Spring 2019 Purdue University

ECE 255: L5

Energy Band Diagrams

Mark Lundstrom
School of ECE
Purdue University
West Lafayette, IN USA

Energy band diagrams

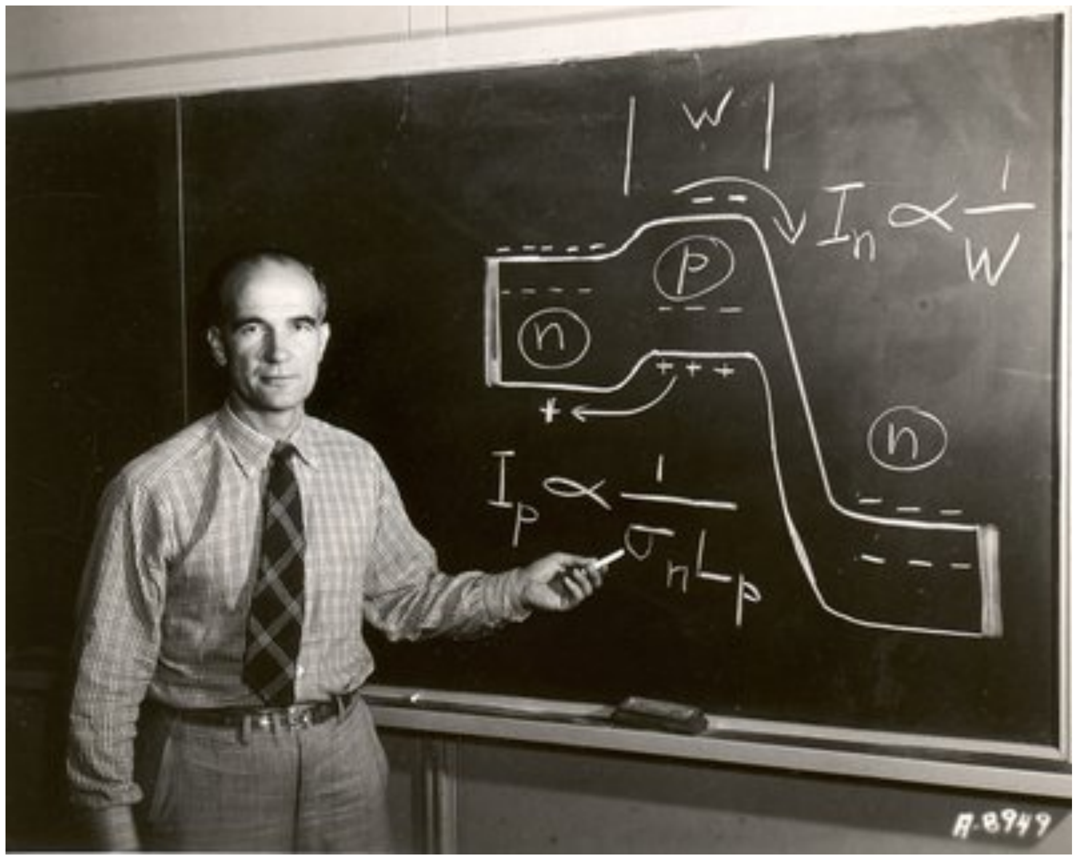
1) Band bending and the electrostatic potential
2) “Reading” an energy band diagram
3) PN junctions
4) Energy band diagram of a PN junction in equilibrium
5) Forward bias and reverse bias
6) The built-in potential

Energy band diagrams

An energy band diagram is a plot of the bottom of the conduction band and the top of the valence band vs. position.

Energy band diagrams are a powerful tool for understanding semiconductor devices because they provide **qualitative solutions to the semiconductor equations**.

Energy band diagrams



https://www.pbs.org/wgbh/americanexperience/features/silicon-timeline-silicon/

Kroemer's lemma of proven ignorance

"Whenever I teach my semiconductor device physics course, one of the central messages I try to get across early is the importance of energy band diagrams. I often put this in the form of "Kroemer's lemma of proven ignorance:

> If, in discussing a semiconductor problem, you cannot draw an **Energy Band Diagram**, this shows that **you** don't know what you are talking about."

(Nobel Lecture, 2000)

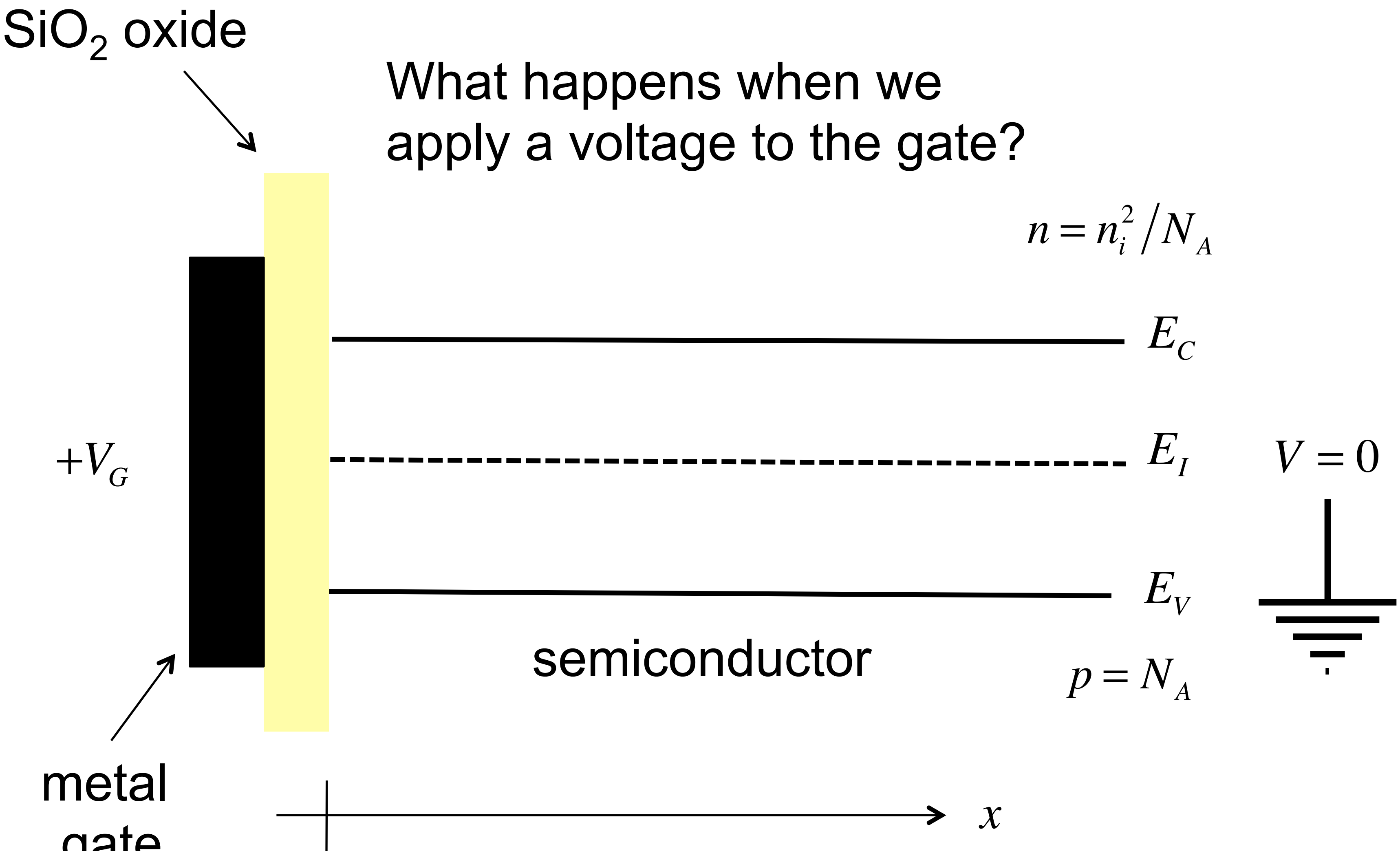
Kroemer's corollary

If you can draw one, but don't, then **your audience** won't know what you are talking about."

(Nobel Lecture, 2000)

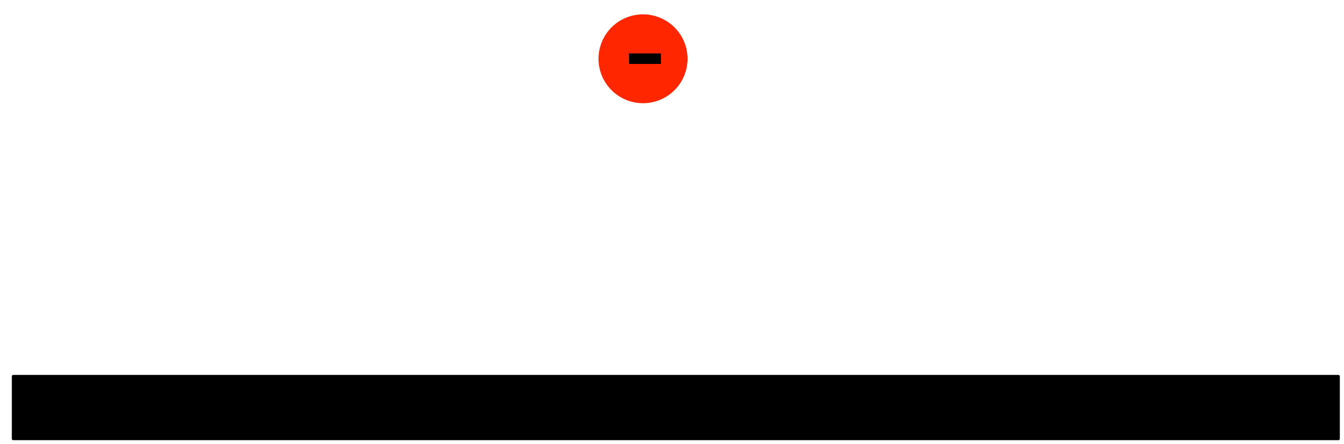
Band bending in an MOS structure

What happens when we apply a voltage to the gate?



