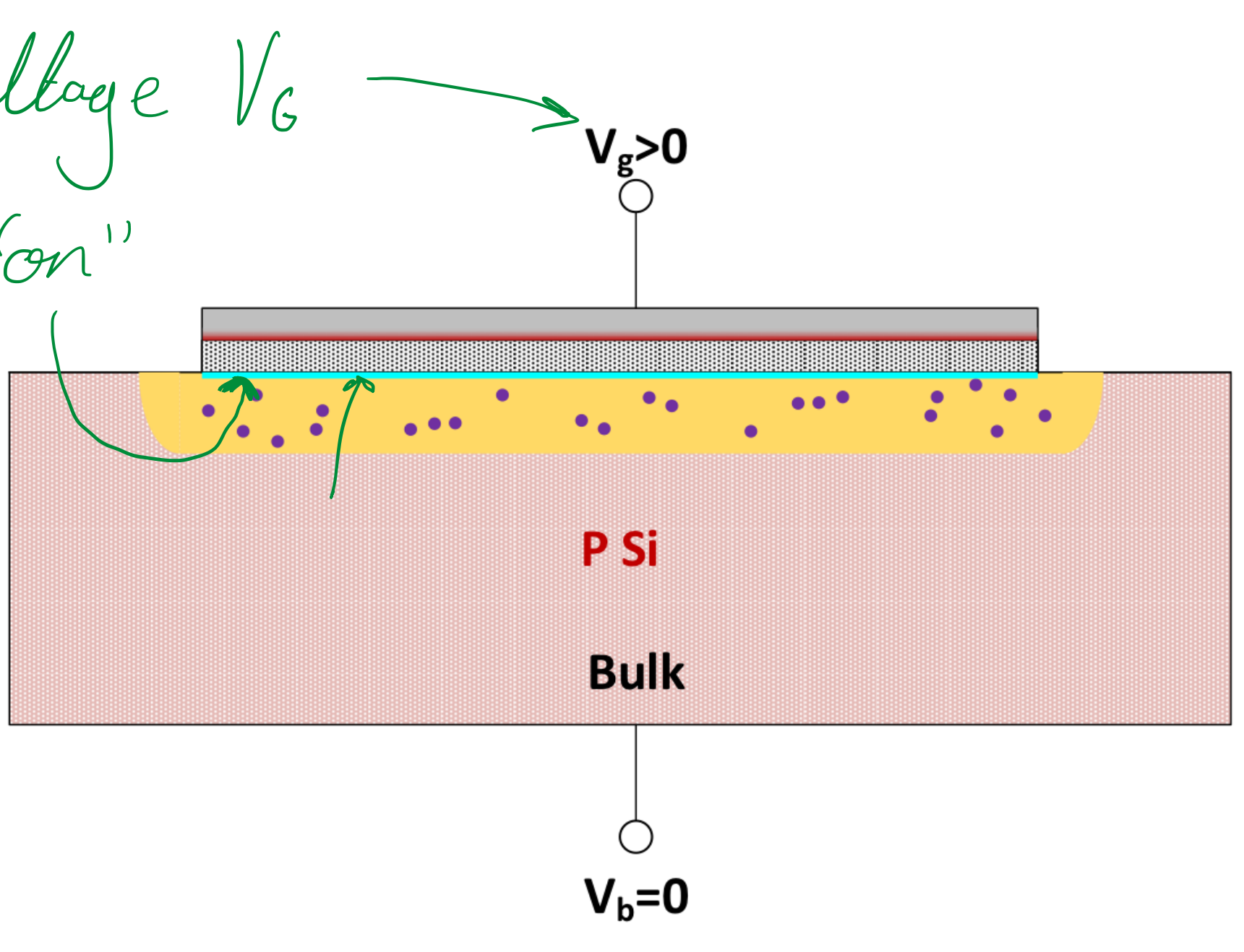
MOSFETs Part 9: Threshold Voltage

Wednesday 18 March 2020 16:42

What Gate Voltage V_G

Is the device turned "on"



① Strong Inversion

② Flat band Voltage

③ Oxide Charges

Gate Voltage to achieve Strong Inversion

- Ignoring All Else, Gate Voltage is given by:

