Unit 2: Essential Physics of the MOSFET

Lecture 2.1:
Energy Band Diagram Review

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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**.

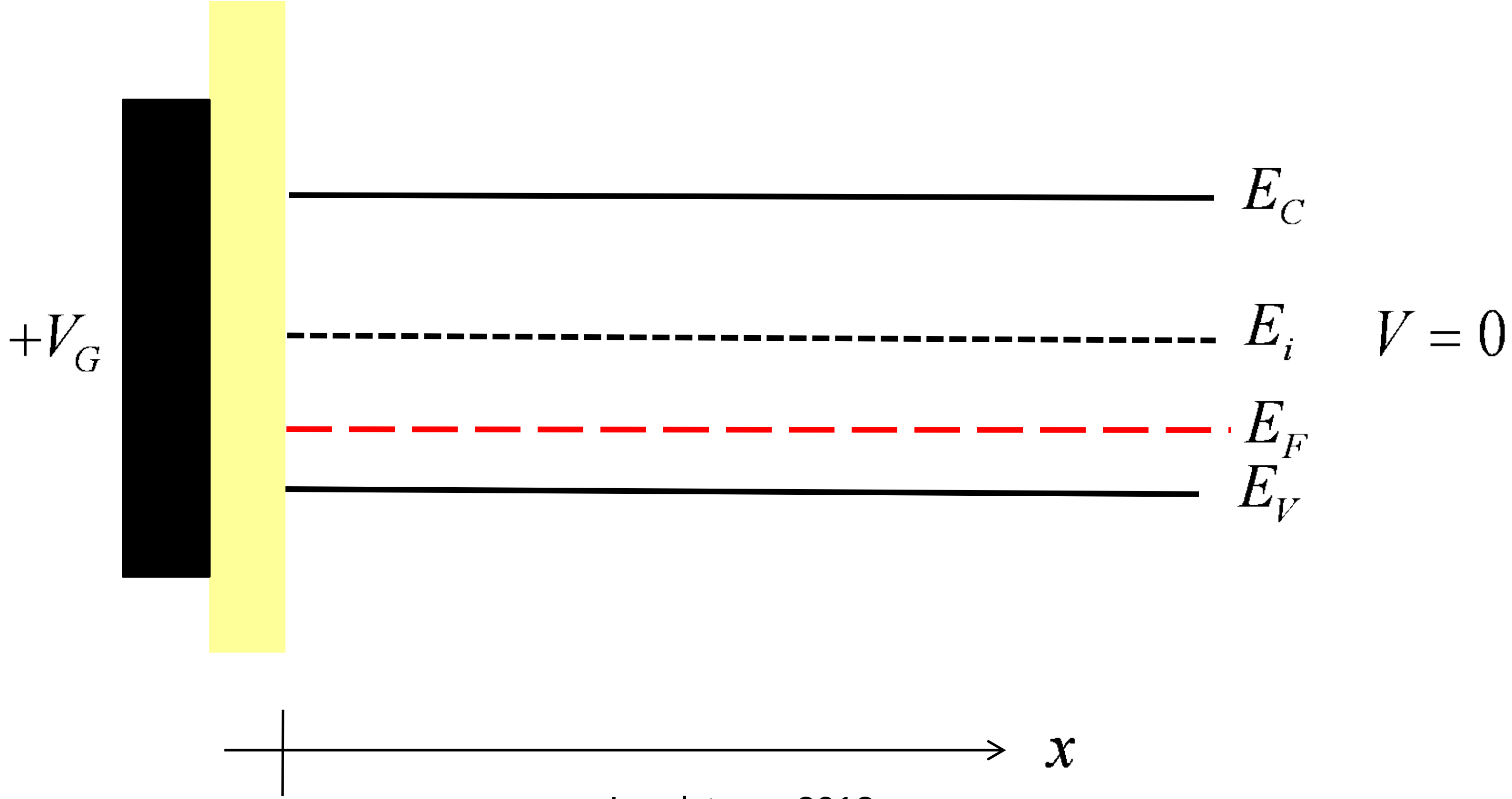
The Fermi level in equilibrium

The Fermi level is constant in equilibrium.