Voltage and electron potential energy

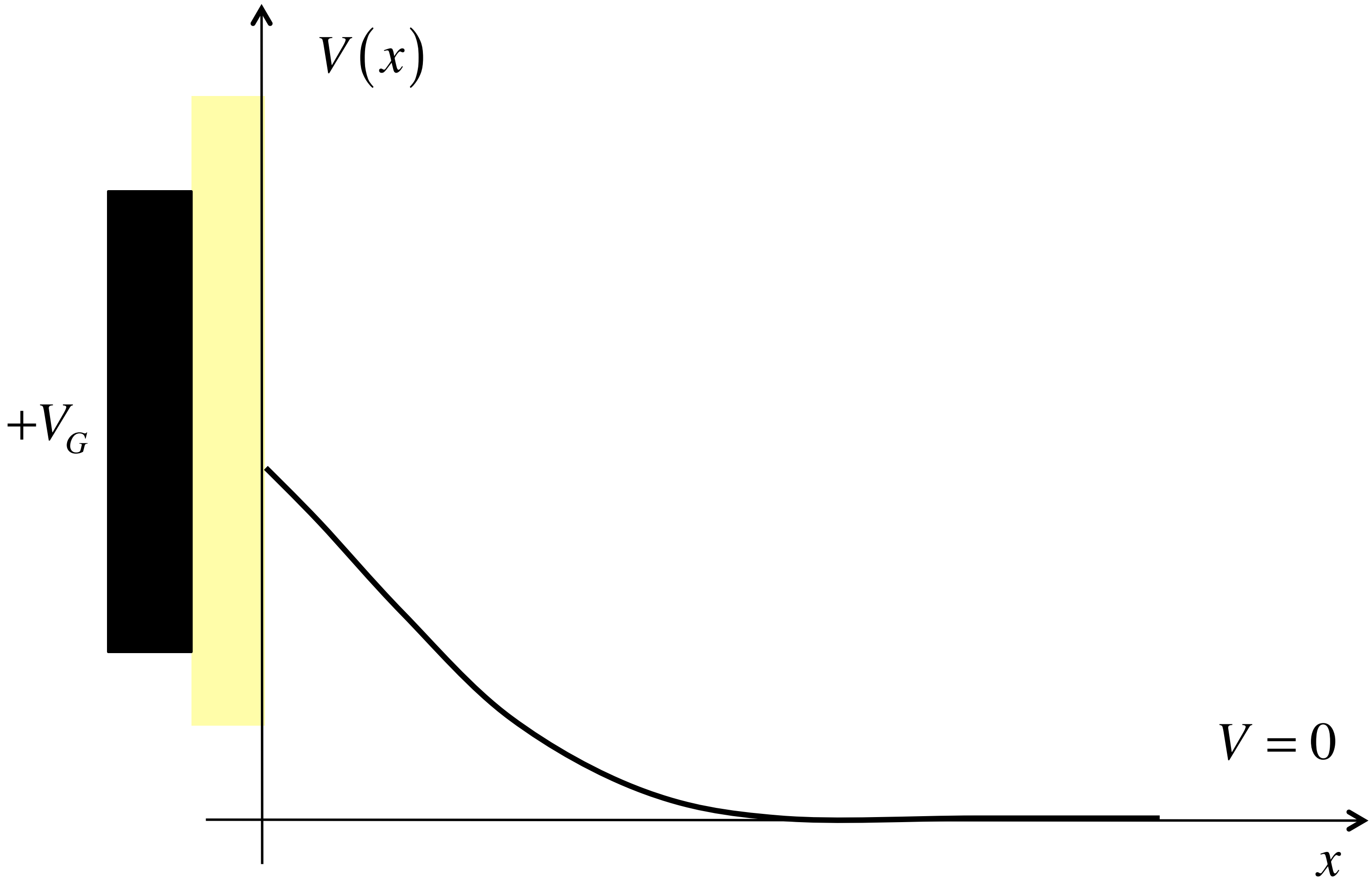
$$E = -qV$$



$$+V$$

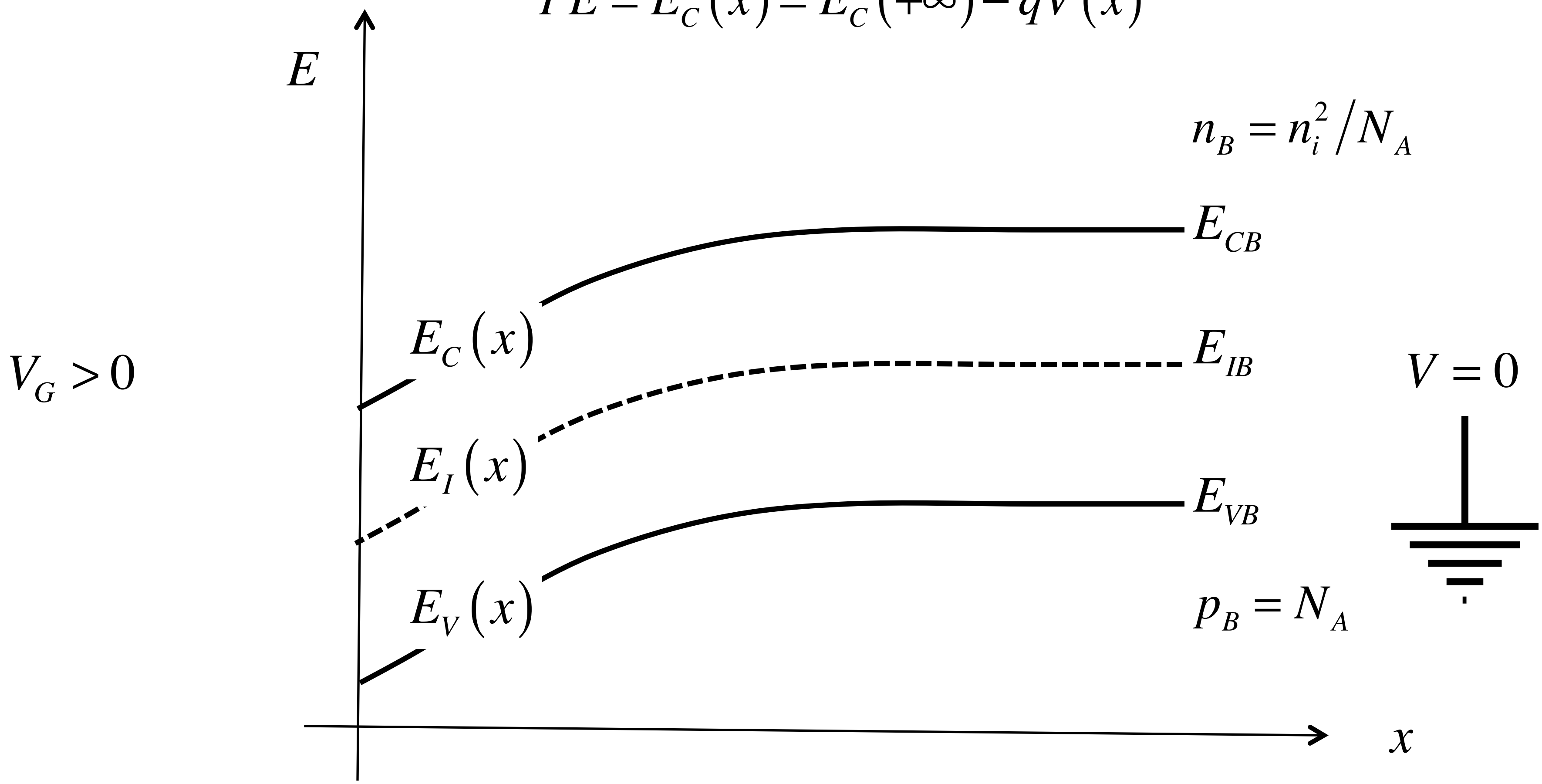
A positive potential **lowers** the energy of an electron.

