MOSFETs Part 8: Inversion

Monday 16 March 2020 22:07

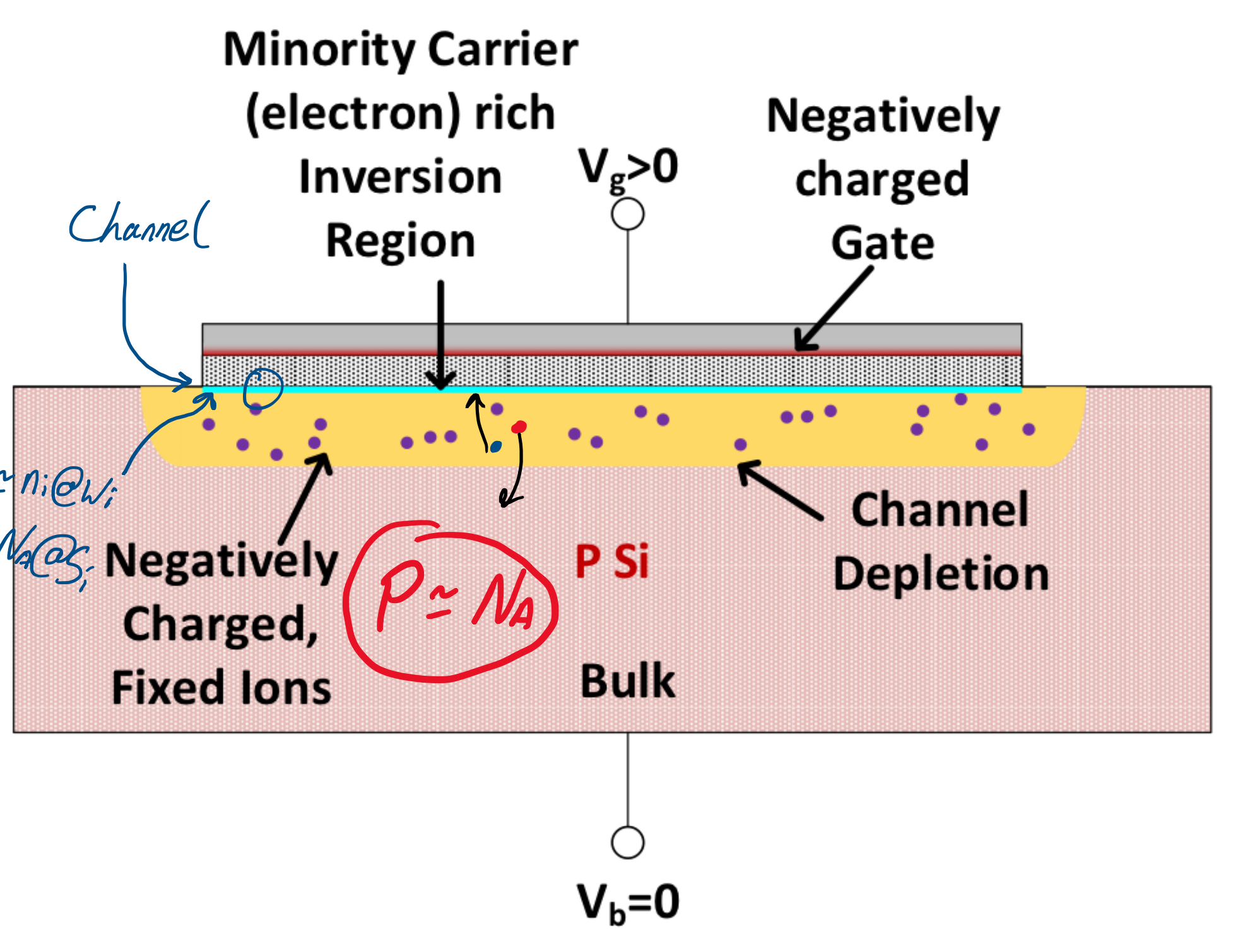
Weak

- **Inversion:** when the minority carrier concentration becomes the same as the intrinsic carrier concentration:

$$n = n_i = p$$

- **Strong Inversion:** when the minority carrier concentration becomes the same as the majority carrier concentration in the bulk:

$$n = N_A$$



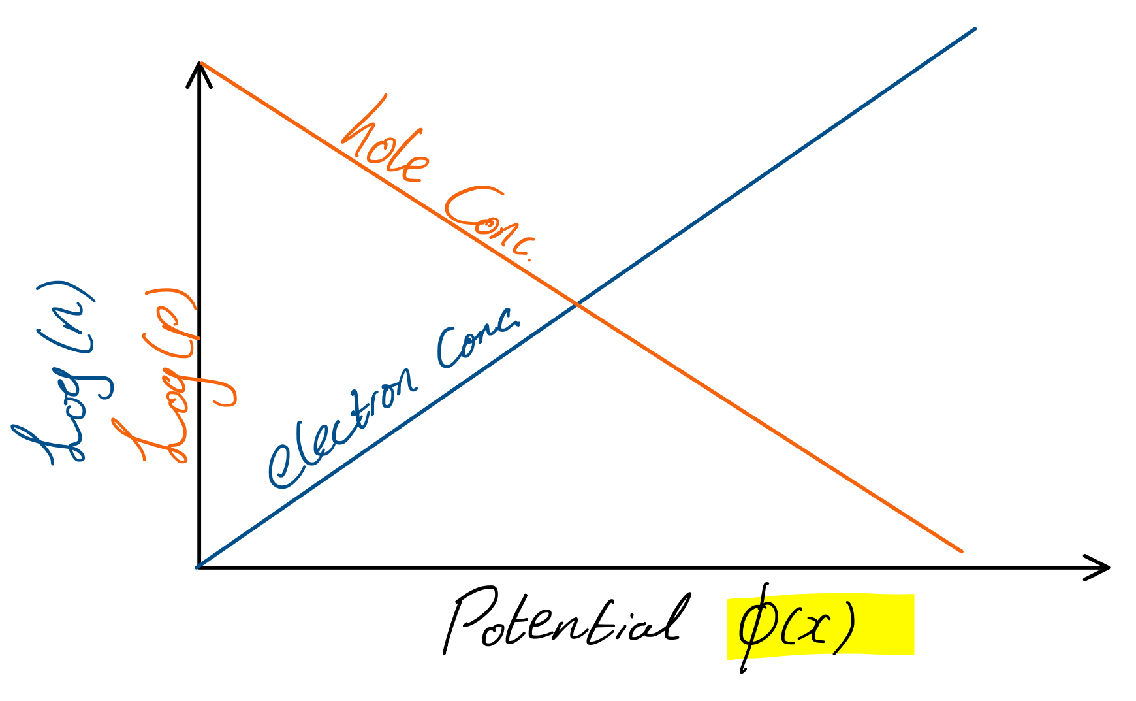
- Thermally generated e-h pairs no longer recombine in depletion region, but split due to $\phi(x)$ gradient
  - Holes go to bulk
  - Electrons go to interface to form channel!

Surface Potential ϕ_s Req.d for Inversion

- Remember Free Carrier Concentration Equations:

free hole Conc: $P(x) = N_A e^{\frac{-q\phi(x)}{kT}}$ ↓

free e Conc.: $n(x) = \frac{n_i^2}{N_A} e^{\frac{+q\phi(x)}{kT}}$ ↑



- At the Interface:

$$p(x=0) = N_A e^{\frac{-q\phi_s}{kT}}$$

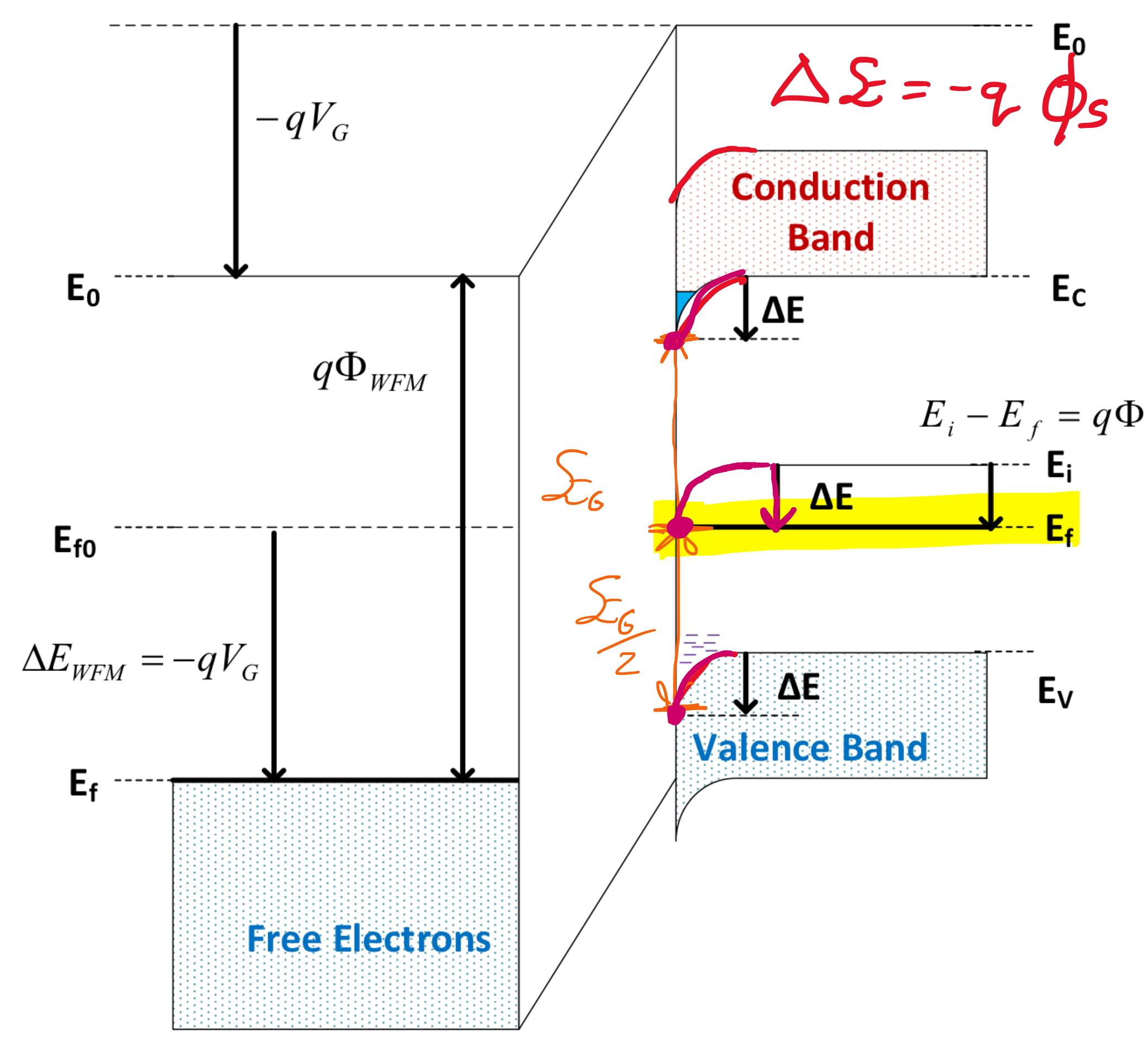
$$n(x=0) = \frac{n_i^2}{N_A} e^{\frac{q\phi_s}{kT}}$$