$$J_n = n\mu_n \frac{dF_n}{dx} = 0 = n\mu_n \frac{dE_F}{dx} \rightarrow E_F \text{ is constant}$$

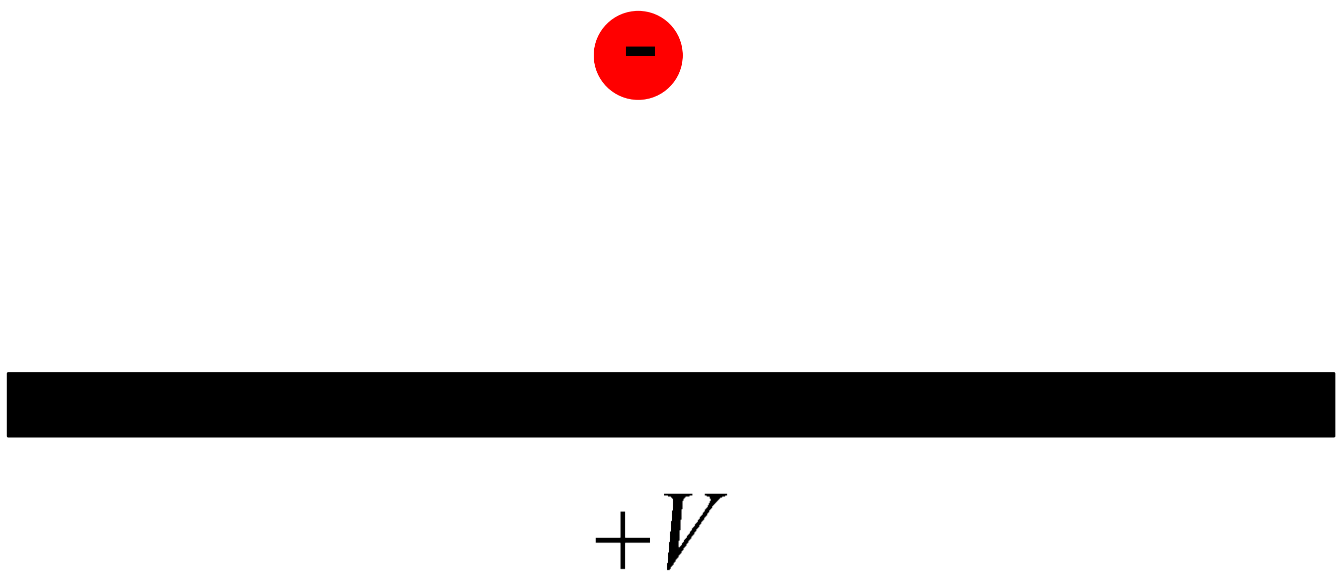
Band bending

What happens when we apply a voltage to the gate?