Electrostatic potential vs. position

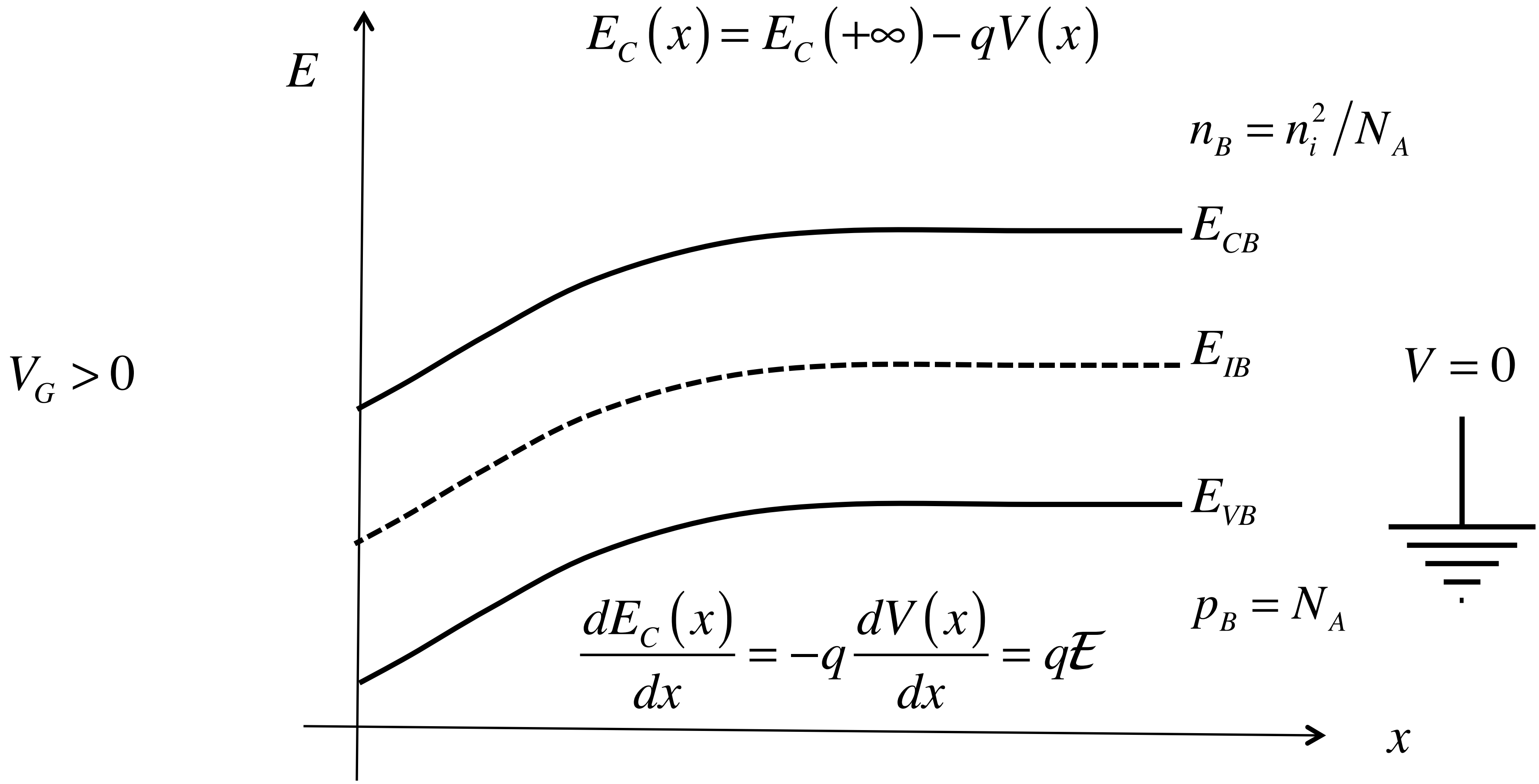


Electrostatic potential causes band bending

$$PE = E_C(x) = E_C(+\infty) - qV(x)$$

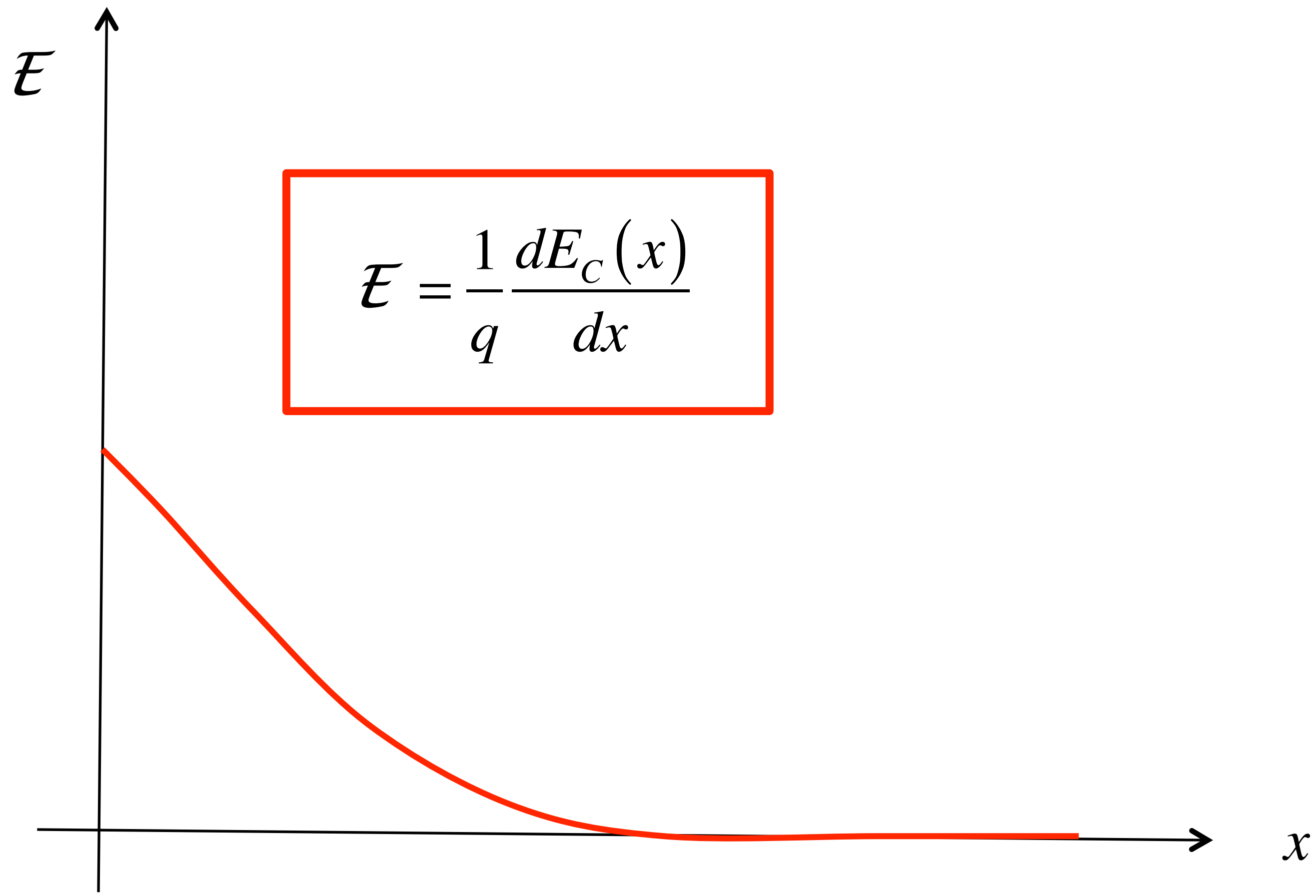


Electric field



The electric field is proportional to the slope of *E*$_C$

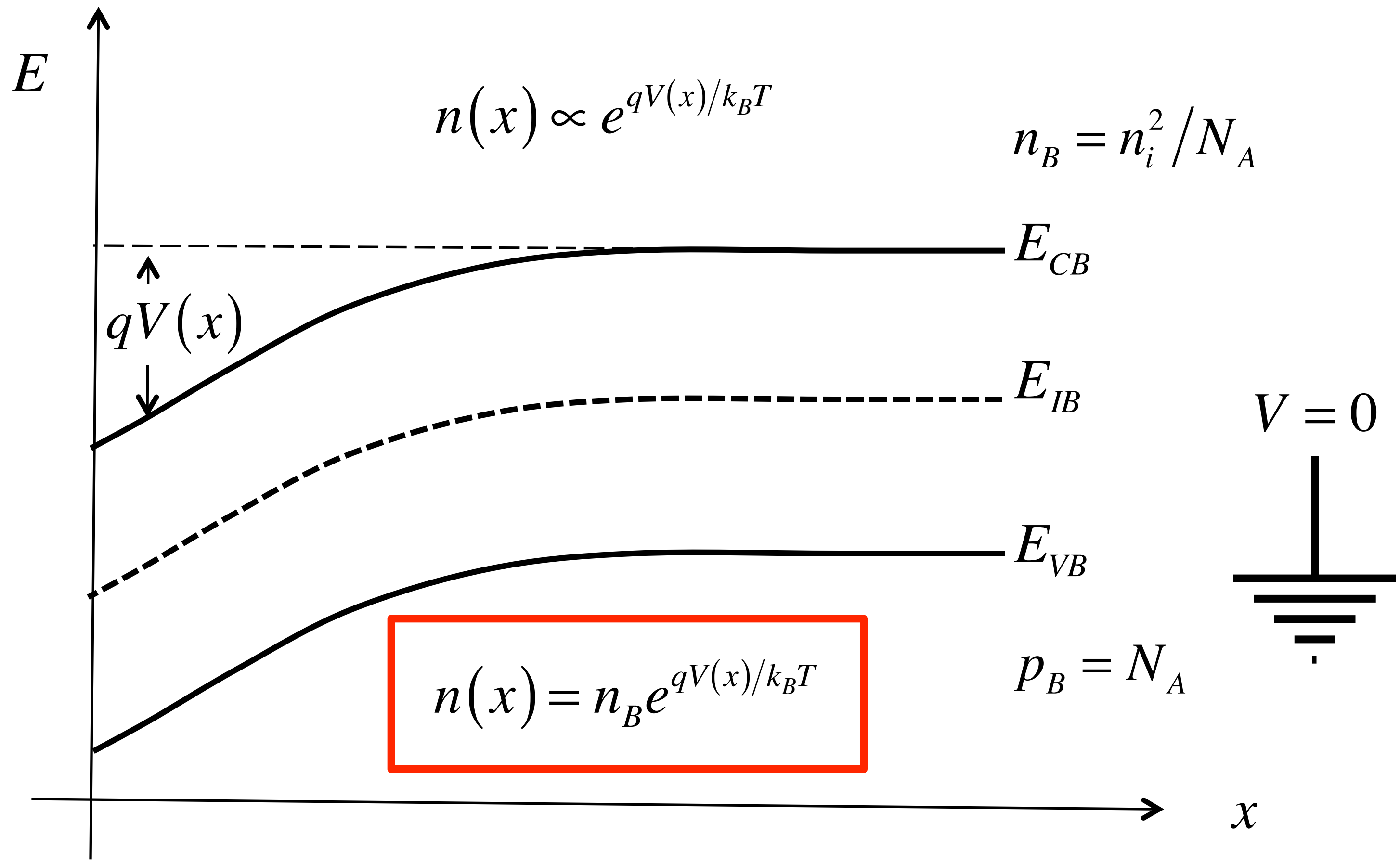
Electric field



$$\mathcal{E} = \frac{1}{q}\frac{dE_C(x)}{dx}$$

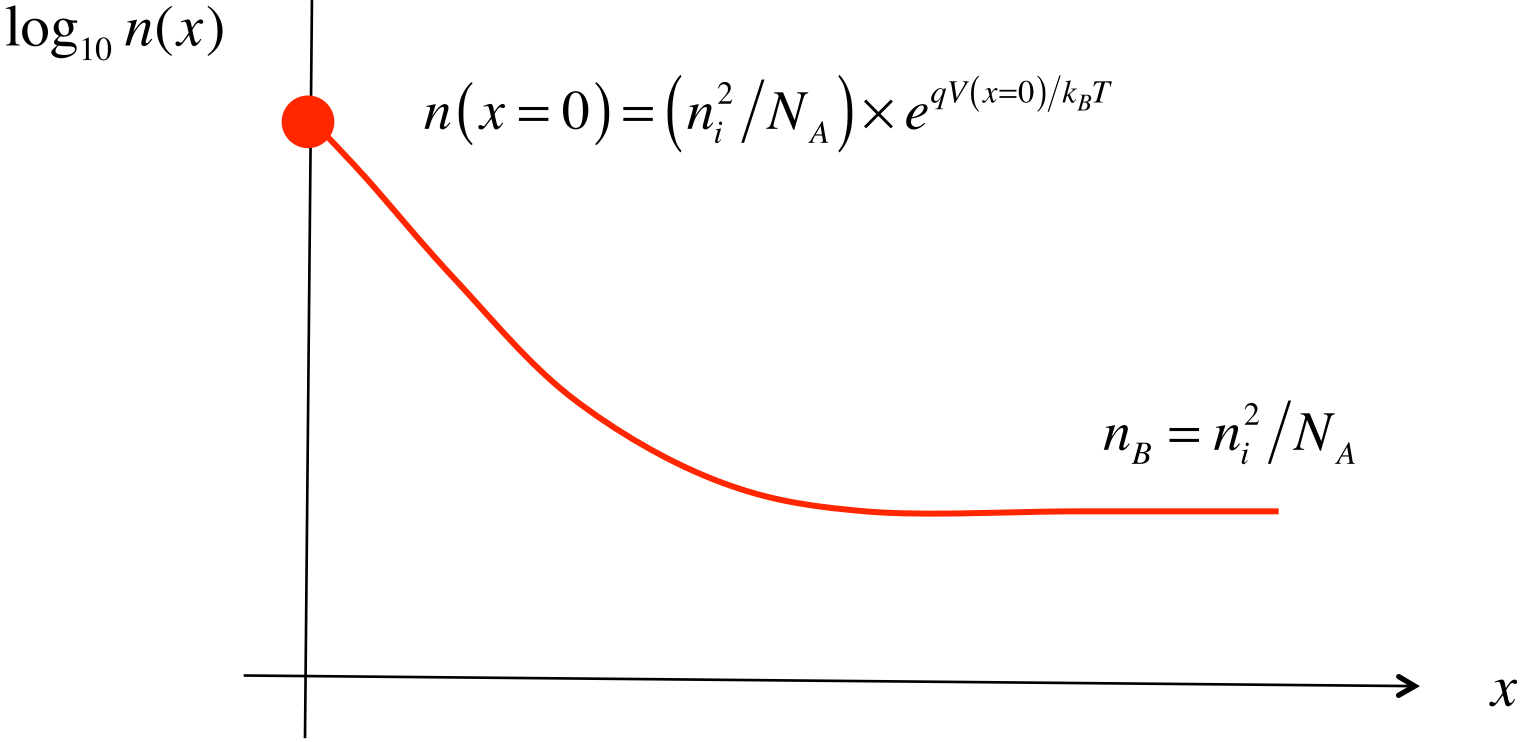
The electric field is proportional to the slope of E_C

