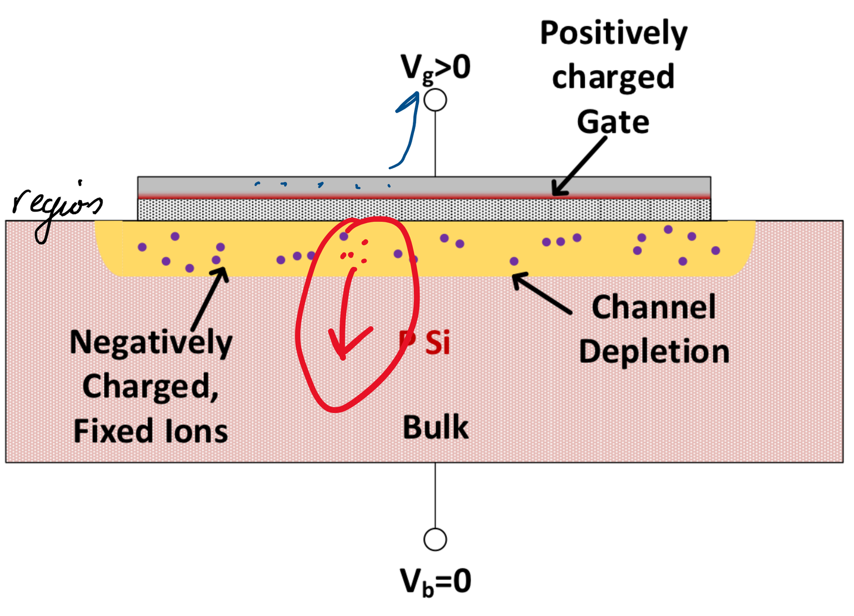
MOSFETs Part 7: Depletion

Monday 16 March 2020 17:03

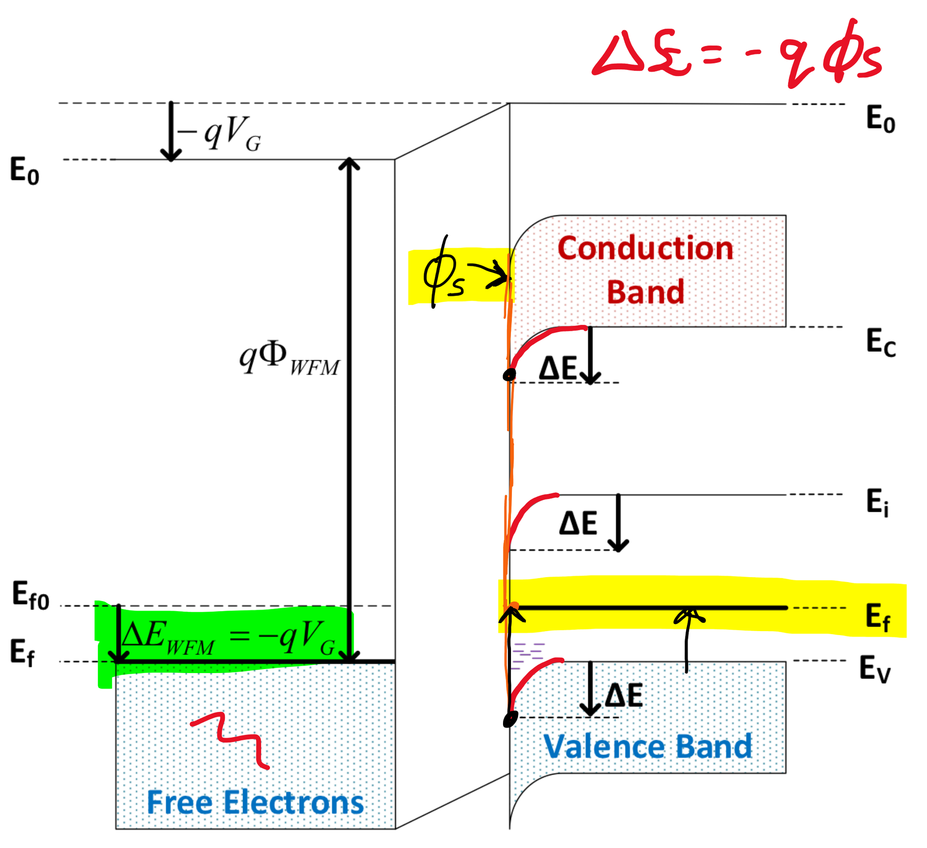
- Device is off
- No free carriers in the interface region