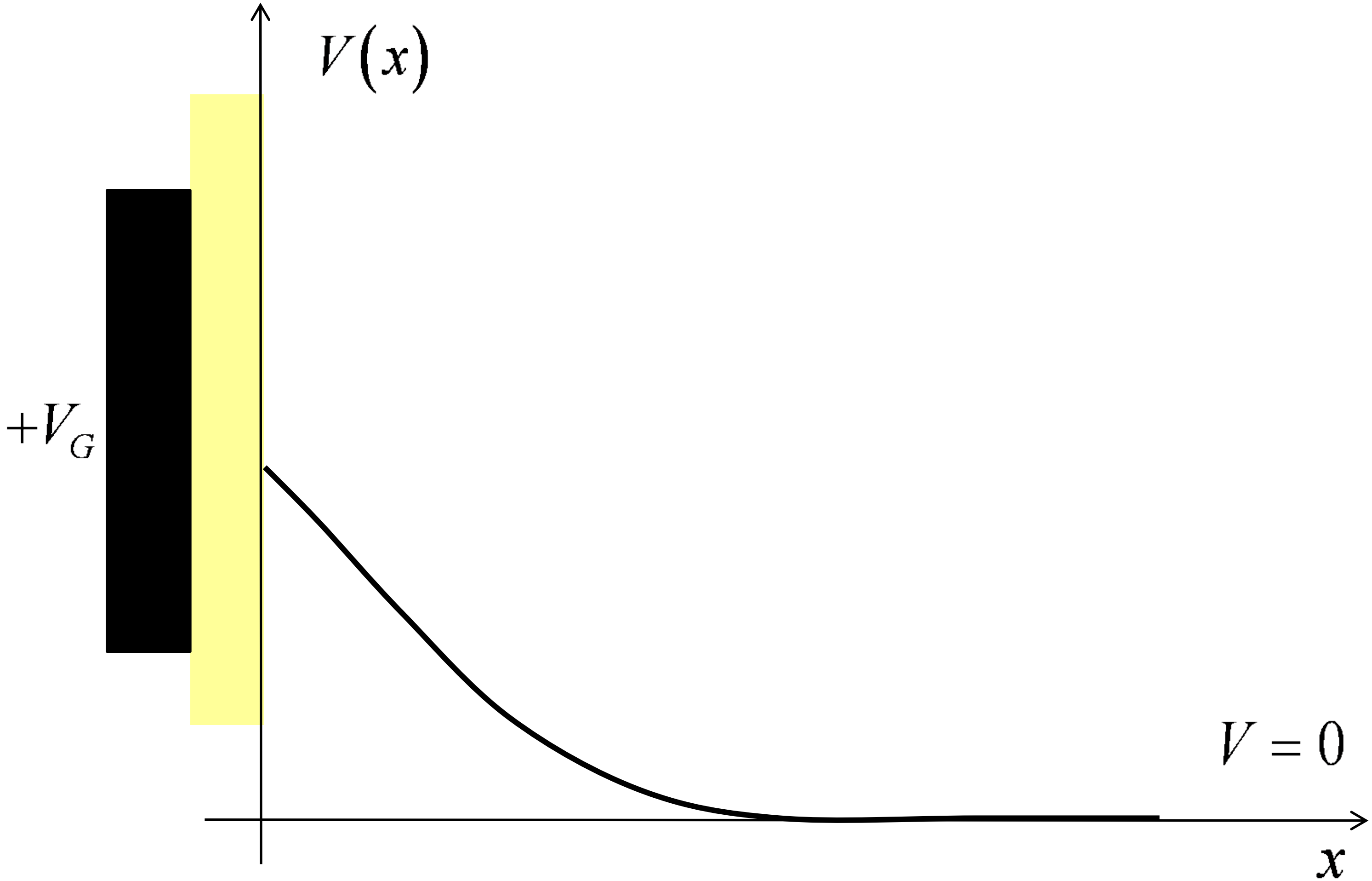
Voltage and electron potential energy

$$E = -qV$$



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

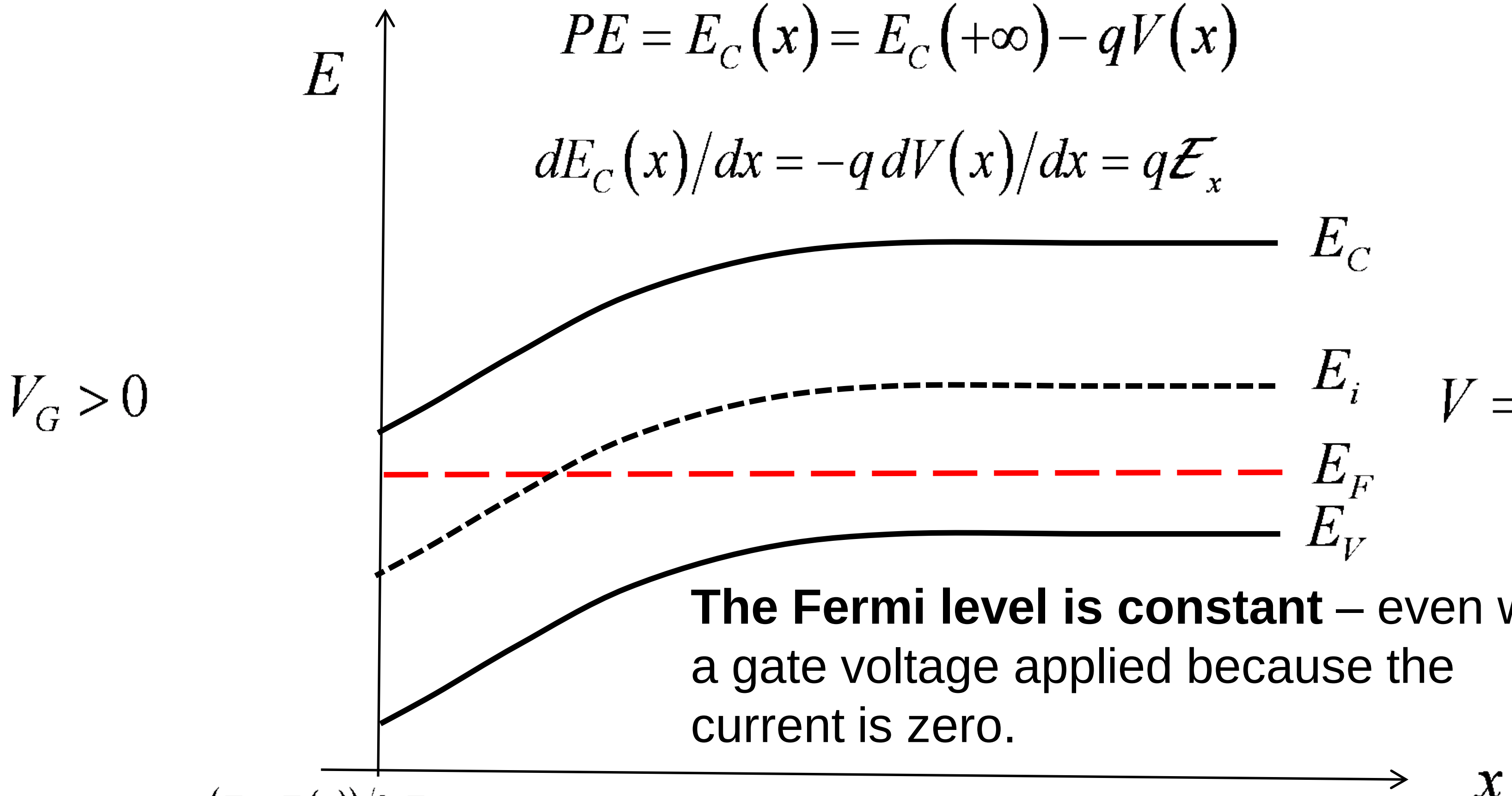
Electrostatic potential vs. position



Electrostatic potential causes band bending