Electron concentration

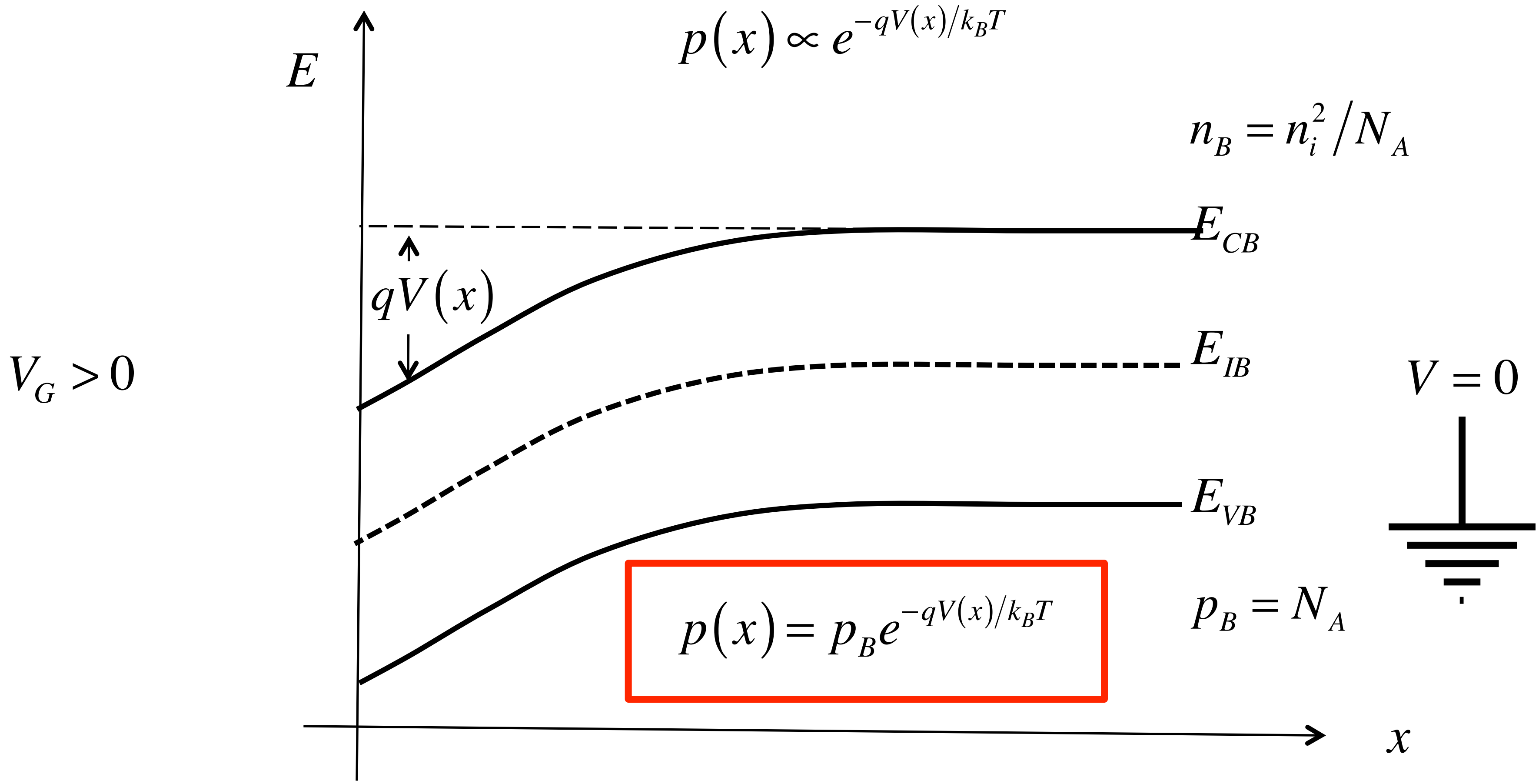


Electron concentration

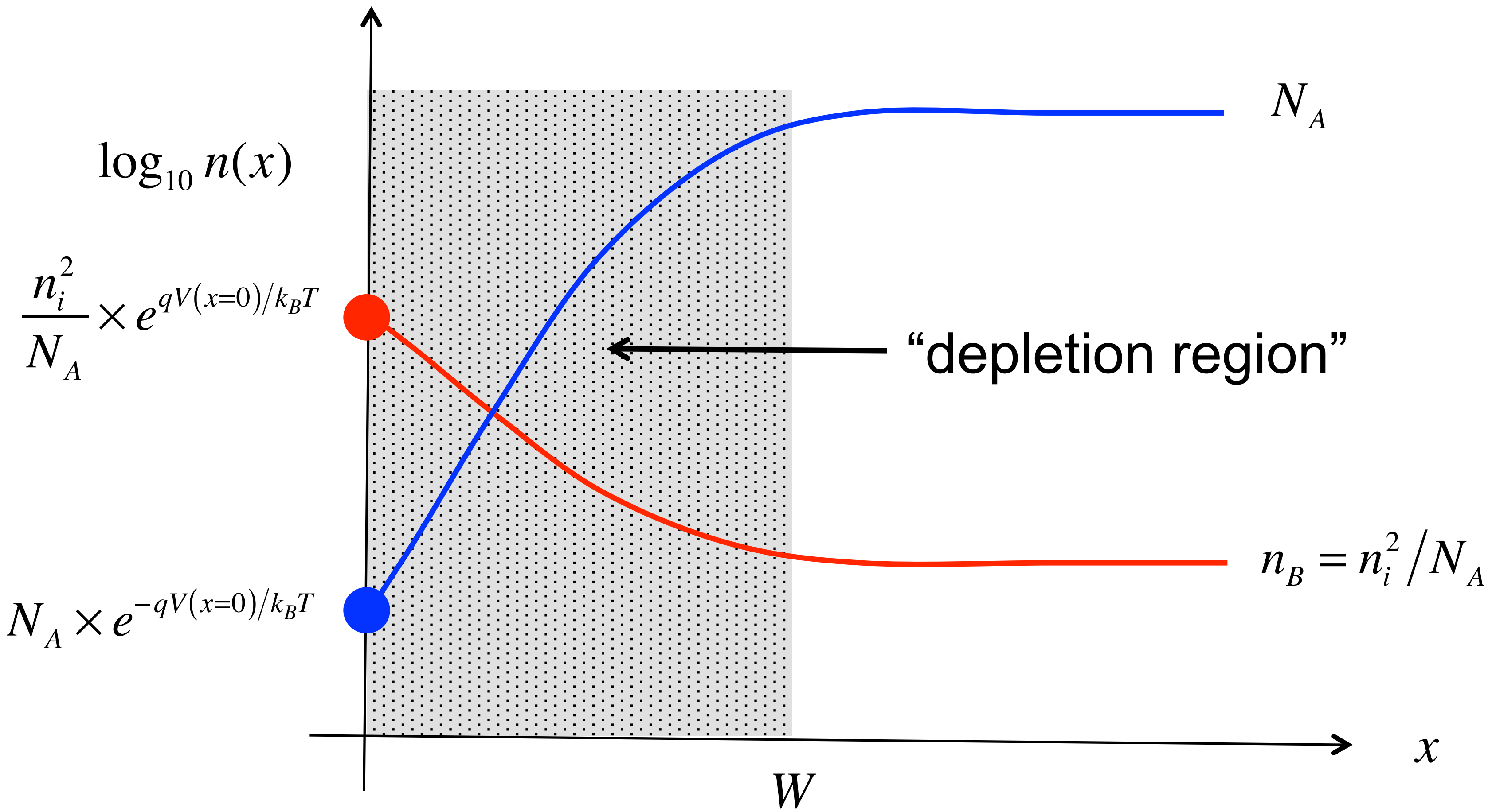
$$n(x) = n_B e^{qV(x)/k_B T}$$



Hole concentration

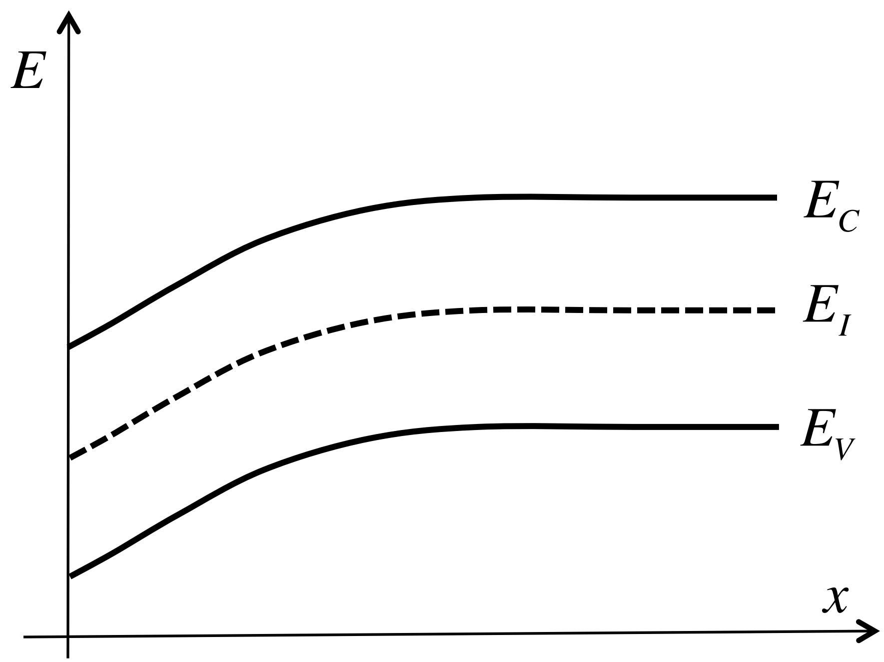


Electron and hole concentrations



Summary: Band diagrams

A band diagram