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

- For Strong Inversion, we know Surface Potential ϕ_s must be:

$$\phi_s = 2\phi_{FP}$$

- Oxide Voltage V_{ox} is given by:

$$V_{ox} = \frac{Q_{ox}}{C_{ox}} \qquad \frac{\varepsilon_{SiO_2}}{t_{ox}}$$

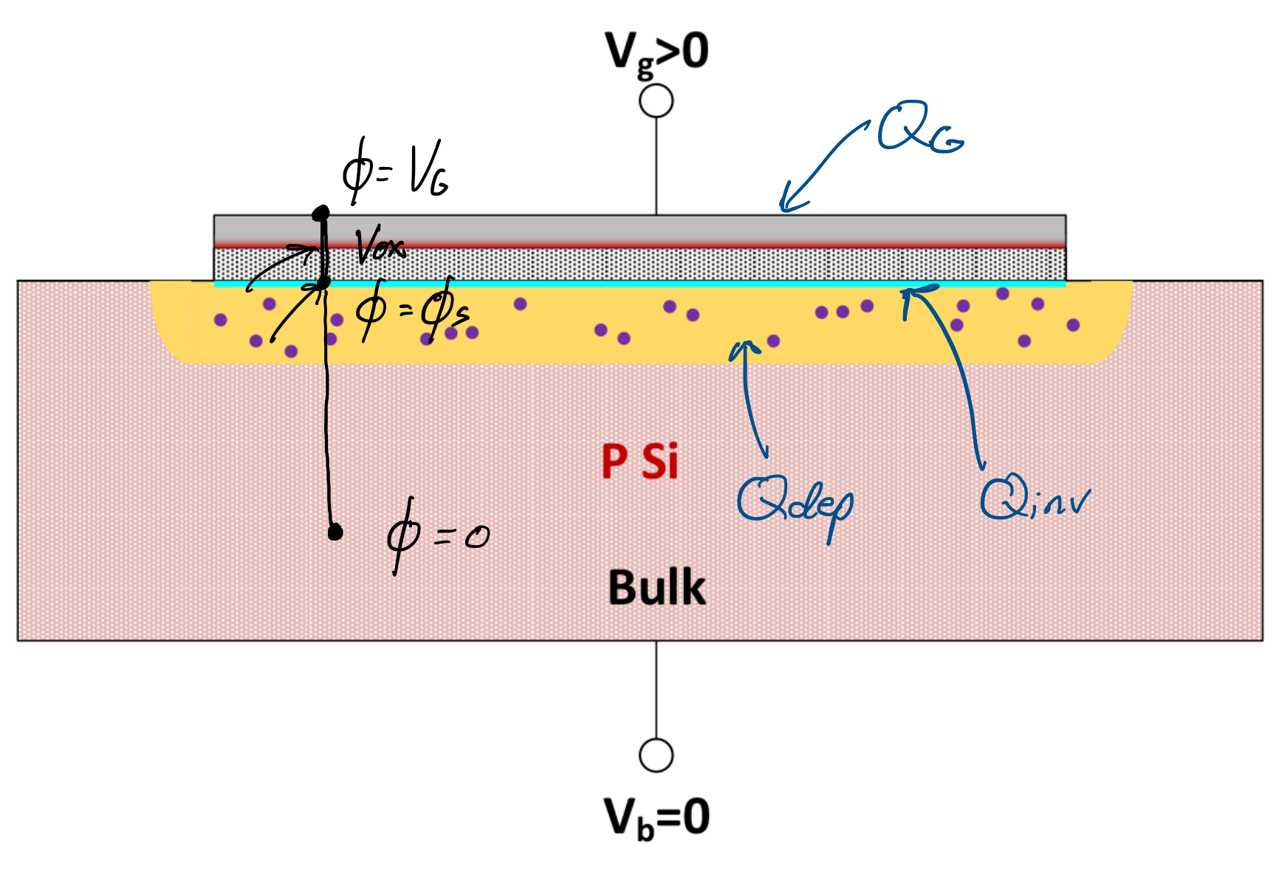
- Q_{ox} is the charge across the oxide - or the gate charge Q_G
- We saw before that:

$$Q_G = -(Q_{dep} + Q_{inv})$$

- When the device is *just* turning on, there's very little inversion channel charge ($Q_{dep} >> Q_{inv}$)

$$Q_G \simeq -Q_{dep}$$

$$= \sqrt{4q\varepsilon_{Si} N_A \phi_{FP}}$$



- The Gate Voltage required to turn on the device is called the Threshold Voltage V_{TO}
- In an ideal world, the threshold voltage would thus be given by:

In an Ideal world

$$V_{TO}' = V_G^{SI} = \phi_s + V_{ox}$$

$$= 2\phi_{FP} - \frac{Q_{dep}}{C_{ox}}$$

$$V_{TO}' = 2\phi_{FP} + \frac{\sqrt{4q\varepsilon_{Si} N_A \phi_{FP}}}{C_{ox}}$$

