From *Semiconductor Physics and Devices: Basic Principles* (4th Edition), Donald A. Neamen, McGraw Hill, 2012, ISBN 978-0-07-352958-5.

p type MOS

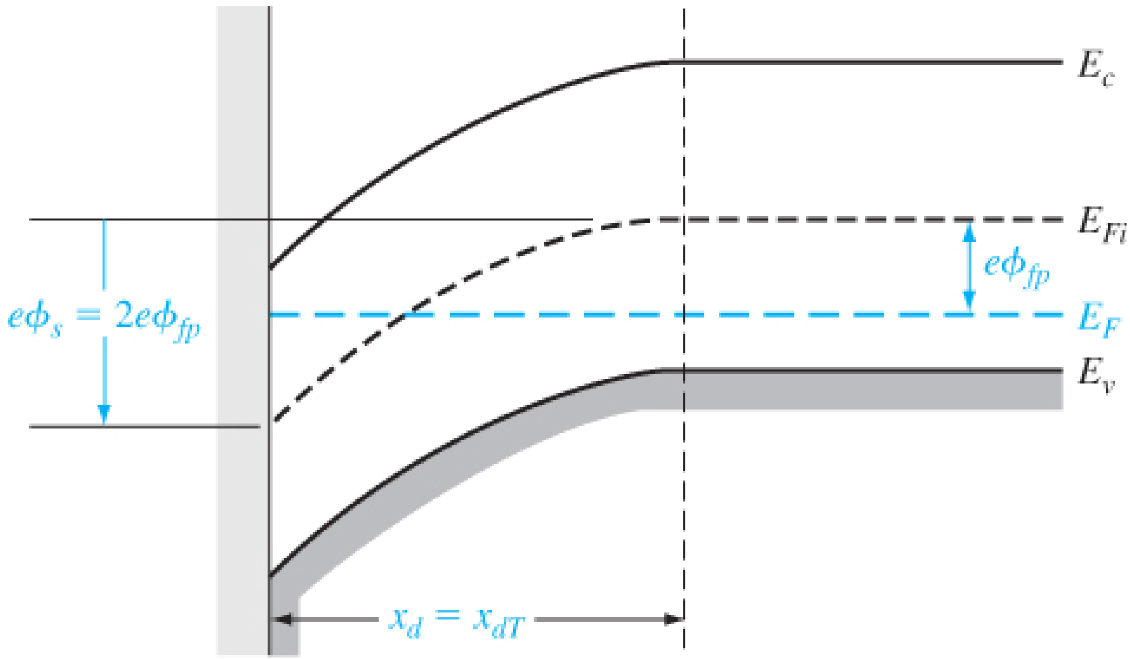

Figure 10.9 | The energy-band diagram in the p-type semiconductor at the threshold inversion point.

- We choose to define the surface inversion as "The point at which the surface is as much n type as the bulk material is p type." This is called the **threshold inversion point**.
- This means E_{Fi} must be as much below E_F at the surface (boundary between the semiconductor and oxide) as it is above E_F in the bulk semiconductor substrate. For energy levels expressed in terms of these potentials, $e\,\phi_s = 2\,e\,\phi_{fp}$ at the threshold inversion point.
- This implies that the surface potential $\phi_s = 2\,\phi_{fp}$ (called the **threshold voltage**) where $\phi_{fp} = V_t \ln\left(\frac{N_a}{n_i}\right)$.
- Therefore, the depletion layer depth/thickness is $x_{dT} = \left(\frac{4\varepsilon_s \phi_{fp}}{eN_a}\right)^{1/2} = \sqrt{\frac{4\varepsilon_s \phi_{fp}}{eN_a}}$.

  It does not change much with increasing ϕ_s beyond the threshold voltage.