Reading the band diagram

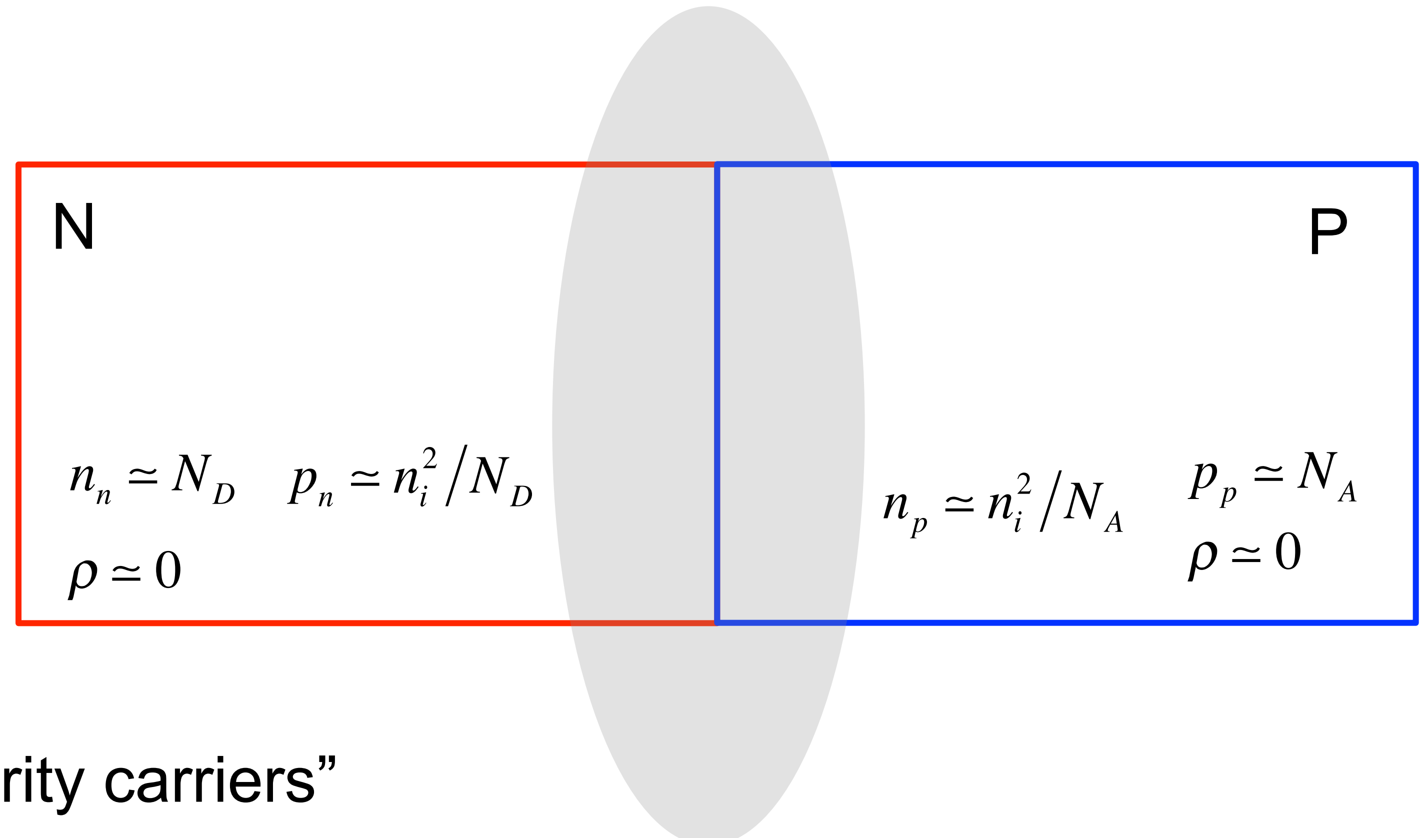
$$V(x) \propto -E_C(x)$$

$$\mathcal{E} \propto dE_C(x)/dx$$

$$\log n(x) \propto E_{CB} - E_C(x)$$

$$\log p(x) \propto E_V(x) - E_{VB}$$

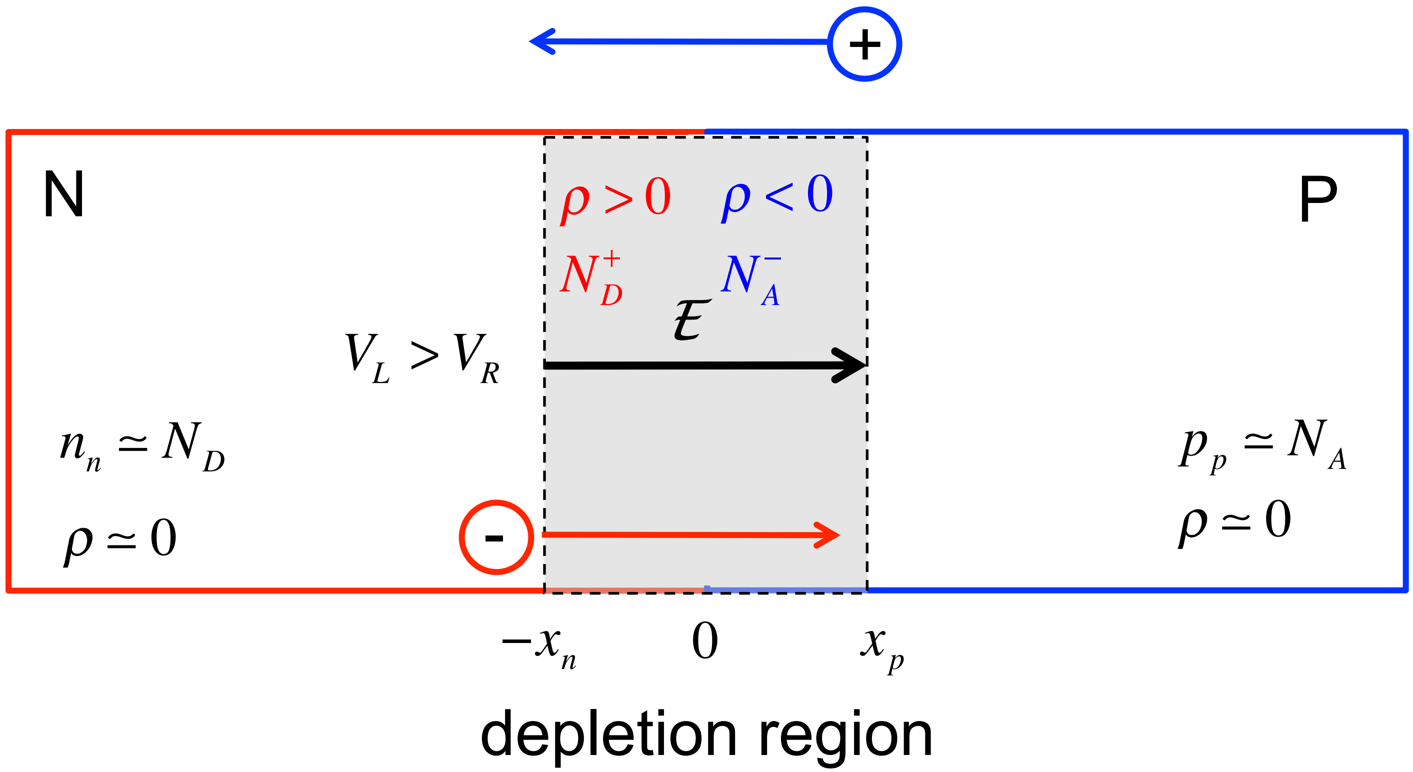
Another example: NP junction (equilibrium)



