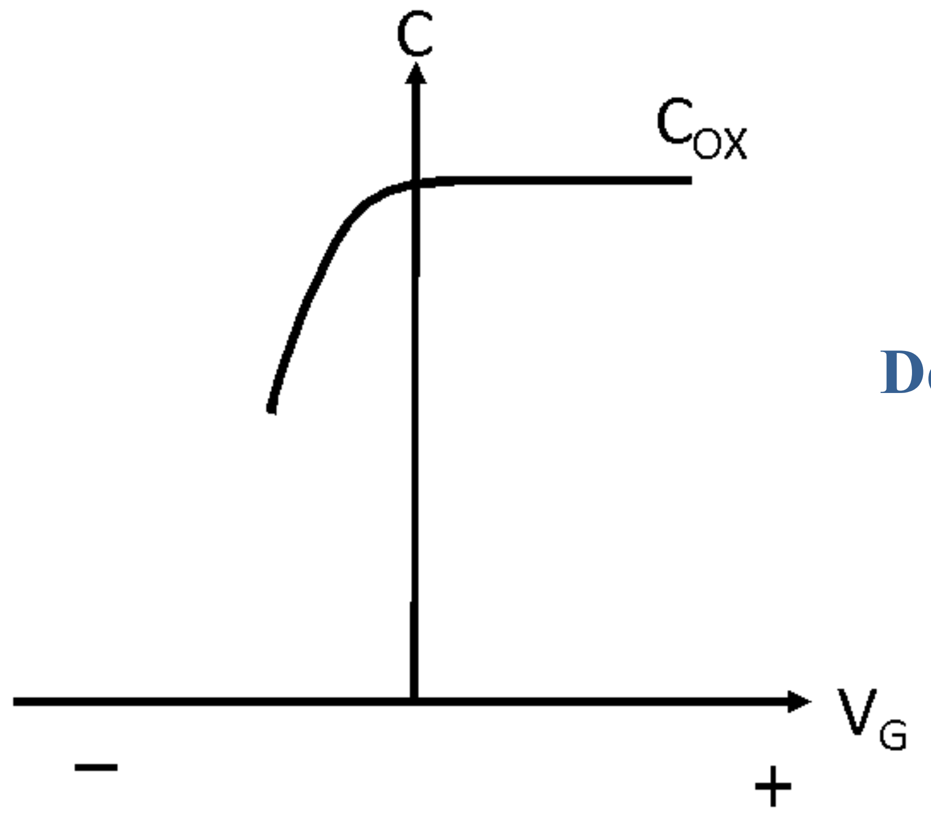


Accumulation



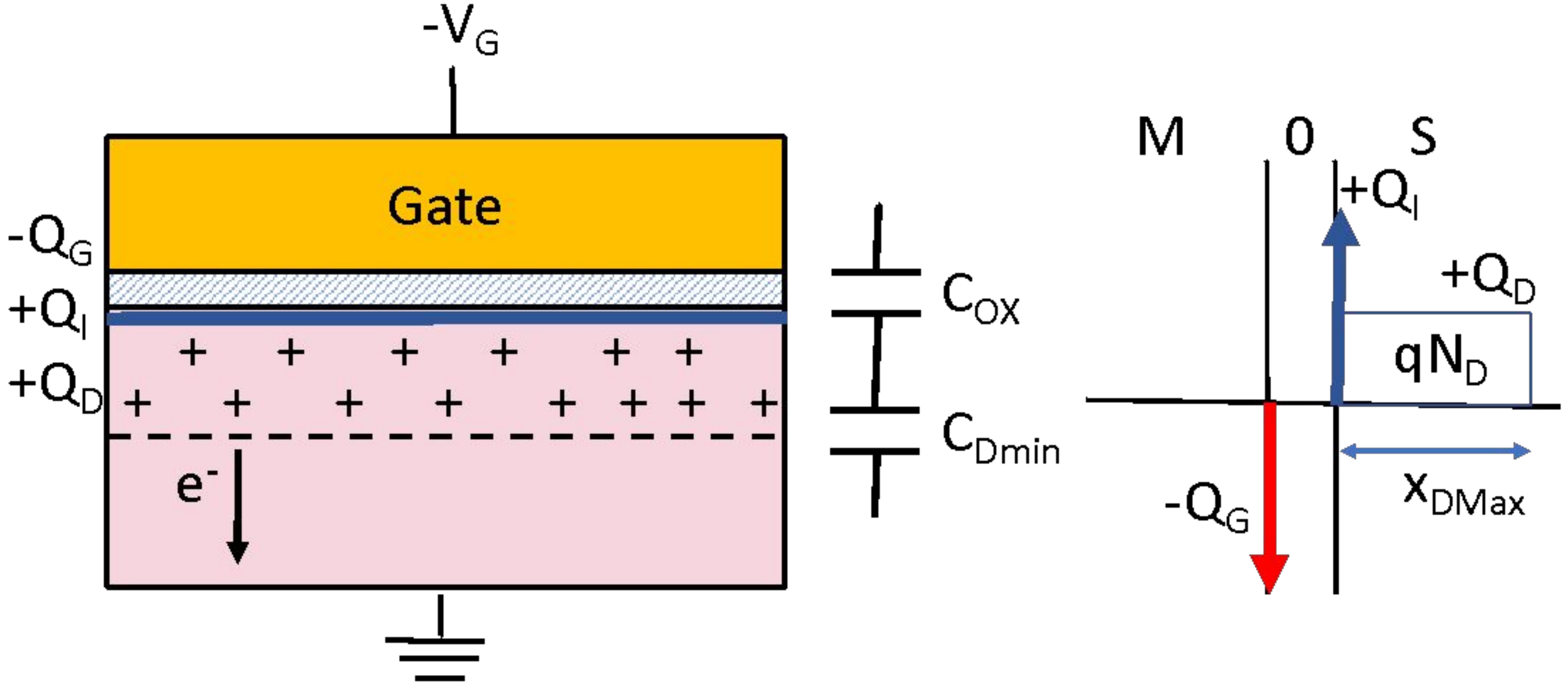
CV Measurements – Characterizing Oxide

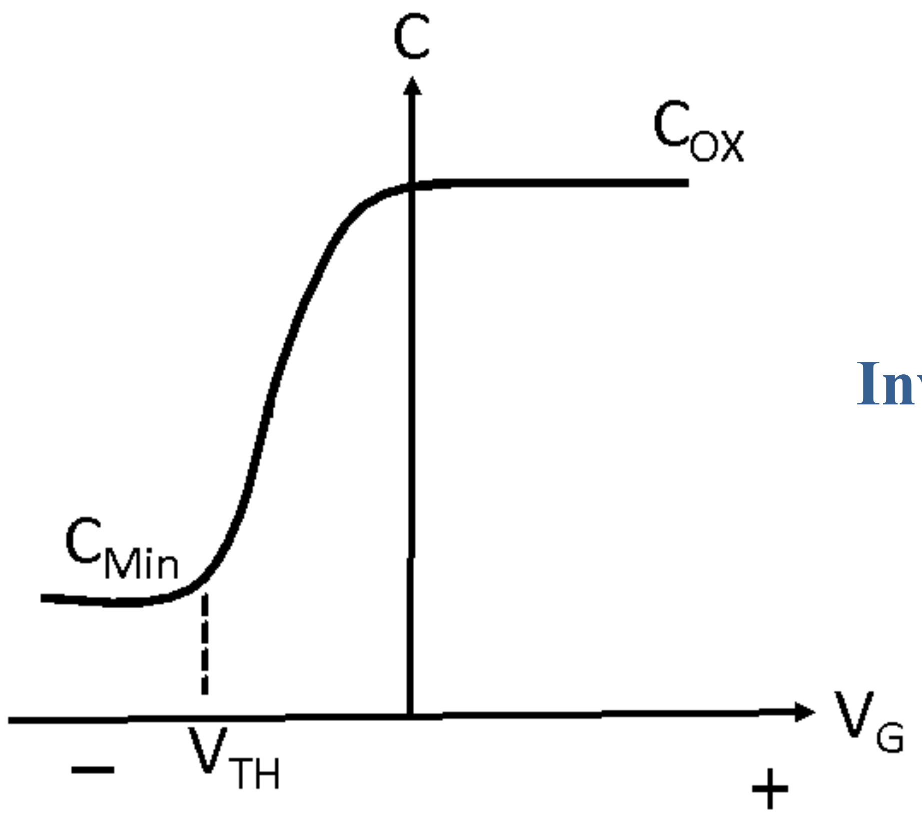




Depletion