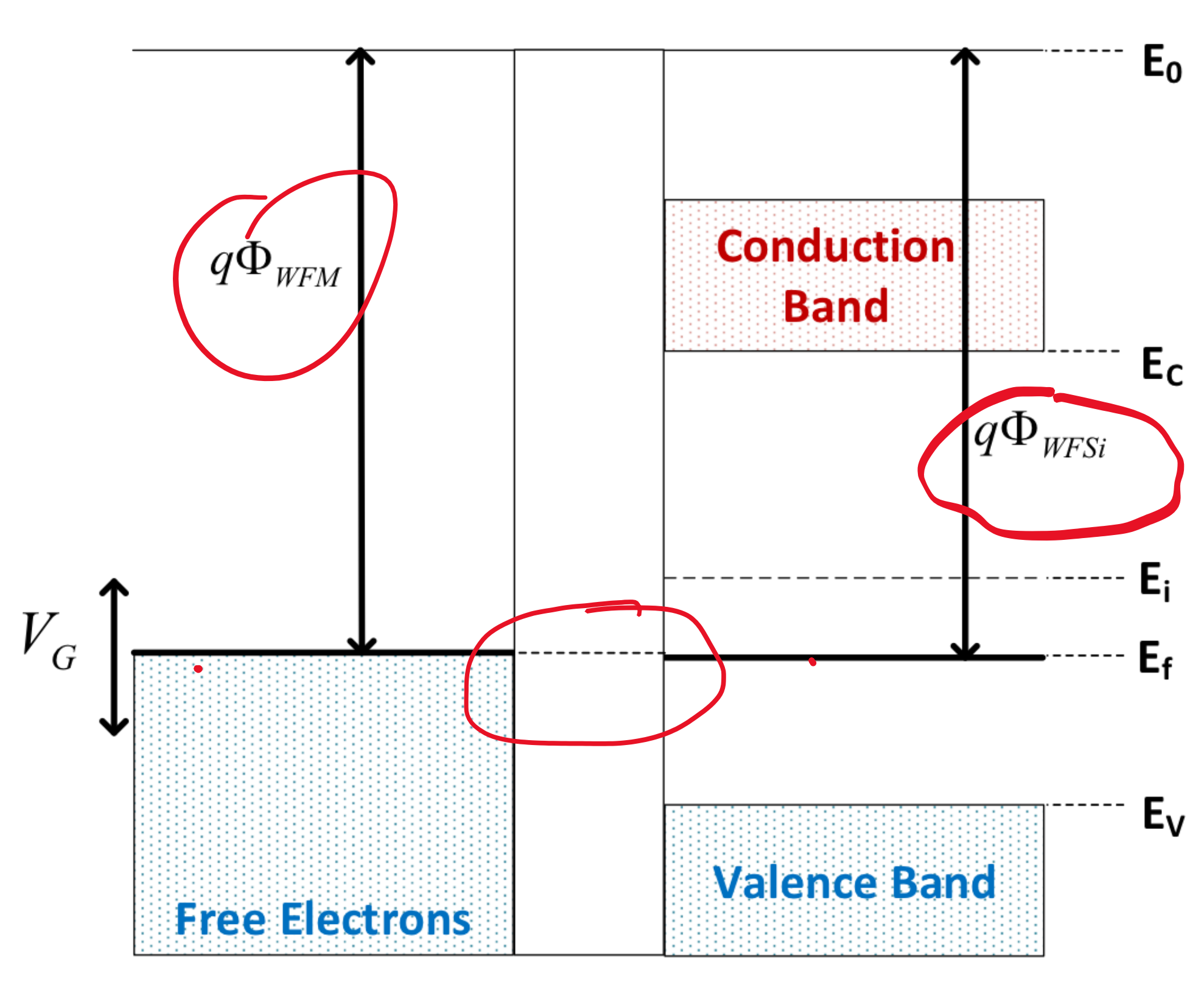
Gate Voltage to turn on an Ideal MOSFET

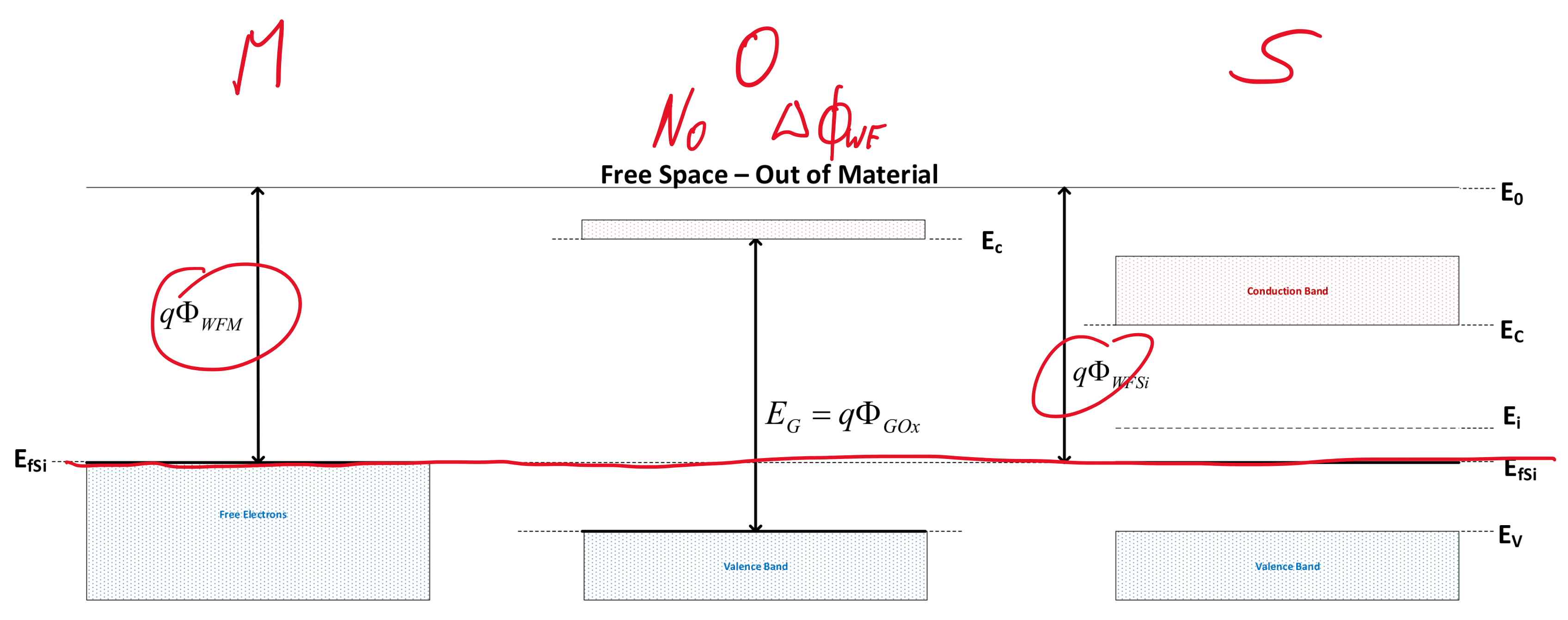
Flat band Voltage