W_i : $n(x=0) = n_i$

S_i : $n(x=0) = N_A$

What ϕ_s is req.d for WI & SI

Inversion: The Band View



- As V_G increases: ϕ_s increases
  - n increases at the interface
  - p decreases at the interface
- From semiconductor basics we know:

$n = P = n_i$

When $\mathcal{E}_f = \mathcal{E}_i$

- When the Fermi Level equals the intrinsic level!
- Why not bend the bands at the interface so the fermi-level now sits in the middle of the gap?
- For this, we need the surface potential to equal the fermi potential:

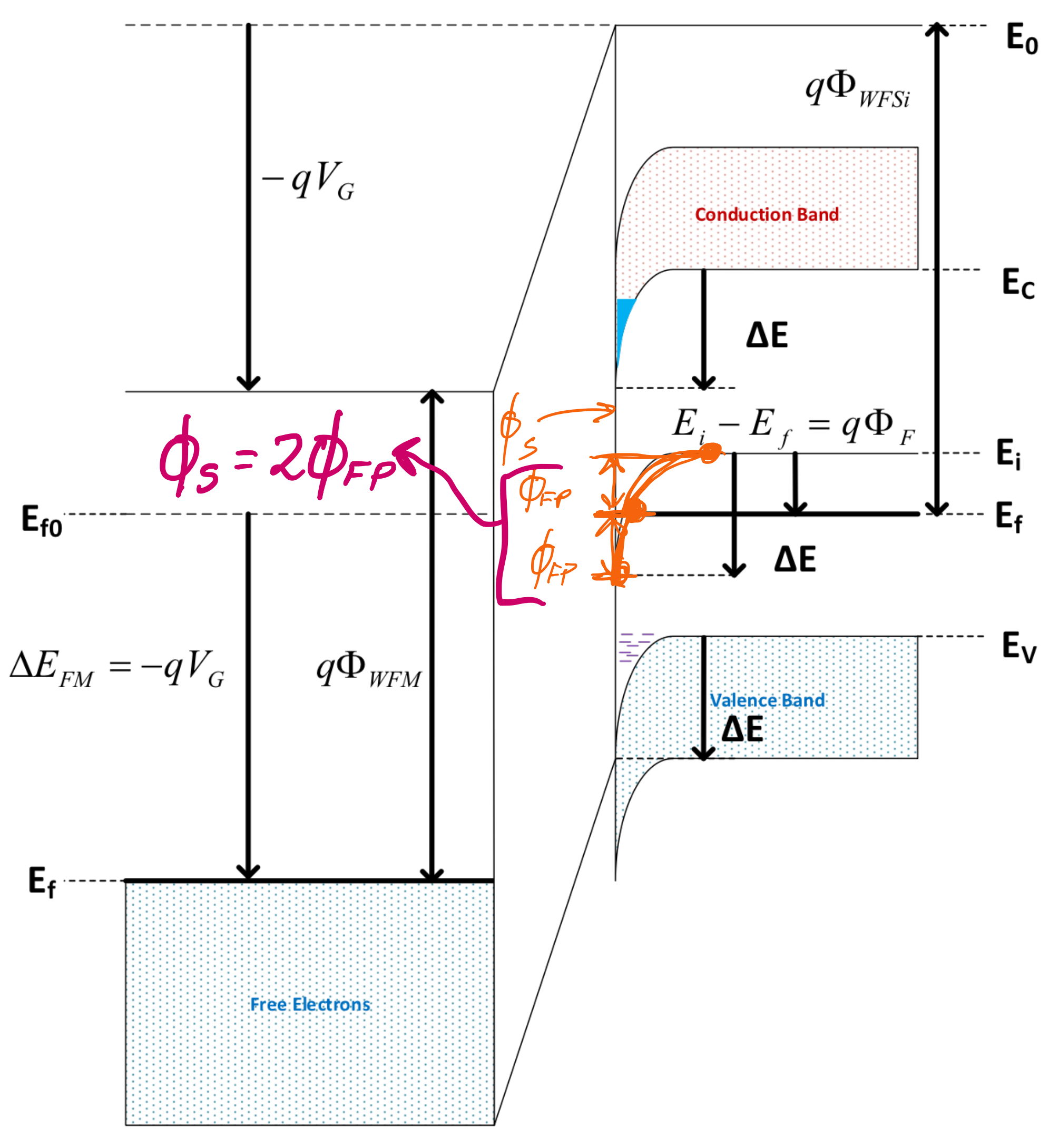
$$\Delta \mathcal{E} = (\mathcal{E}_f - \mathcal{E}_i)$$