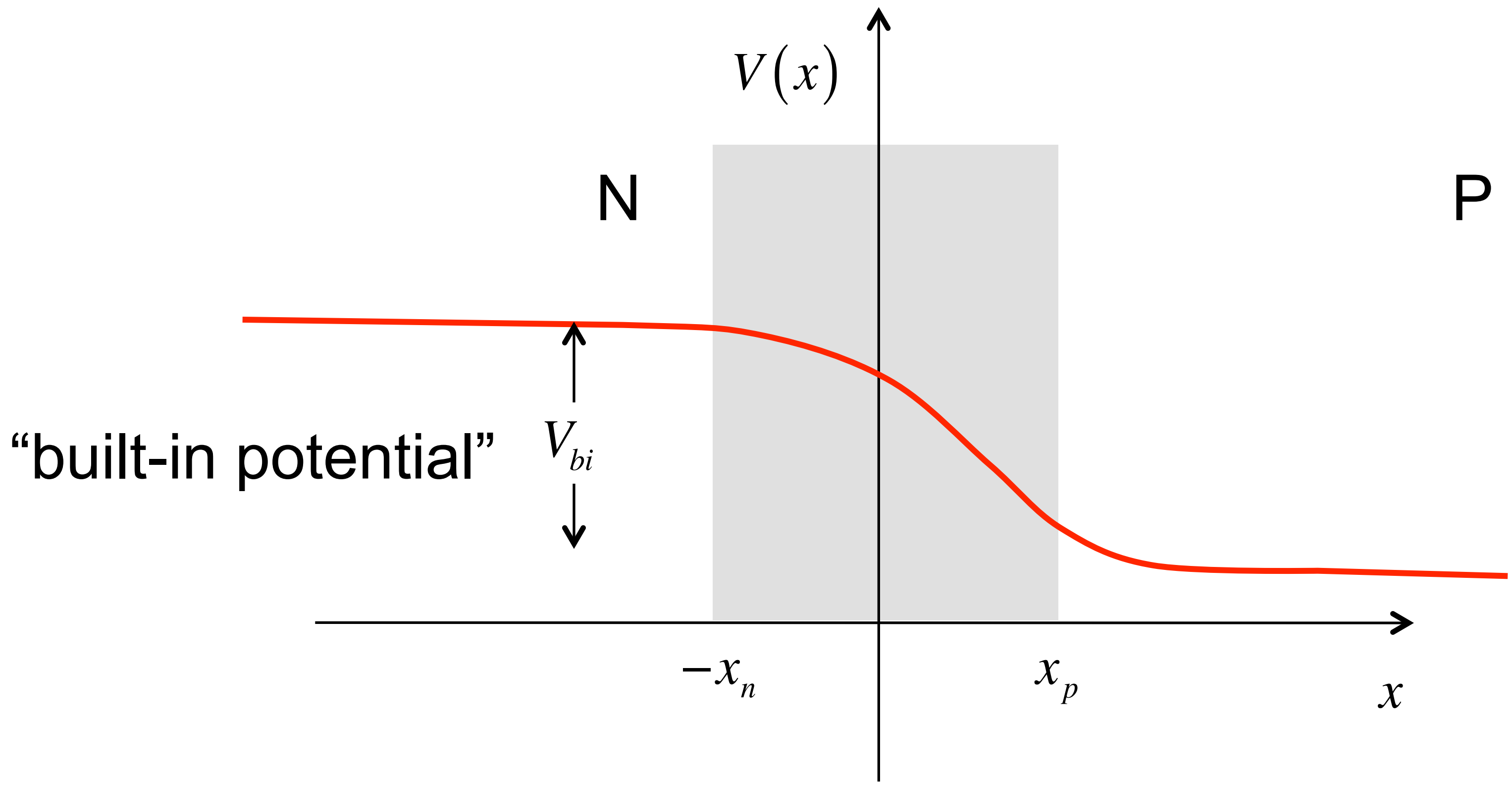
“majority carriers”

“minority carriers”

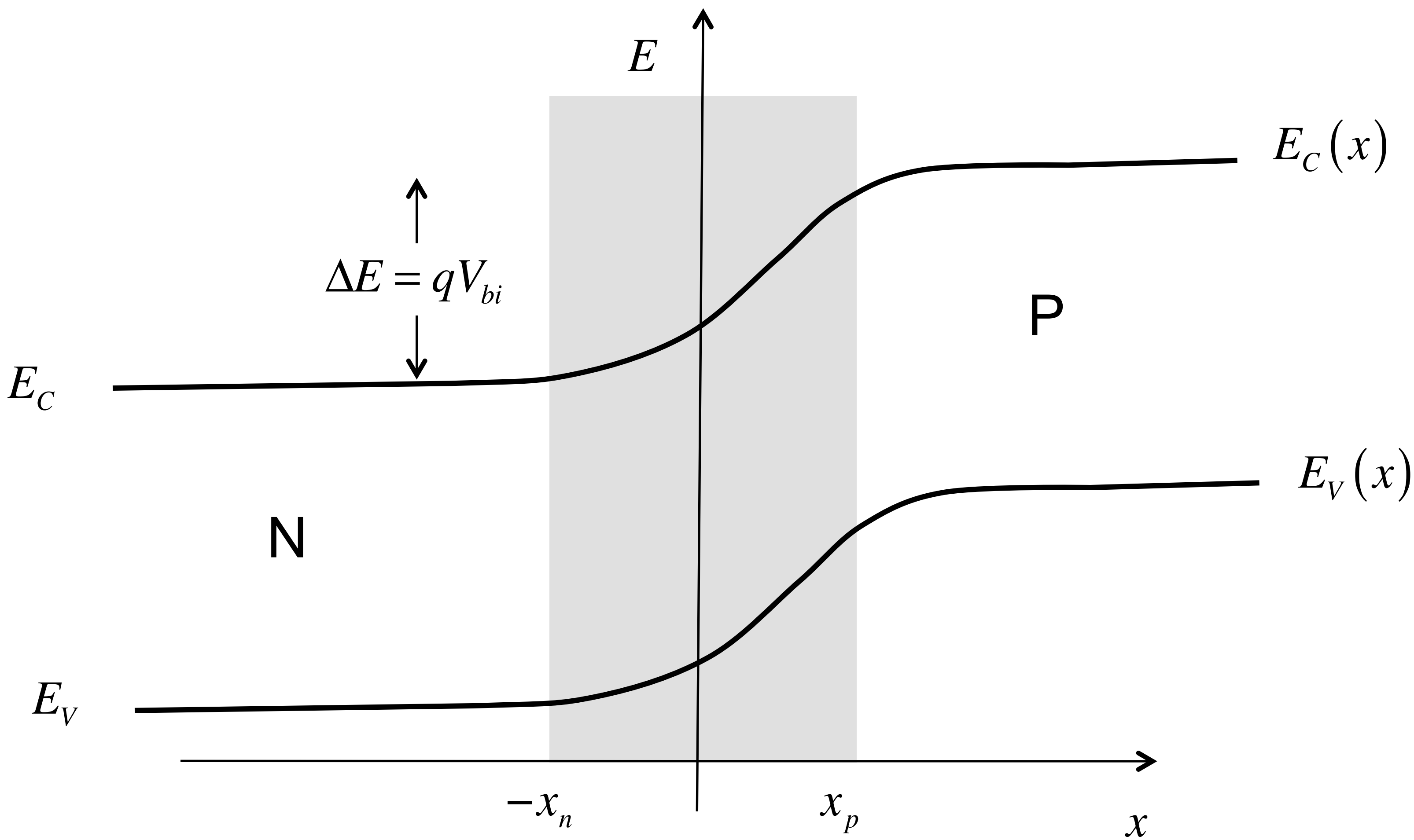
NP junction (equilibrium)