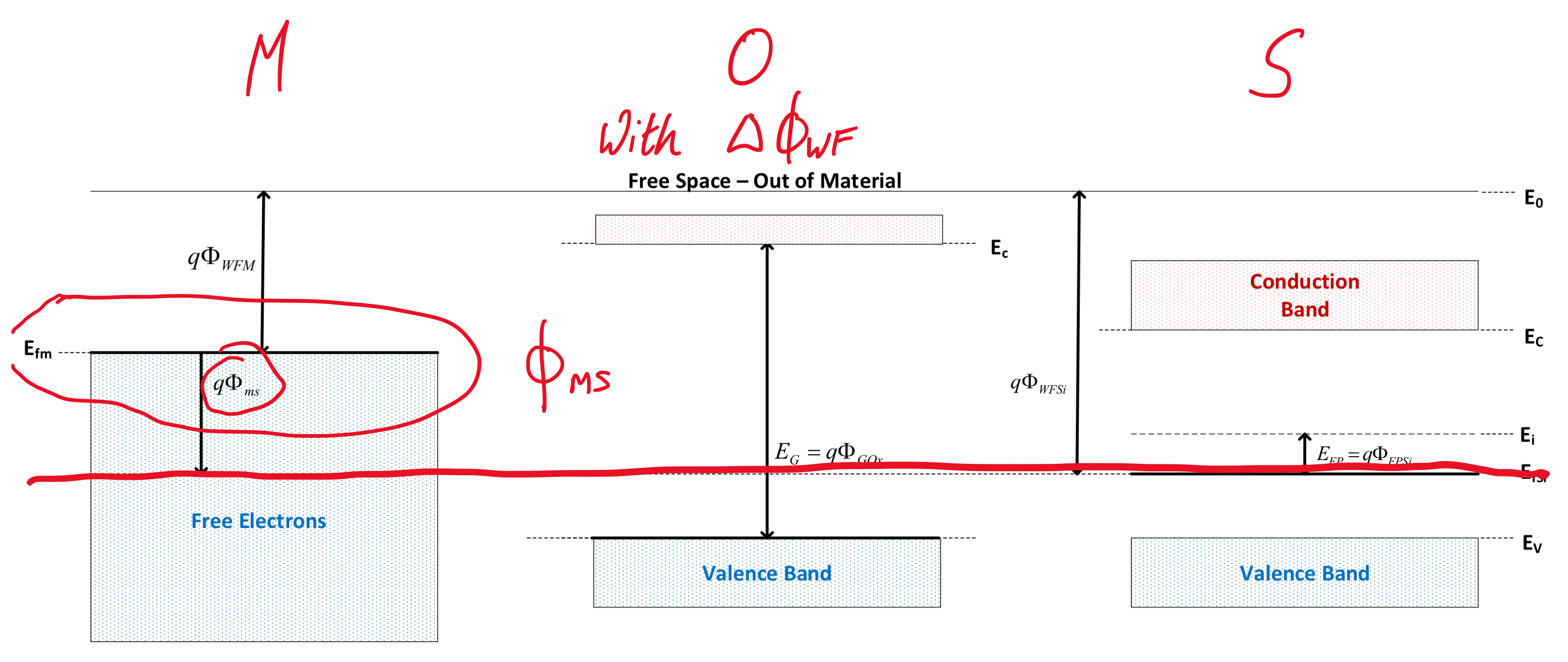
- Until now, we've been making the assumption the work function of the metal is the same as the work function of the Silicon:

$$\phi_{WFM} = \phi_{WFSi}$$

- Remember that the Work Function ϕ_{WF} dictates the Fermi Level in the material.
- The Fermi Level in any device under thermal Equilibrium must be flat
  - When there is no gate Voltage applied to the device, the Fermi Levels of the Metal and Si will be flat.
- When The Fermi Level of the materials is the same, this is trivial
- But when the fermi levels of the materials are different, something must give - thus a built in voltage is generated and the bands bend.

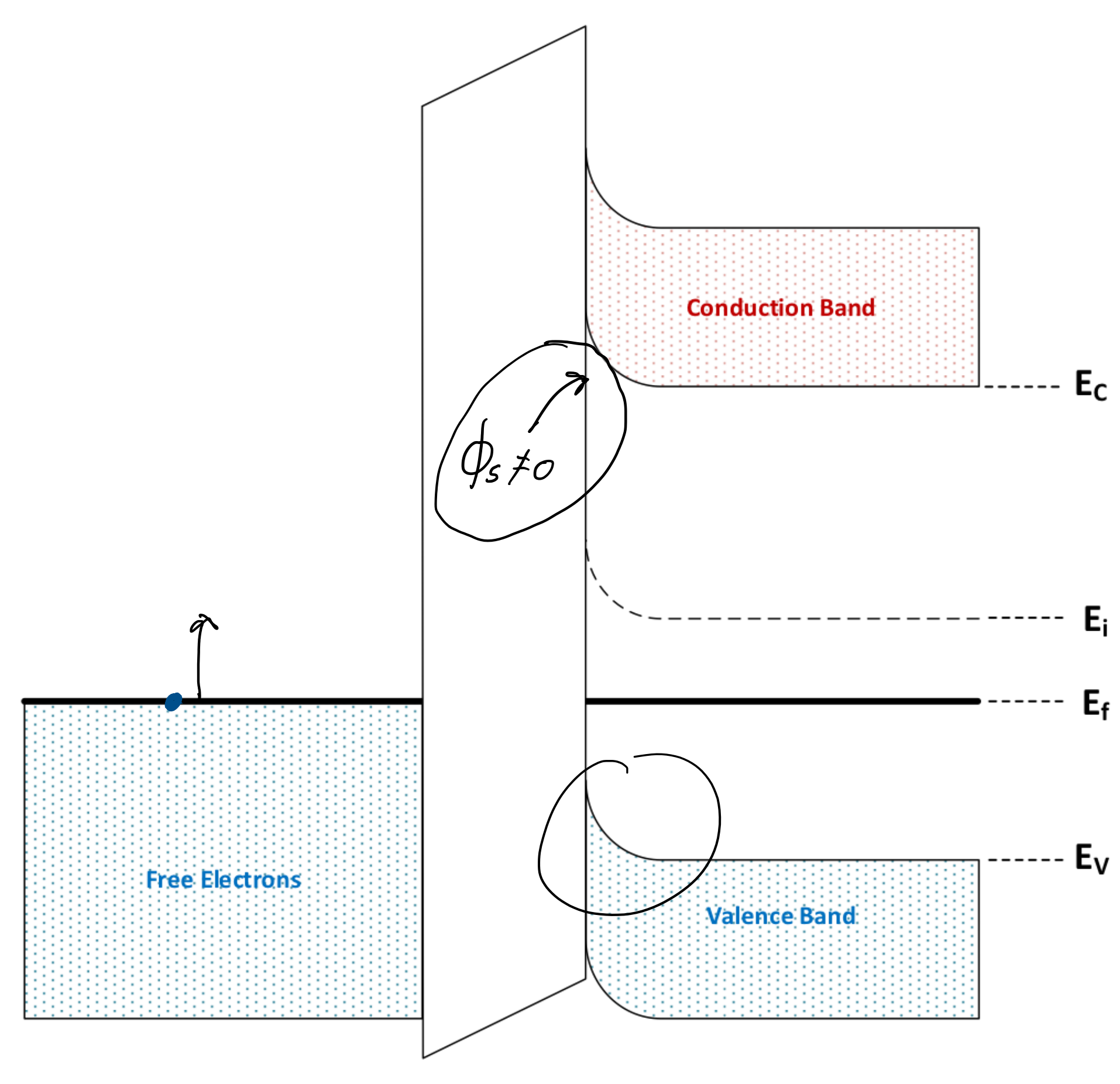






Band Bending with Zero Bias

- *Zero Bias = Fermi Level must be flat!*
- When the M O & S are separate, they have different Fermi-Levels. Something has to give!
- A (built-in) potential must be present in the device to account for the Fermi-Level difference
- This built-in Potential forms at the interface as a Surface Potential ϕ_s
- In order to overcome this work function difference, we must restore the Fermi-Level in the metal using an external Bias...