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

$$dE_C(x)/dx = -q\,dV(x)/dx = q\mathcal{E}_x$$



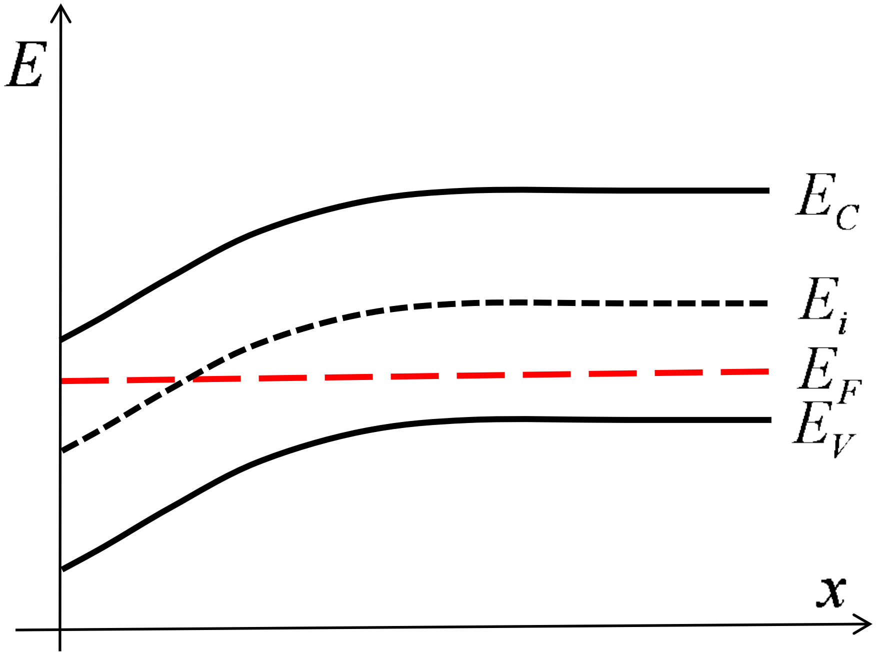
The Fermi level is constant – even with a gate voltage applied because the current is zero.