n type MOS

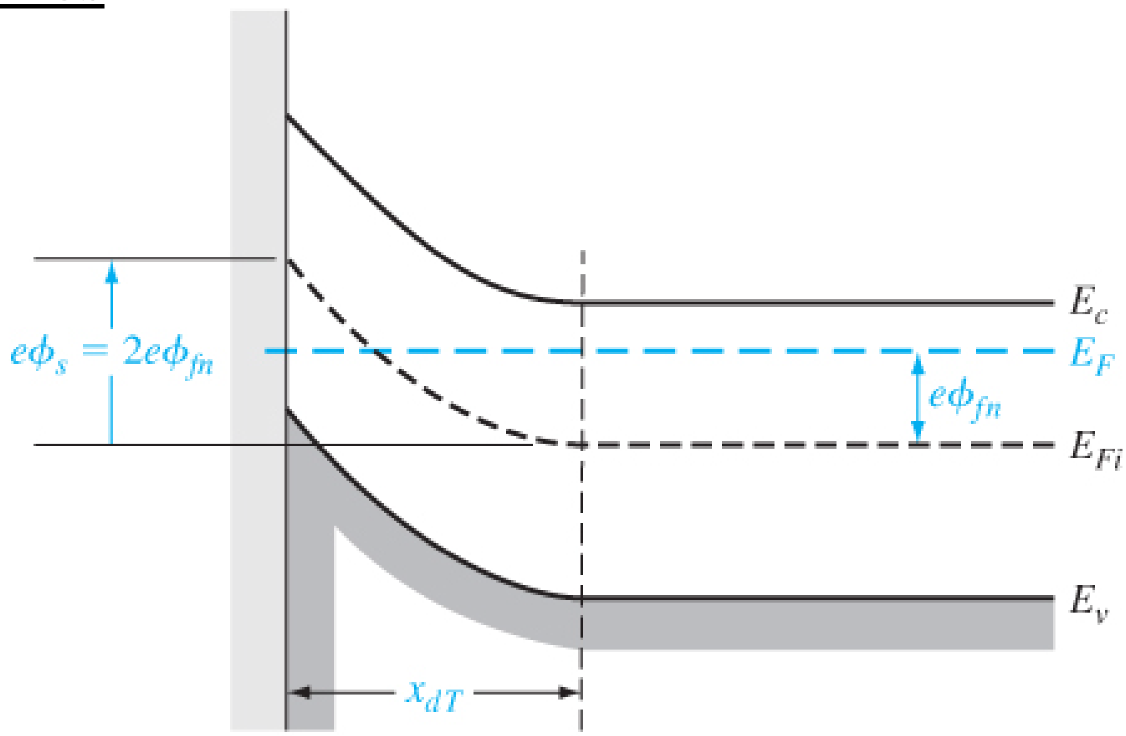

Figure 10.10 | The energy-band diagram in the n-type semiconductor at the threshold inversion point.

- We choose to define the surface inversion as "The point at which the surface is as much p type as the bulk material is n type."
- This means E_{Fi} must be as much above E_F at the surface (boundary between the semiconductor and oxide) as it is below E_F in the bulk n type substrate.
- In terms of energy, $e\,\phi_s = 2\,e\,\phi_{fn}$.
- This implies that the surface potential $\phi_s = 2\,\phi_{fn}$ where $\phi_{fn} = V_t \ln\left(\frac{N_d}{n_i}\right)$.
- Therefore, the depletion layer depth/thickness is $x_{dT} = \left(\frac{4\varepsilon_s \phi_{fn}}{e N_d}\right)^{1/2} = \sqrt{\frac{4\varepsilon_s \phi_{fn}}{e N_d}}$.

Threshold Point

- One might assume that the threshold would occur as soon as surface potential $\phi_s = \phi_{fp}$, because the concentration of majority carriers has been reduced to that of an intrinsic semiconductor at that point.
- However, as ϕ_s increases, the retreating holes "uncover" the negatively charged dopant ions N_a^- in the crystal lattice of the p-type substrate at the boundary. These fixed ions repel the electrons needed to produce a current between the source and drain (when we get to the MOSFET).
- When ϕ_s is increased to $\mathbf{2\phi_{fp}}$, the dopant ions are completely uncovered, such that further increases in the gate-source voltage causes electrons to flood into the channel instead of making significant increases in band bending.
- In other words, an n-layer starts to form when $\phi_s = \phi_{fp}$, but moving charges don't happen until $\phi_s = 2\phi_{fp}$.

Example- Find the potential ϕ_{fn} and depletion layer depth x_d when we have germanium doped to $N_d = 10^{15}$ cm^{-3} = 10^{21} m^{-3} at 300 K. Also, find the threshold surface potential and depth.

From Table B.4- $n_i = 2.4 \times 10^{13}$ cm^{-3} and $\varepsilon_s = 16\varepsilon_0$.

Per (7.10), $V_t = \dfrac{k_B T}{e} = \dfrac{8.617333\times10^{-5}\,\text{eV/K (300 K)}}{e} \quad \Rightarrow \quad \underline{V_t = 0.025852\text{ V}}$.

Per (10.7), $\phi_{fn} = V_t \ln\left(\dfrac{N_d}{n_i}\right) = 0.025852\ln\left(\dfrac{10^{15}}{2.4\times10^{13}}\right) \quad \Rightarrow \quad \underline{\phi_{fn} = 0.09642\text{ V}}$.

Adapting equation (10.5), we get

$$x_d = \sqrt{\frac{2\varepsilon_s\phi_{fn}}{eN_d}} = \sqrt{\frac{2(16)8.8541878\times10^{-12}(0.09642)}{1.602176634\times10^{-19}(10^{21})}} \quad \Rightarrow \quad \underline{x_d = 4.13\times10^{-7}\text{ m}}.$$

The threshold voltage is $\phi_s = 2\phi_{fn} = 2(0.09642) \quad \Rightarrow \quad \underline{\phi_s = 0.19284\text{ V}}$.

The maximum depth, per equation (10.8), is

$$x_{dT} = \sqrt{\frac{4\varepsilon_s\phi_{fn}}{eN_d}} = \sqrt{\frac{4(16)8.8541878\times10^{-12}(0.09642)}{1.602176634\times10^{-19}(10^{21})}} \quad \Rightarrow \quad \underline{x_{dT} = 5.84\times10^{-7}\text{ m}}.$$