The Flatband Condition

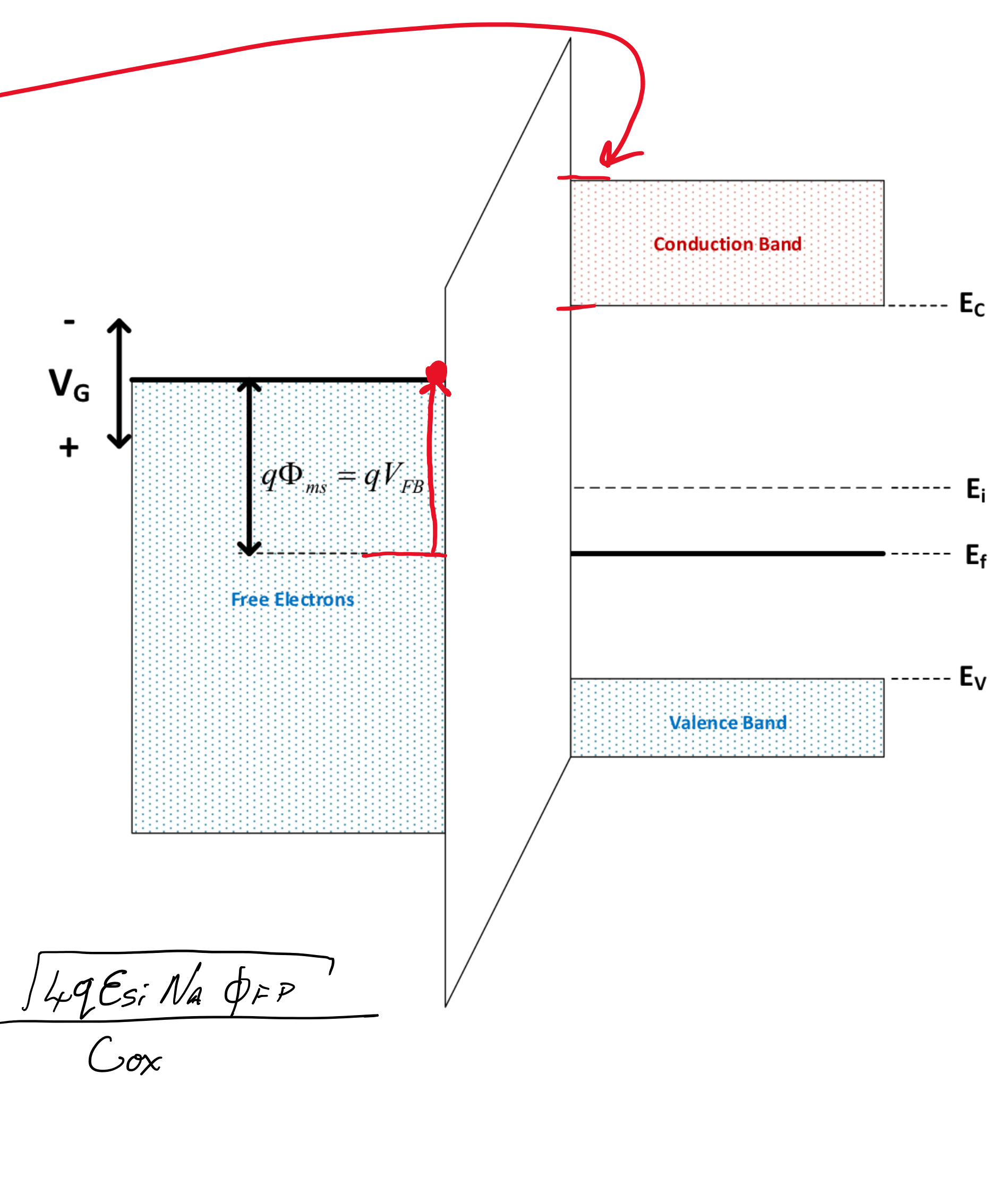
- We must apply a Gate Voltage to flatten the bands again. We call this the Flatband Voltage:

$$V_G = V_{FB}$$

- When the M O S is separate and the Fermi Levels allowed be their natural values, the bands are flat
- The Flatband Voltage V_{FB} thus is the Voltage Required to restore the Metal Fermi Level back to its Original Value
- This can be calculated as the Work Function Difference between the Metal and Si:

$$V_{FB} = \phi_{MS} = \phi_{WFM} - \phi_{WFSi}$$

- We Must Meet the Flatband Condition before starting to turn on the device, so the Threshold Voltage Becomes:

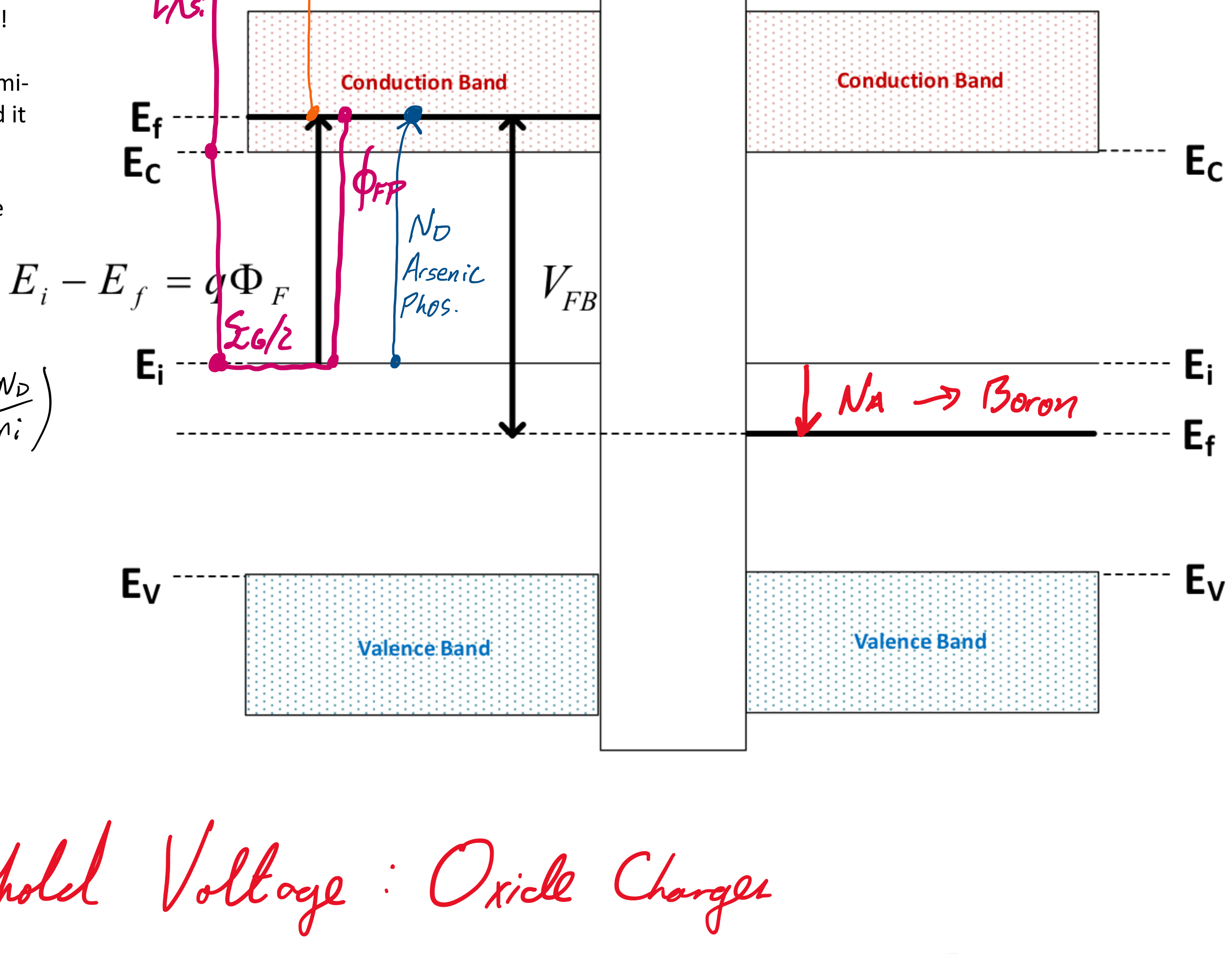


$$V_{TO} = V_{FB} + 2\phi_{FP} + \frac{\sqrt{4q\varepsilon_{Si} N_A \phi_{FP}}}{C_{ox}}$$

Aside: Polysilicon Gates

- A Gate Does not have to be made from Metal!
- If you Dope Polycrystalline Si heavily, The Fermi-Level moves far into the Conduction Band and it begins to look like a Metal!
- The Doping of the Poly Gate is of the opposite type to the Bulk
- Work Function of Poly Gate: ϕ_{FP}