$$n(x) = n_i e^{(E_F - E_i(x))/k_B T}$$

$$p(x) = n_i e^{(E_i(x) - E_F)/k_B T}$$

Band diagrams

1) Draw the band diagram



$$\frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{K_S \varepsilon_0}$$

2) Read the band diagram

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

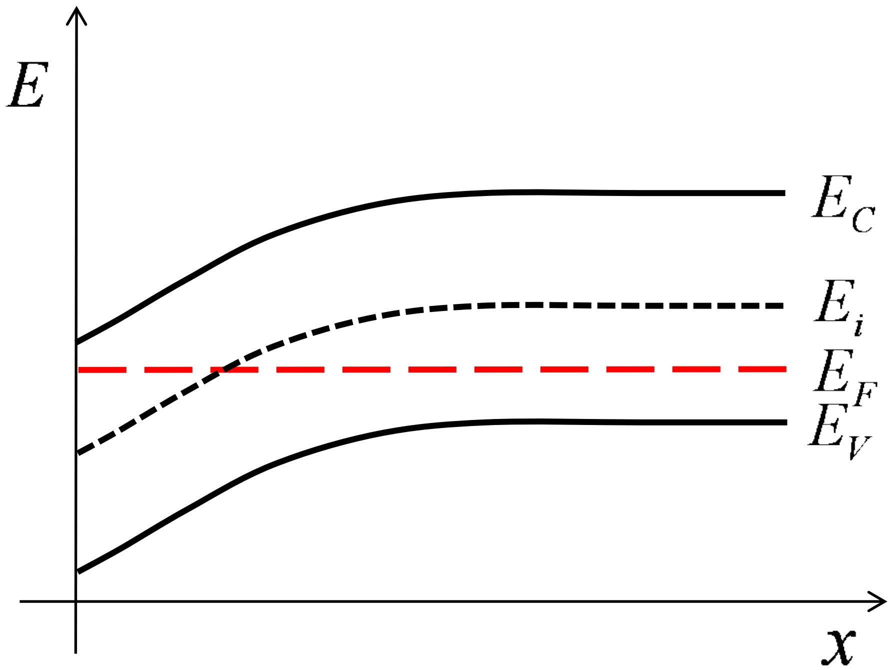