Depletion Band View

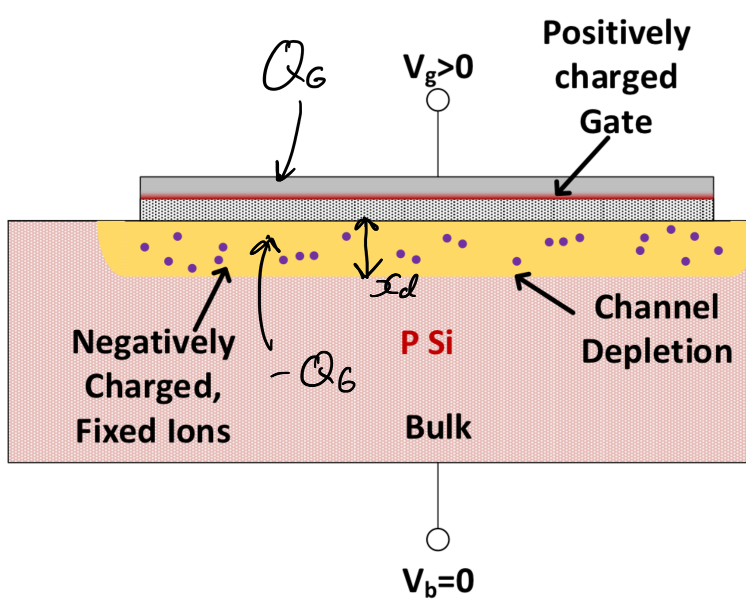
- Set $V_G > 0$, Small
- Results in Metal Fermi Level Shift of:

  $\Delta \mathcal{E}_{FM} = -q V_G$
  - Shifted down so less 'free' electrons in gate
- Causes Si Bands to bend near interface
  - Bends by an amount $-q\phi_s$
    - Where ϕ_s is the potential at the interface
- Si Fermi Level Fixed by Doping
- Bent Valence band further from $\mathcal{E}_f$
  - Less free holes for conduction!



The Depletion Region

- Band Diagram shows less 'free holes' in the interface region
- Holes are pushed into the bulk
  - Or e pulled into interface region
- Donor atoms N_A filled with e can't move
- Donor atoms become Negatively charged Ions. These form the depletion charge!
- Since there is finite doping concentration, the depletion depth must be deep enough to balance charge.
- The depletion depth is non-negligible



Potential $\phi(x)$ & Depletion Thickness x_d

- Bands tell us to expect less free holes
- Let's solve Poisson's Equation:

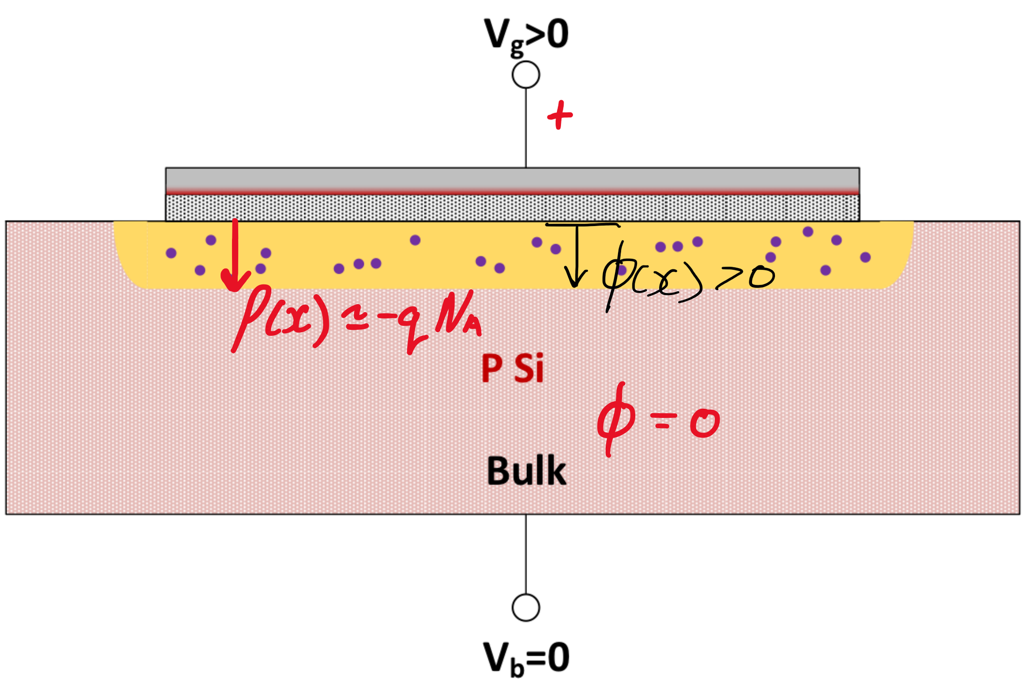
p-type

$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\mathcal{E}_{si}} = \frac{-q}{\mathcal{E}_{si}}\left[p(x) - \cancel{n(x)} + \cancel{N_D} - N_A\right]$$