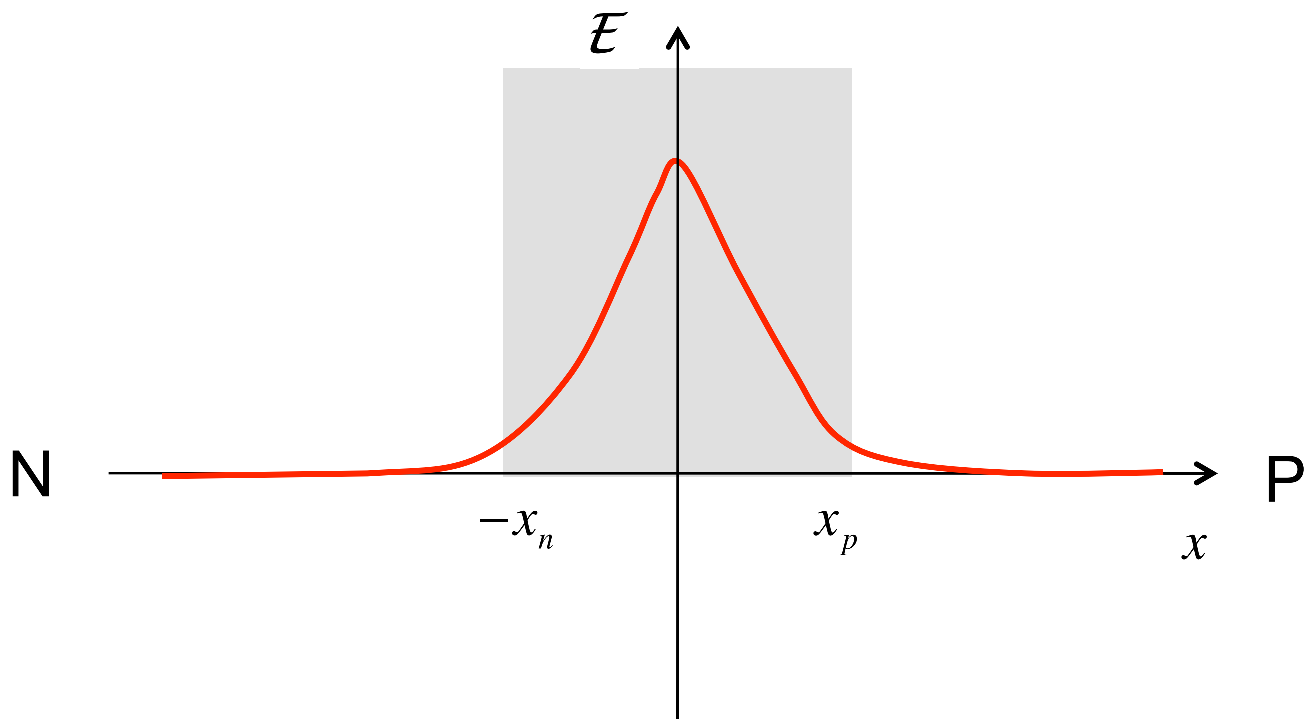
Voltage vs. position



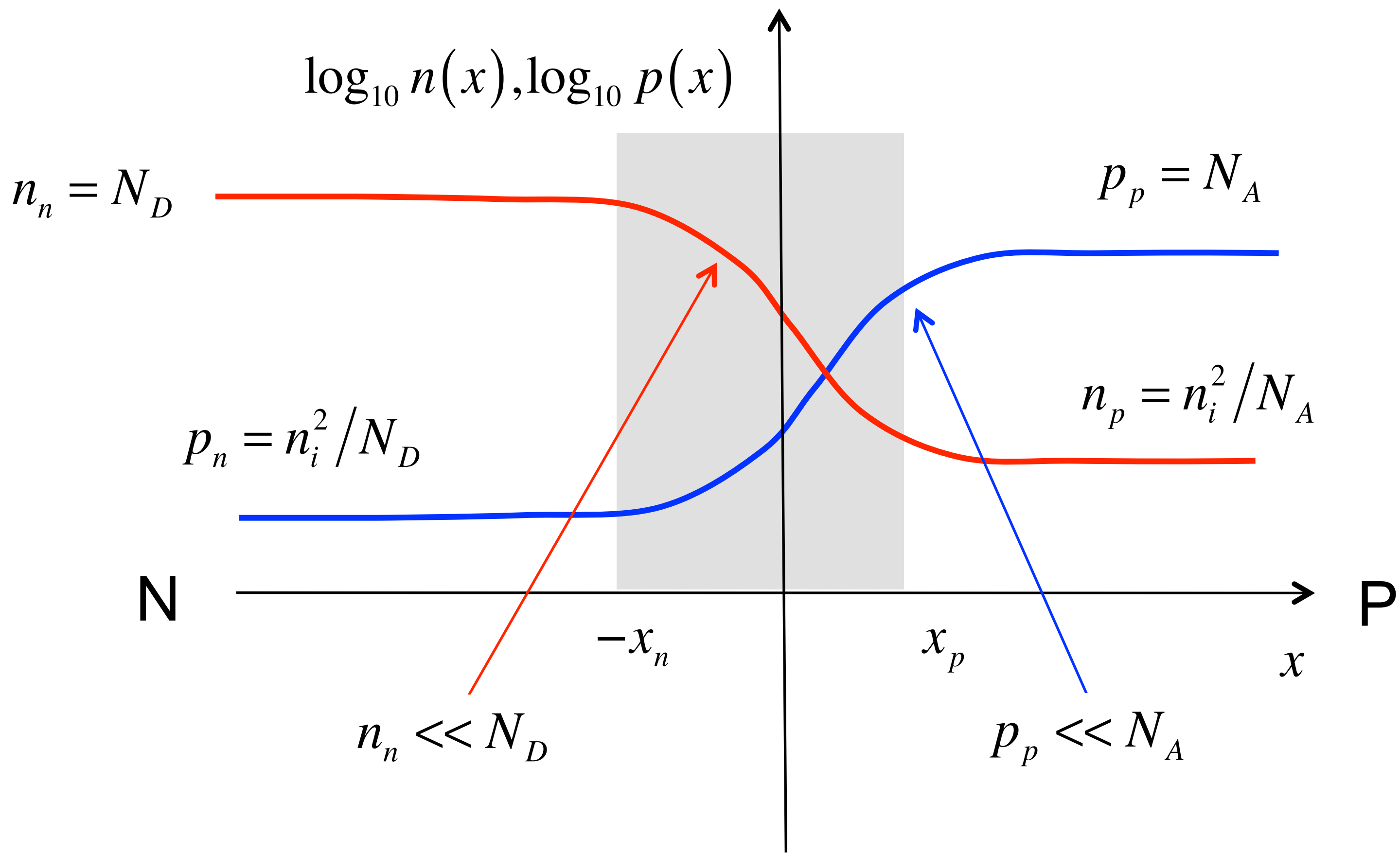
Electron energy vs. position



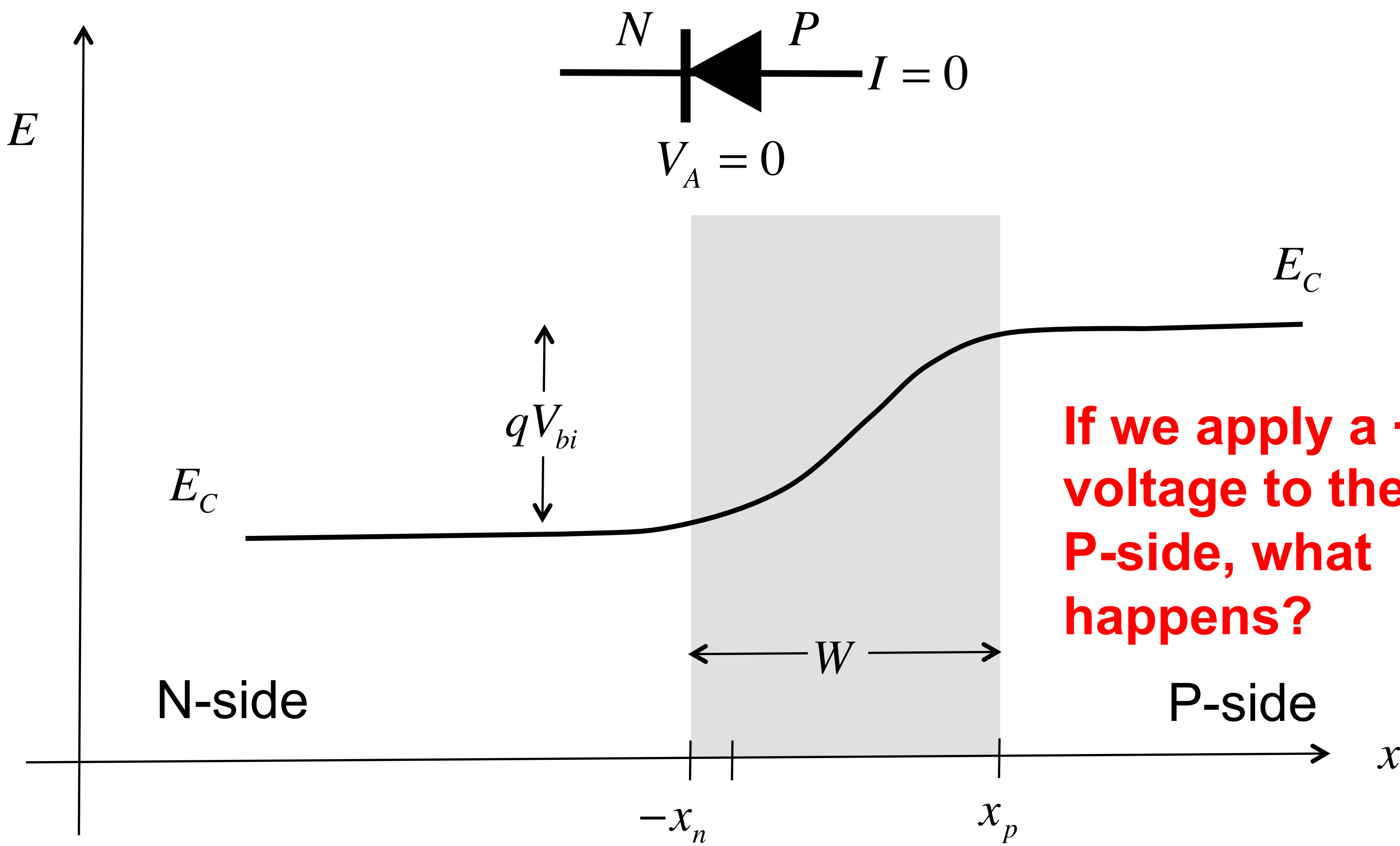
Electric field vs. position



Carrier densities vs. position



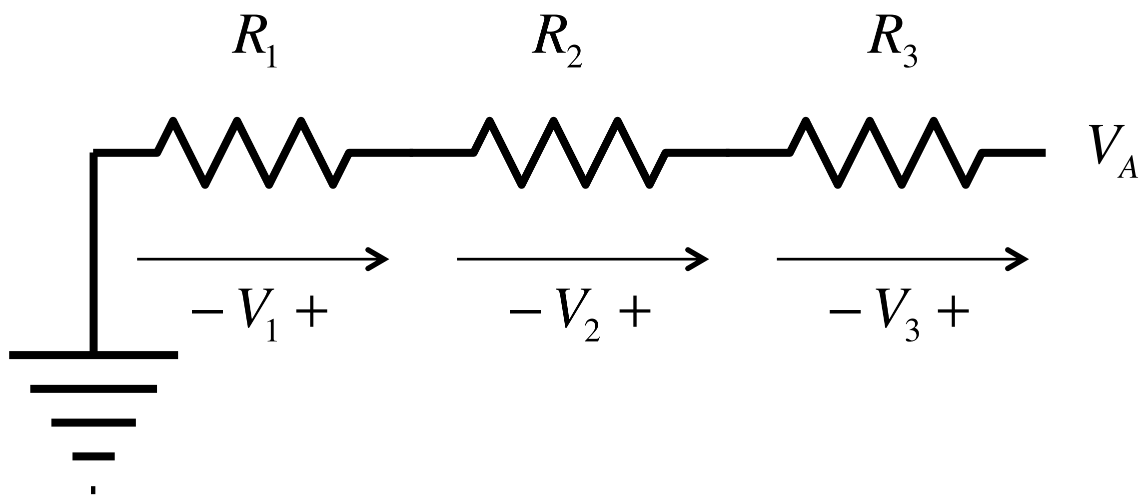
Equilibrium energy band diagram



If we apply a + voltage to the P-side, what happens?

Where does the voltage drop?