$$\mathcal{E} \propto dE_C(x)/dx$$

$$\log n(x) \propto E_F - E_i(x)$$

$$\log p(x) \propto E_i(x) - E_F$$

$$\rho(x) \propto d^2 E_C(x)/dx^2$$

Practice

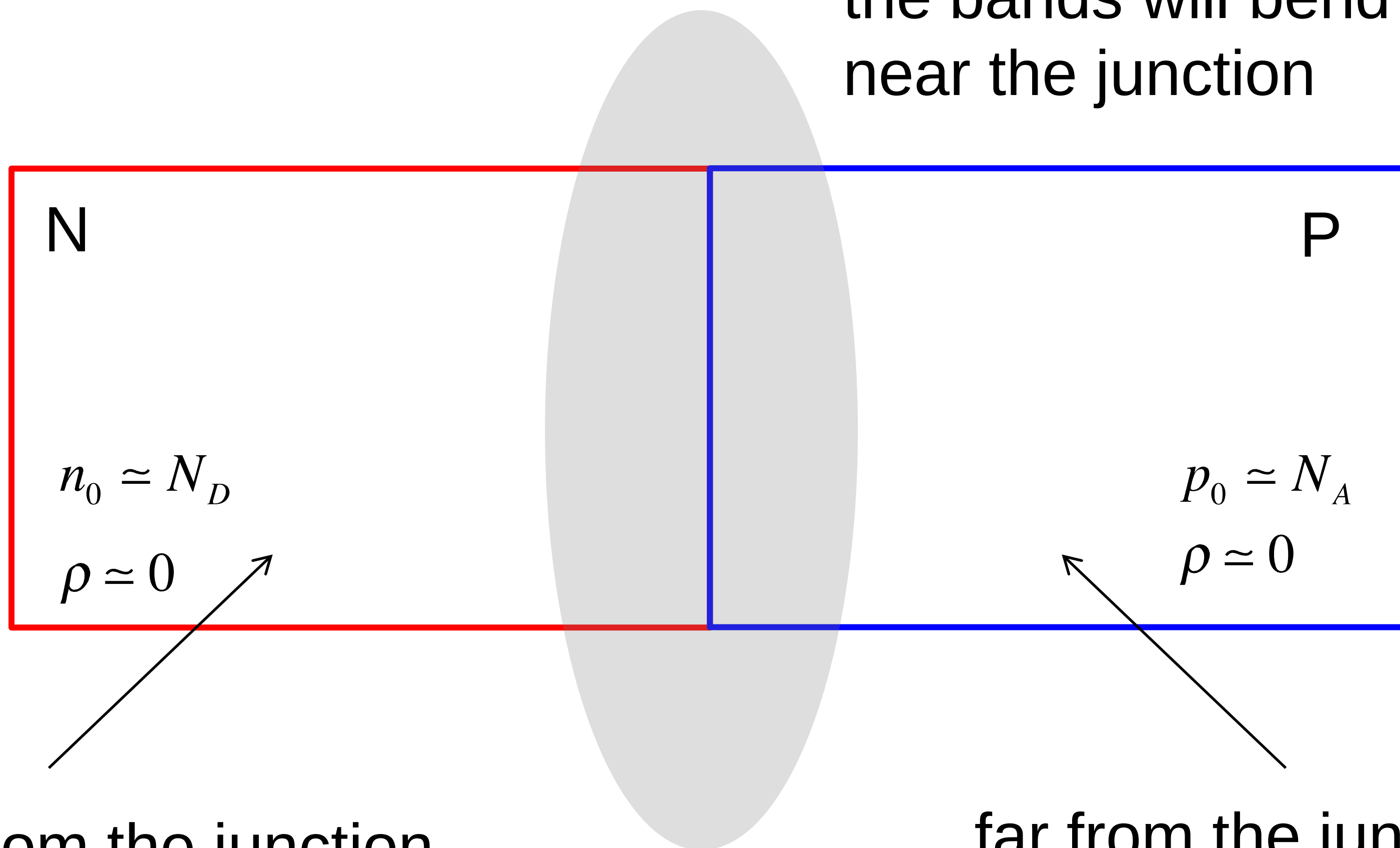


Sketch vs. position:

- Electrostatic potential
- Electric field
- Electron density
- Hole density
- Space charge density