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

$$\phi_s = \phi_F$$

- **This is the surface potential required for onset of weak inversion!**

Strong Inversion: The Band View



- For **Strong Inversion** we require:

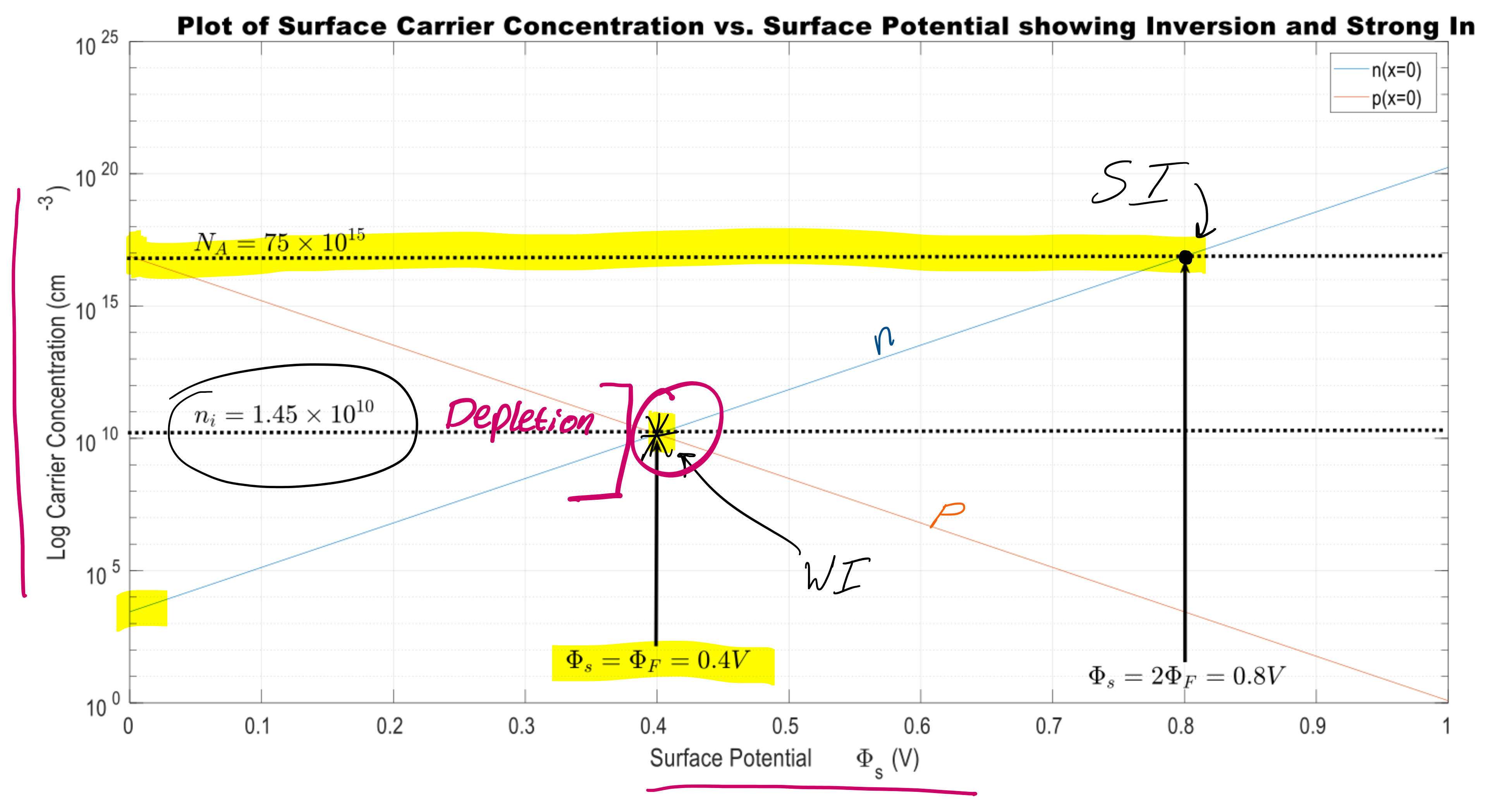
$$n(x=0) = N_A$$

- A Fermi Potential ϕ_{FP} yields $P = N_A$ in the unbent case.
- In order to flip this, and obtain $n = N_A$, our bands must bend so that the Fermi Level $\mathcal{E}_f$ crosses the intrinsic level $\mathcal{E}_i$ and then continues the same distance again
- Thus for Strong Inversion, we require Surface Potential:

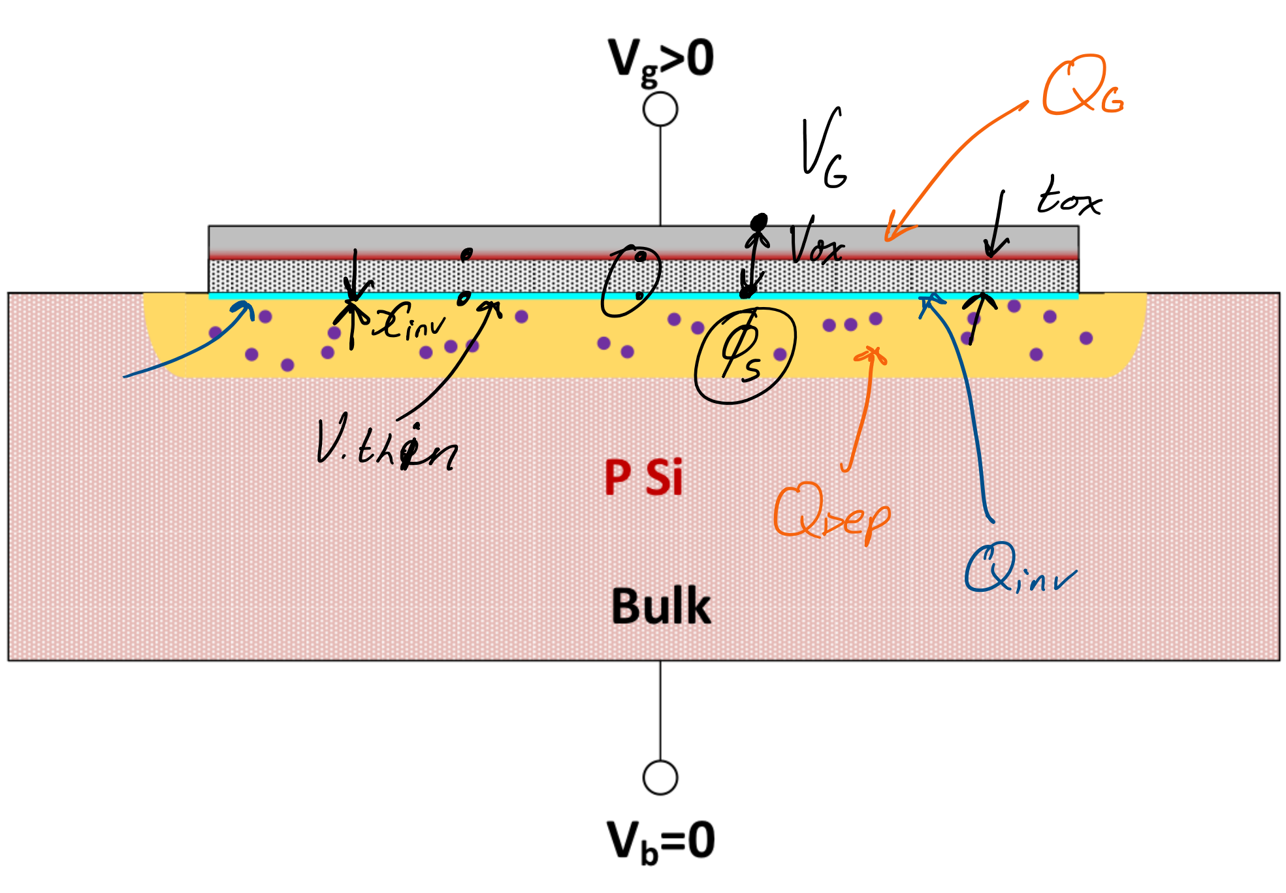
$$\phi_s = 2\phi_{FP}$$

- **This is the Surface Potential Required for the Onset of Strong Inversion!**
- We have moved the bands here and kept the Fermi Level the same.
  - This is equivalent to flipping the Fermi Level about the Intrinsic level by removing the p-type dopant and replacing it with with an equal amount of n-type
    Thus flipping the Fermi Level

A Practical Example of Surface Inversion



Inversion Charge & Inversion Capacitance



- Let's focus on Strong Inversion
  - Device is fully 'on' → Strong Inversion

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

- High Concentration of minority carriers (e) forming channel at the interface
- Similar to Accumulation, the Potential, thus charge is governed by the Debye Length:

$$x_{inv} \leq \frac{\pi}{\sqrt{2}} L_D$$

  - This layer is thus very thin, only nm thick
  - This allows us to assume a parallel plate Capacitor similar to Accumulation Case
- Total Capacitance Given by:

$$C_{inv} \simeq C_{ox} \rightarrow \frac{\varepsilon_{SiO_2}}{t_{ox}}$$

- To Relate Surface Potential ϕ_s to Inversion Charge, use KVL:

$$V_G = \phi_s + V_{ox} = \phi + \frac{Q_G}{C_{ox}}$$

- So then what is Q_G ?
- We know that minority carrier conc. (Inversion Charge) is given by:

$$n(x) = \frac{n_i^2}{N_A} e^{\frac{q\phi(x)}{kT}}$$

We imagine if we integrate this for inversion charge, we would get a term:

$$Q_{inv} \propto e^{\frac{q\phi_s}{kT}} \rightarrow \phi_s \propto Log(Q_{inv})$$

Changes by a lot...

ϕ_s Stays pretty Const

- This tells us that our surface potential ϕ_s will change very little as inversion charge increases. Thus we can approximate in Strong Inversion:

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

- We know Q_G is the combination of Depletion & Inversion Charge:

$$Q_G = Q_{dep} + Q_{inv}$$

- From before:

$$Q_{dep} = \sqrt{2q\varepsilon_{Si} N_A \phi_s}$$

$$Q_{dep} = \sqrt{4q\varepsilon_{Si} N_A \phi_{FP}}$$ ← Constant

- Inversion Charge from Capacitor Equation:

$$Q_{inv} = \frac{V_G - \overset{2\phi_{FP}}{\phi_s}}{C_{ox}} = \frac{V_G - 2\phi_{FP}}{C_{ox}}$$

- Total Gate Charge:

$$Q_G = \sqrt{4q\varepsilon_{Si} N_A \phi_{FP}} + \frac{V_G - 2\phi_{FP}}{C_{ox}}$$

* V_G Controls Chg. in Channel
↓
Conductivity function of Charge

Aside: Capacitance Vs Gate Voltage