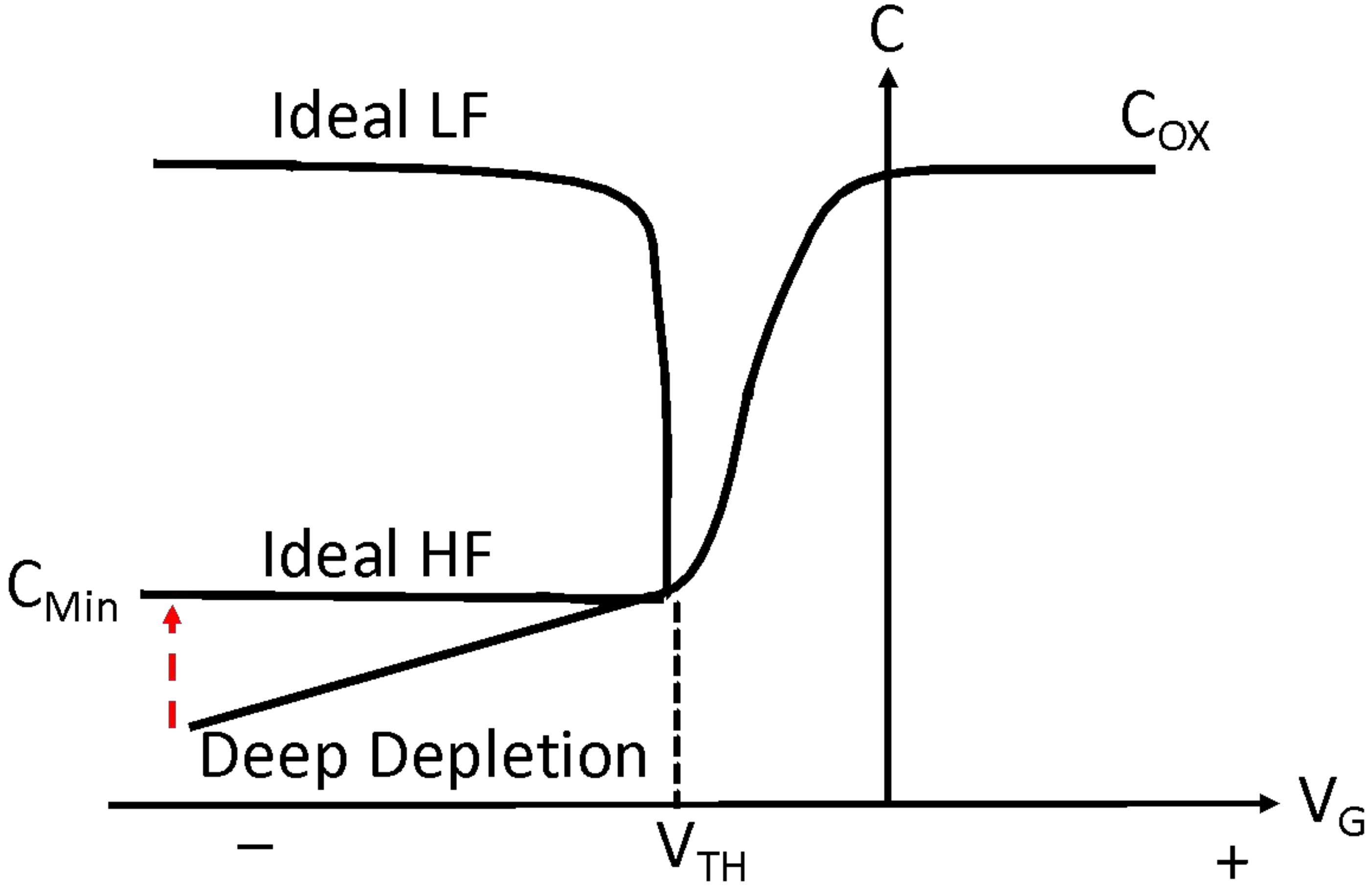
$$Q_G = N_D\, x_D + Q_I$$





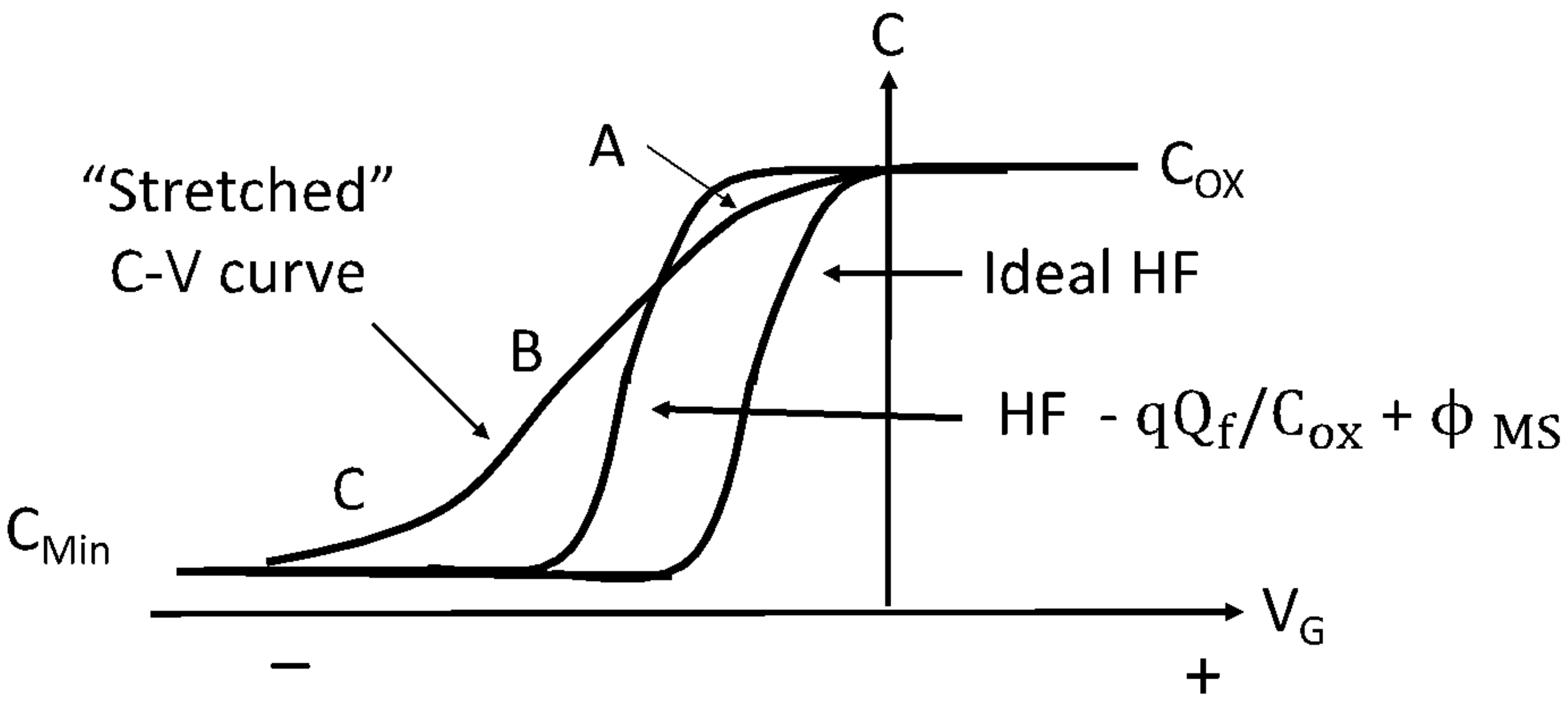
Inversion

CV Measurements – Characterizing Oxide



$$Q_G = N_D x_D + Q_I$$

- At high frequencies, Q_I cannot follow the AC signal so $Q_D = N_D x_D$ has to respond.
- At very low frequencies, Q_I can follow the AC signal.
- In deep depletion, the DC voltage is rapidly swept negative. Q_I cannot be generated that quickly so Q_D must respond.



- Non-ideal systems,
- Q_f and Work function difference shifts the curve laterally
- Q_{it} distorts the curve.