Another example: NP junction in equilibrium

the bands will bend
near the junction



far from the junction,
the bands will be flat

far from the junction,
the bands will be flat

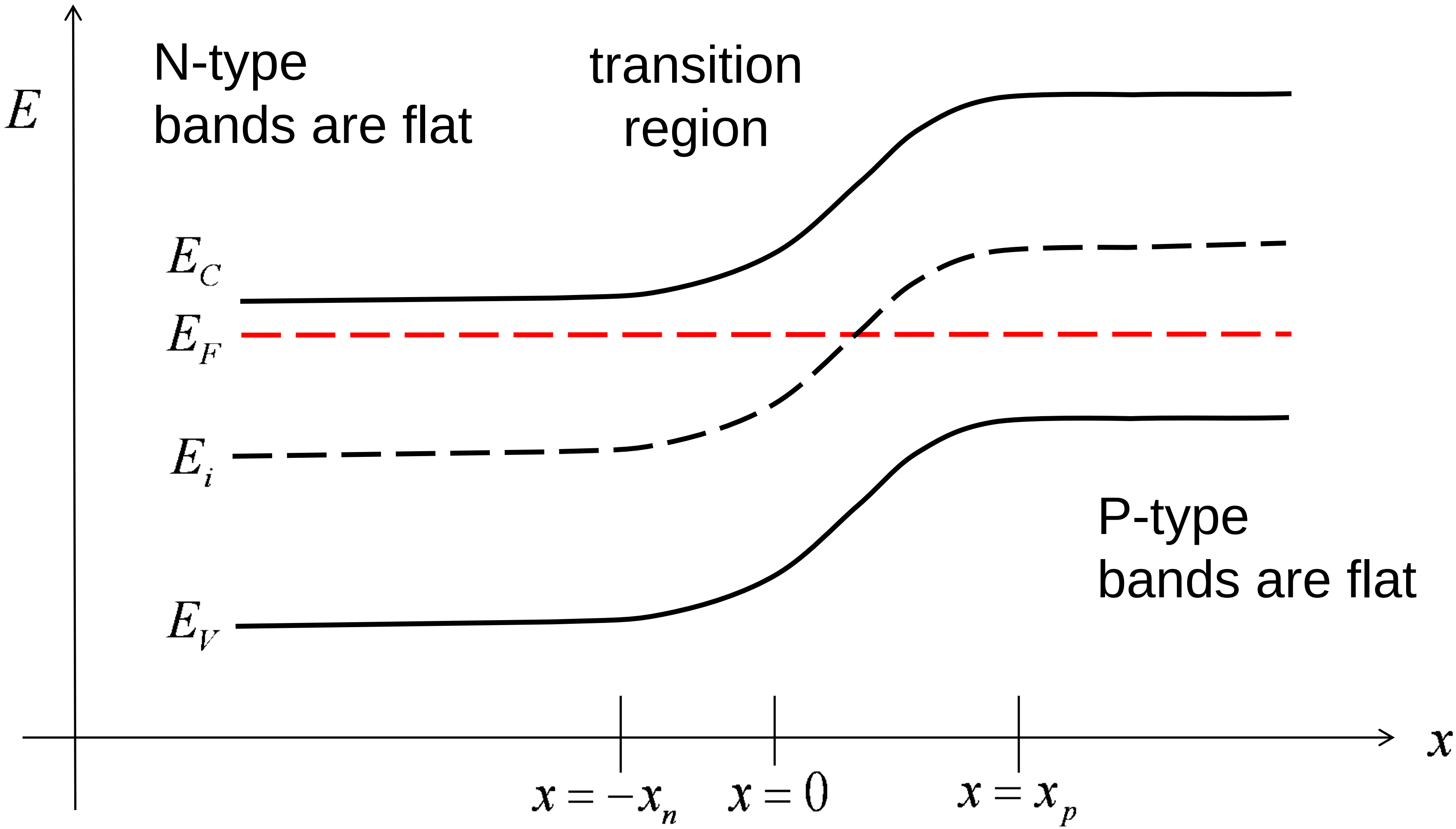
Procedure: Equilibrium energy band diagram

1) Begin with E_F.

2) Draw the E-bands where you know the carrier density then connect the two regions.

3) Then “read” the energy band diagram to obtain the electrostatic potential, electric field, carrier densities, and space charge density vs. position.