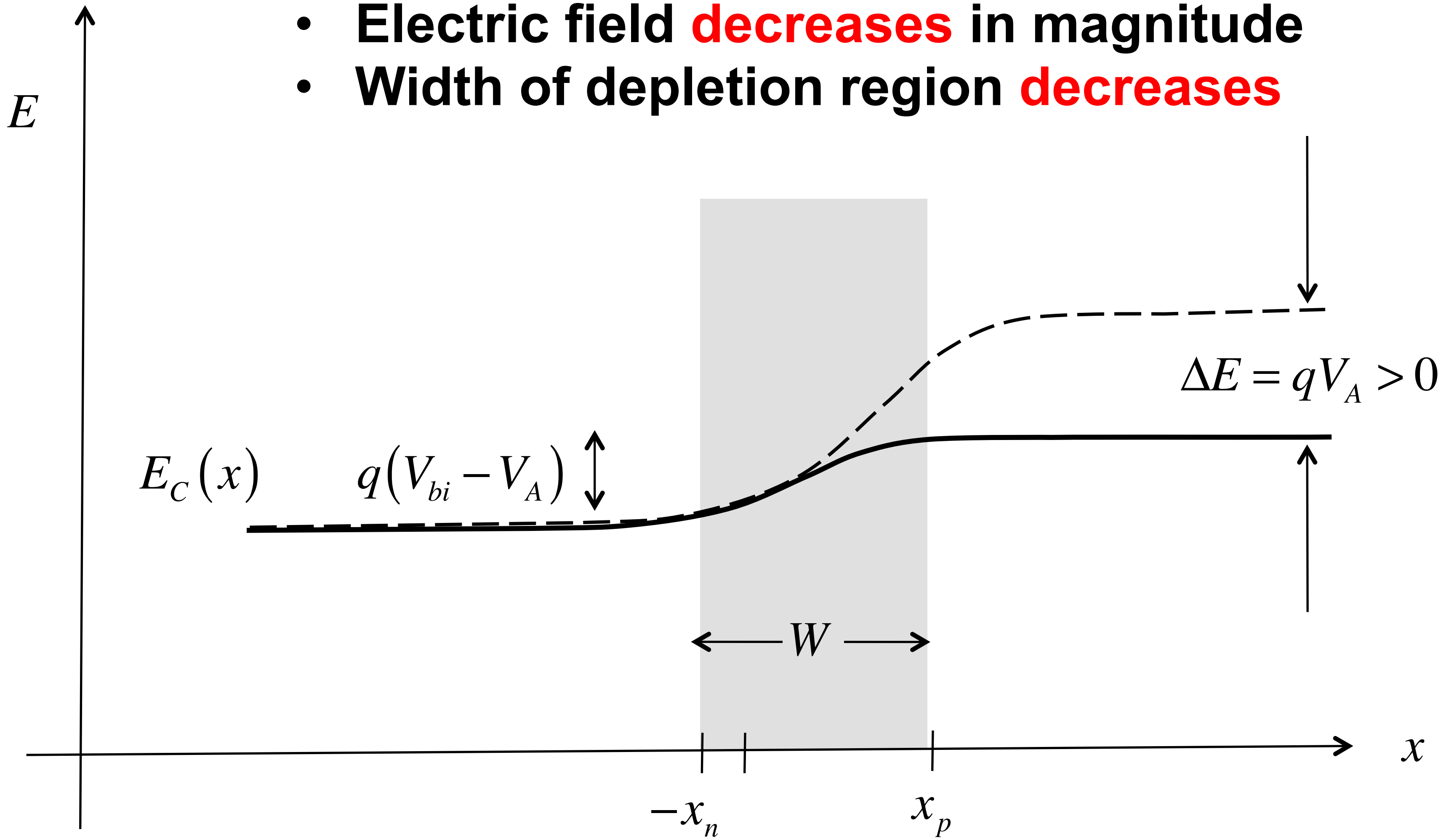
$$R_2 >> R_1, R_2$$



$$V_2 \approx ?$$

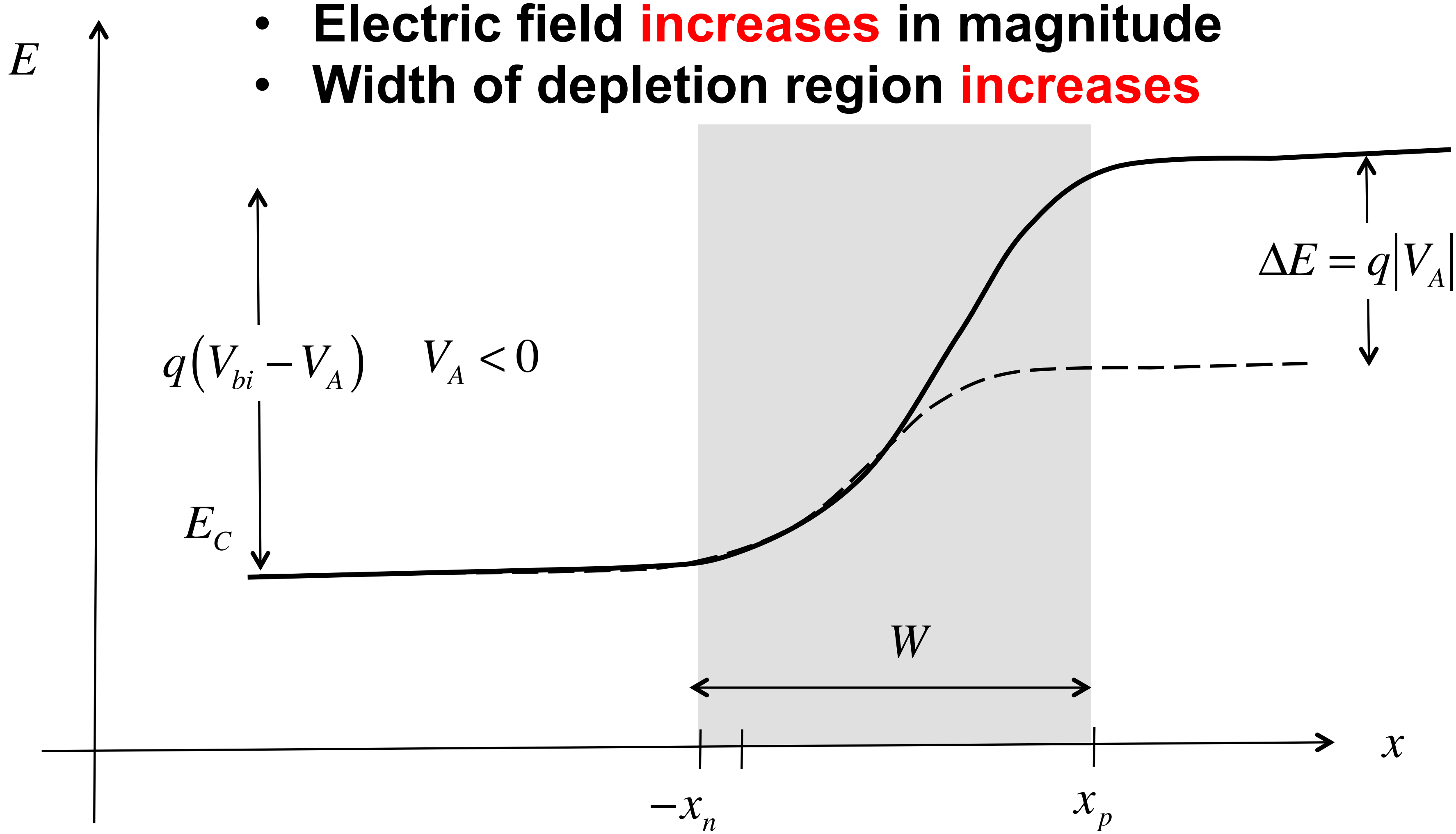
Forward bias → smaller energy barrier

- **Electric field decreases in magnitude**
- **Width of depletion region decreases**

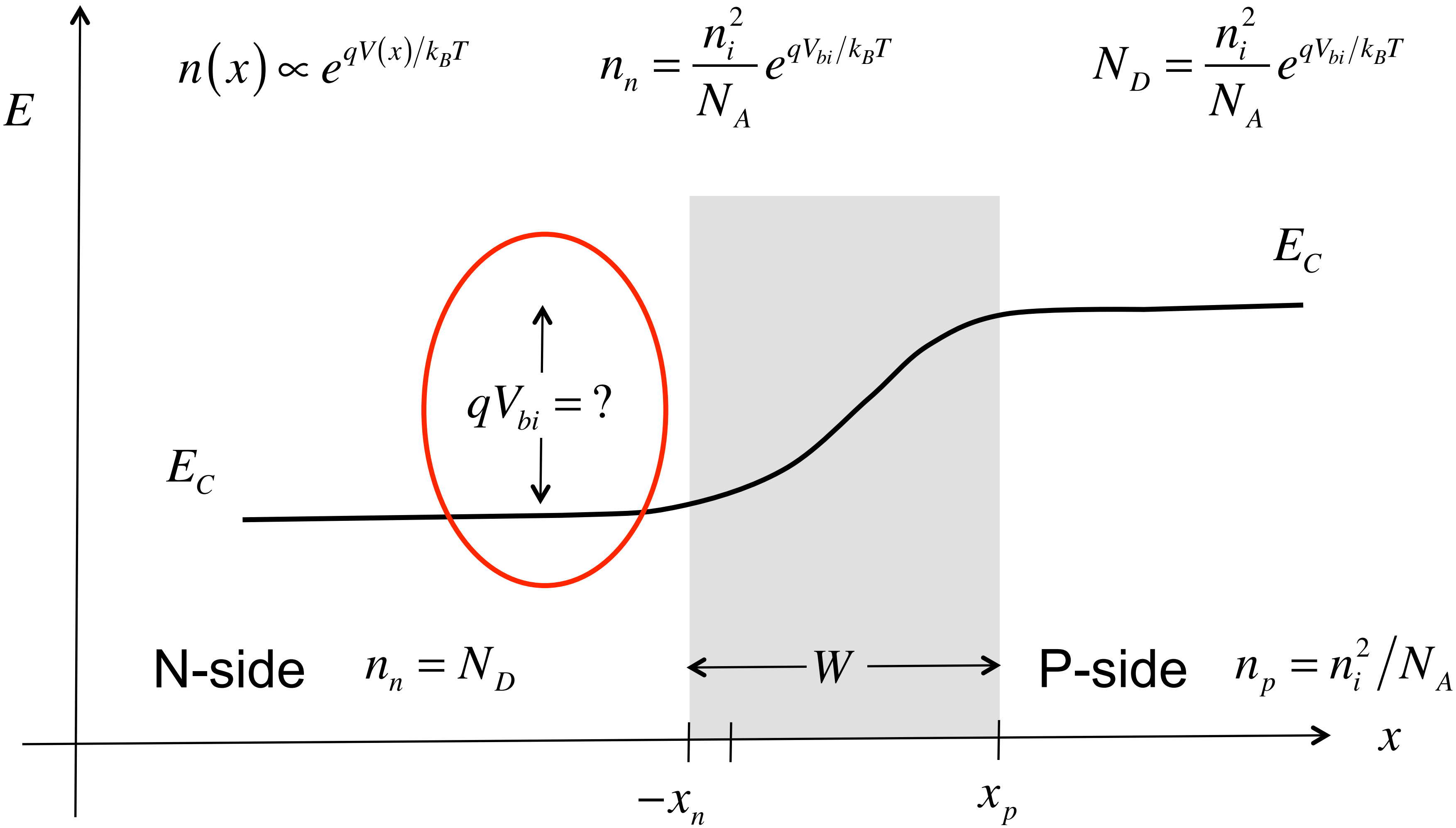


Reverse bias → larger energy barrier

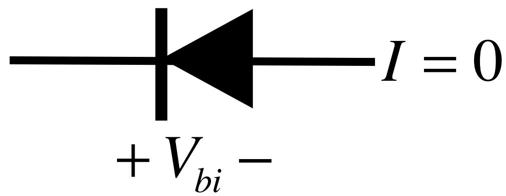
- **Electric field increases in magnitude**
- **Width of depletion region increases**



Equilibrium built-in potential



Equilibrium built-in potential



$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2} \right)$$

Summary

Energy band diagrams are a powerful tool for understanding the operation of semiconductor devices.

To find the electrostatic potential vs. position, turn $E_C(x)$ upside down.

To find the electric field vs. position, take the slope of $E_C(x)$.

To find the carrier density vs. position, begin where it is know, and then exponentially increase or decrease according to the local electrostatic potential.

Energy band diagrams

1) Band bending and the electrostatic potential
2) “Reading” an energy band diagram
3) PN junctions
4) Energy band diagram of a PN junction in equilibrium
5) Forward bias and reverse bias
6) The built-in potential