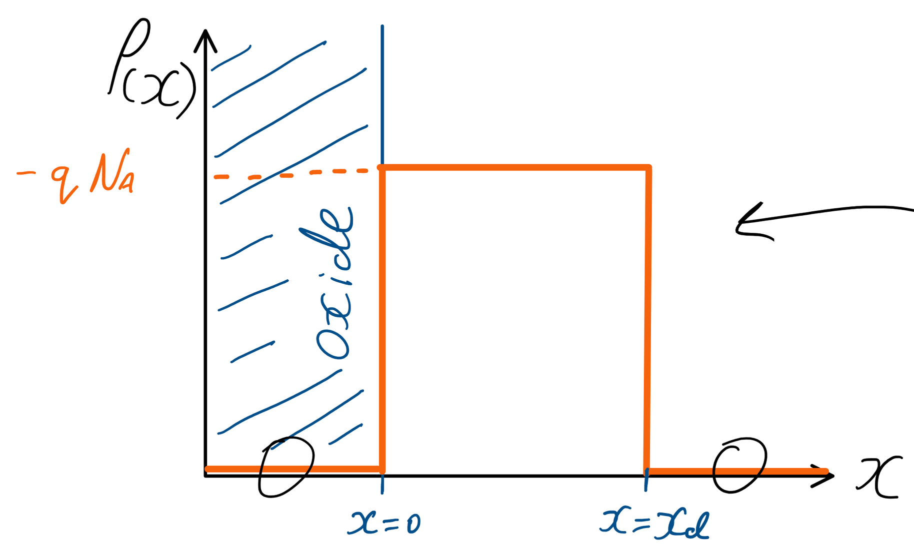
- Simplifies to same result as before:

$$\frac{d^2\phi(x)}{dx^2} \simeq \frac{-q N_A}{\mathcal{E}_{si}}\left[\cancel{e^{\frac{-q\phi(x)}{kT}}} - 1\right]$$

* Don't learn this off *



- $\phi(x)$ is positive this time however
  - Since $V_G > 0$
- As a result, the $e^{\frac{-q\phi(x)}{kT}} \rightarrow 0$



- In this case Poisson's Equation can simplify to:

$$\frac{d^2\phi(x)}{dx^2} \simeq \frac{qN_A}{\mathcal{E}_{si}} \rightarrow \rho(x)$$

- Thus the charge density $\rho(x)$ is approximately const. @

$$\rho(x) \simeq -q N_A \quad *$$

- This makes intuitive sense: Only charges in depletion region are acceptor ions, which are uniformly distributed

- Solving Poisson's Differential Equation is easy in this case:

$$\phi(x) \simeq \frac{qN_A}{2\mathcal{E}_{si}}(x - x_d)^2$$

- Where x_d is the depletion thickness
- We can solve for Surface Potential ϕ_s easily

$$\phi_s = \phi(x=0) = \frac{qN_A}{2\mathcal{E}_{si}} x_d^2$$

* don't need to know these *

- Rearranging for x_d:

$$x_d = \sqrt{\frac{2\mathcal{E}_{si}\phi_s}{qN_A}}$$

Depletion Charge

- We want to know total Depletion Charge Q_{dep}
- As Before, we integrate $\rho(x)$:

$$Q_{dep} = \int_{x=0}^{x_d} \rho(x)\,dx = -\sqrt{2q\mathcal{E}_{si}N_A\phi_s}$$

Linking Depletion Charge to Gate Voltage

- As Before, by KVL:

$$V_G = \phi_s + V_{ox}$$

$$V_G = \phi_s - \frac{Q_{dep}}{C_{ox}}$$

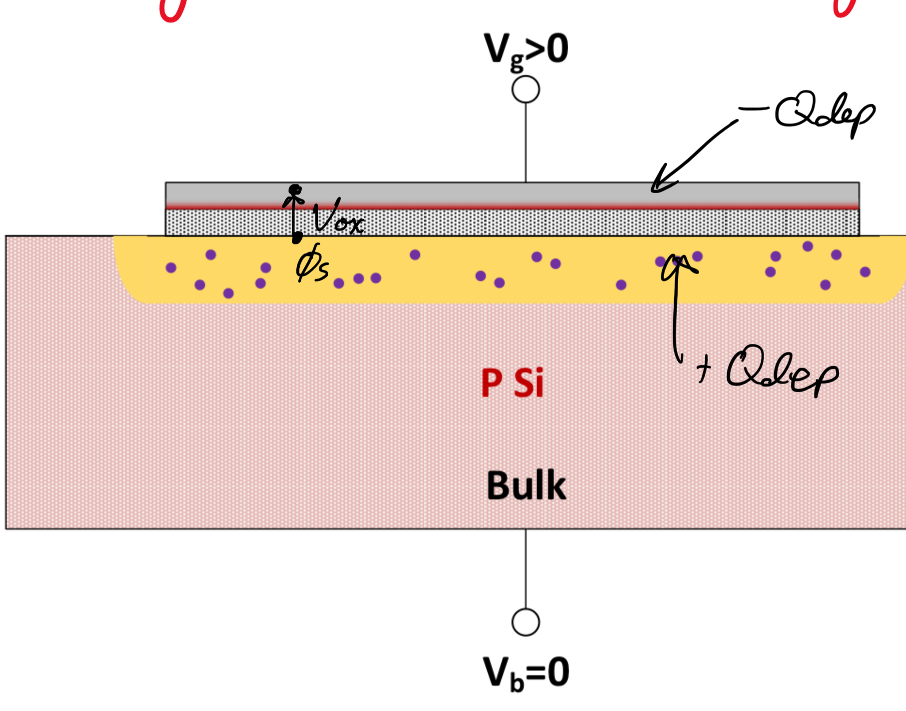
$$C_{ox} = \frac{\mathcal{E}_{SiO_2}}{t_{ox}} \quad [F/m^2]$$

known

$$V_G = \phi_s + \frac{\sqrt{2q\mathcal{E}_{si}N_A\phi_s}}{C_{ox}}$$

→ Solve for ϕ_s

→ Solve for Q_{dep}



Aside : Depletion Capacitance

- Familiar Expression: $Q = CV$
- Differentiated: $dQ = C\,dV$

$$C = \frac{dQ}{dV}$$

- Total Capacitance seen @ Gate:

$$C_G = \frac{dQ_G}{dV_G} = \frac{-dQ_{dep}}{dV_G} = \frac{-dQ_{dep}}{d\left(\phi_s - \frac{Q_{dep}}{C_{ox}}\right)}$$

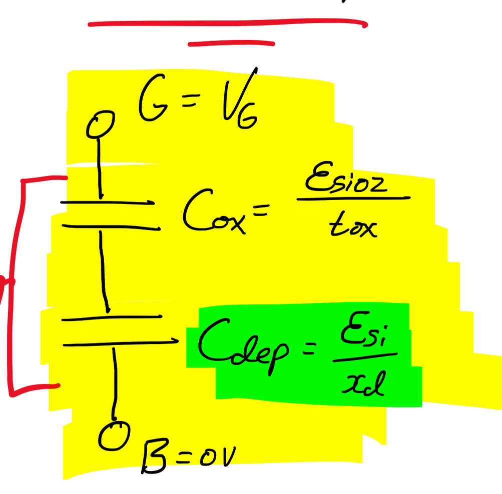
- Divide by $d\phi_s$:

$$C_{dep} = \frac{-dQ_{dep}}{d\phi_s}$$

$$C_G = \frac{\frac{-dQ_{dep}}{d\phi_s}}{\frac{d\left(\phi_s - \frac{Q_{dep}}{C_{ox}}\right)}{d\phi_s}} = \frac{C_{dep}}{1 + \frac{C_{dep}}{C_{ox}}} = \text{Series}(C_{dep}, C_{ox})$$

$$\frac{d\left(\phi_s - \frac{Q_{dep}}{C_{ox}}\right)}{d\phi_s} = 1 - \frac{d\left(\frac{Q_{dep}}{C_{ox}}\right)}{d\phi_s} = 1 + \frac{C_{dep}}{C_{ox}}$$

$C_{Tot} \simeq C_{dep}$



Very Small