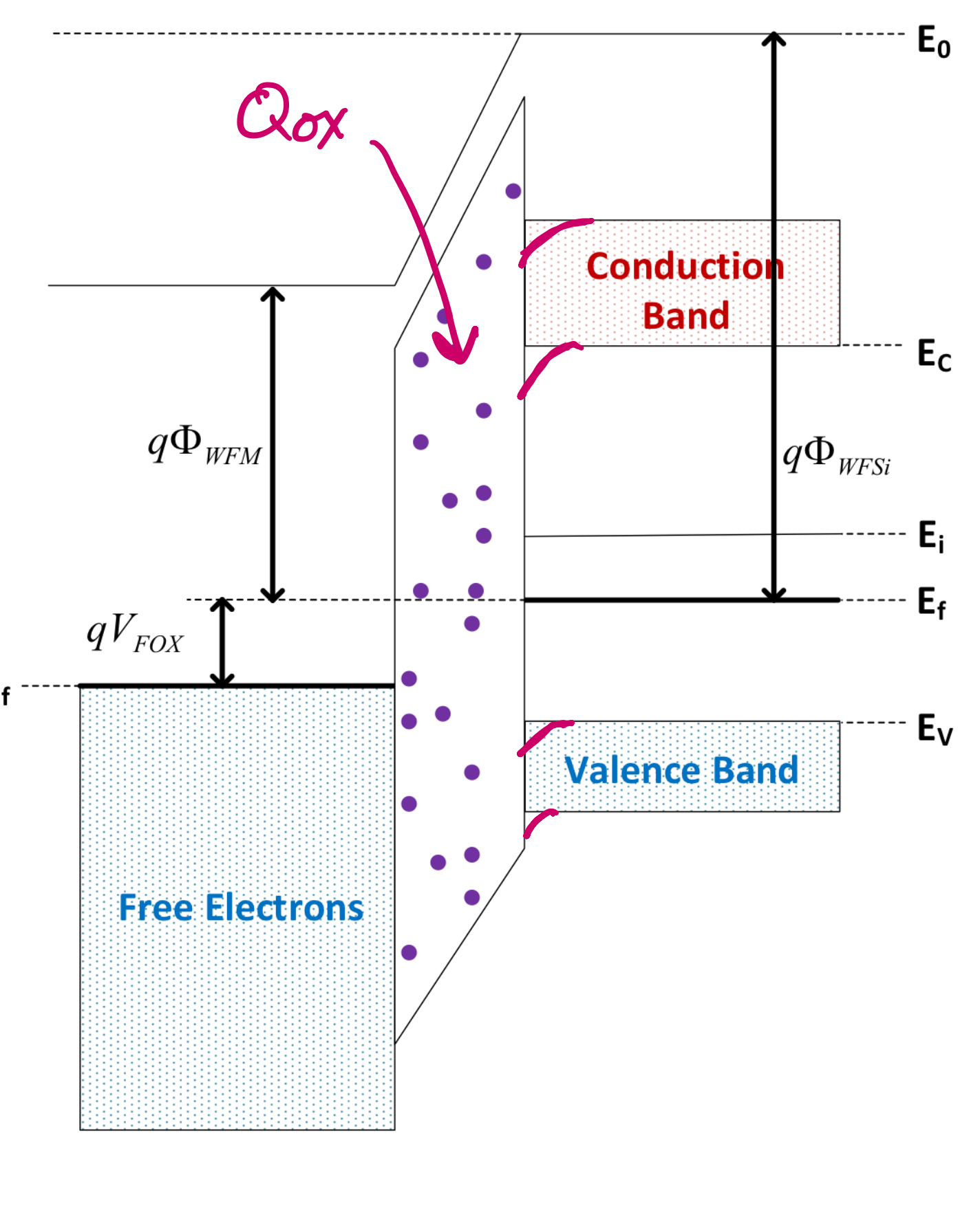
$$\phi_{WF\,Poly} = q\chi_{Si} + \frac{\varepsilon_G}{2} + kT\ln\left(\frac{N_D}{n_i}\right)$$



Back to Threshold Voltage: Oxide Charges

- Often Oxide Contains Fixed Charges
  - Due to Manufacturing or Design
- Fermi Levels Must Flatten, Charges must Balance
  - Balance charge forms in Interface region
  - Surface Potential ϕ_s forms and Band Bending Occurs
- Results in Band Bending at $V_G = 0$
- Like Flatband, need to apply a Gate Bias Voltage to Flatten the Band
  - This Contributes to V_{TO}

$$V_{FOX} = \frac{-Q_{ox}}{C_{ox}}$$



Review: Calculating Threshold Voltage

- Defines the 'ON' State of the Device - When we reach Strong Inversion
  - We form a channel that can Conduct between Drain & Source
- Threshold Voltage defines the Gate Voltage Required to reach Strong Inversion for a Device
- To Achieve SI, The Gate Voltage Must Overcome:
  - Oxide Charge
  - Flatband Condition
  - Depletion Charge
  - Surface Potential = 2 Fermi Potentials (Inversion)

$$V_{TO} = \underset{\text{Oxide Chg}}{V_{FOX}} + \underset{\text{Flatband Cond.}}{V_{FB}} + \underbrace{2\phi_{FP}}_{\text{Strong Inv}} + \underbrace{\frac{\sqrt{4q\varepsilon_{Si} N_A \phi_{FP}}}{C_{ox}}}_{\text{depletion Chg}}$$