Energy band diagram



Now, “read” the e-band diagram

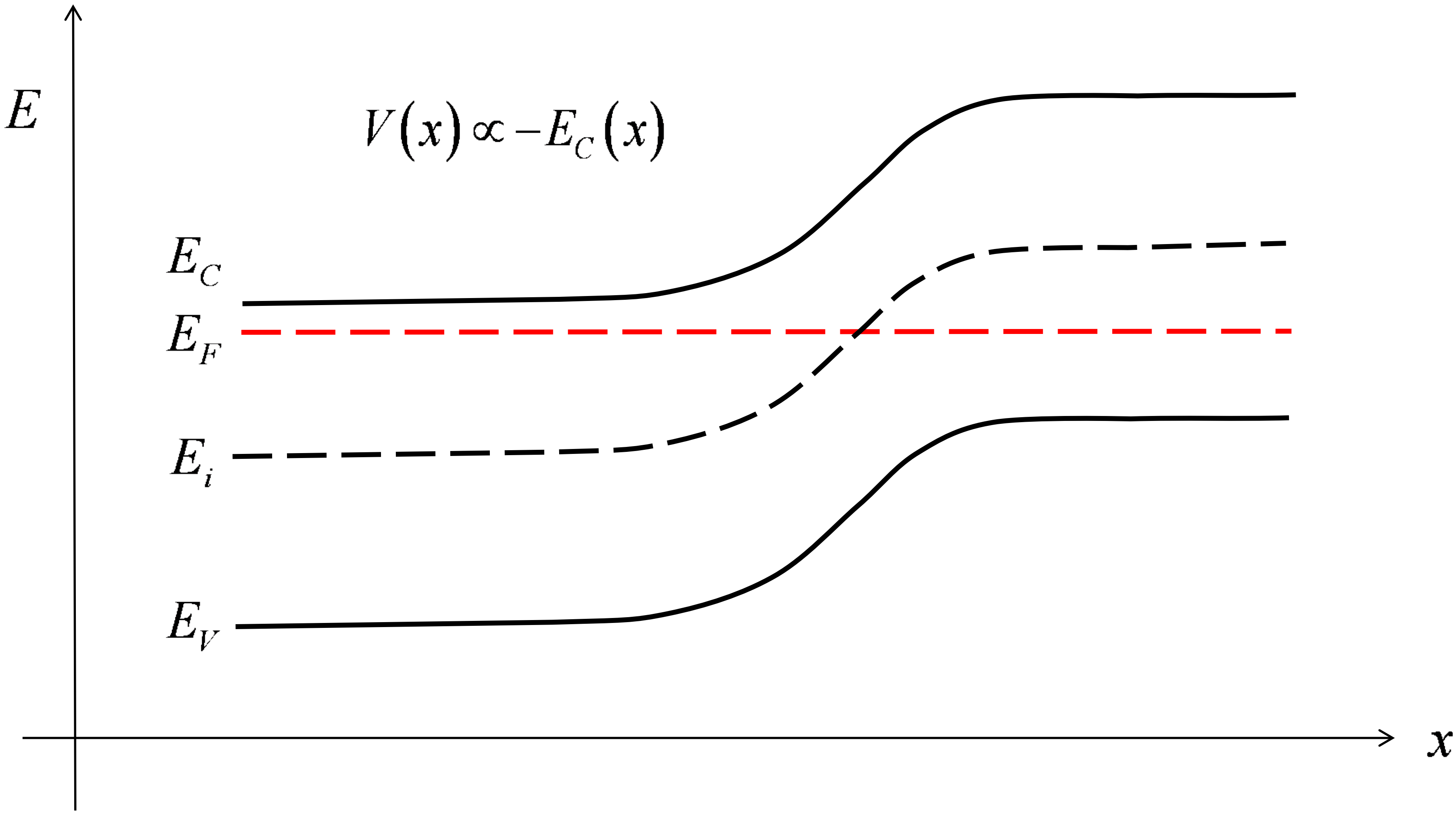
1) Electrostatic potential vs. position

2) Electric field vs. position

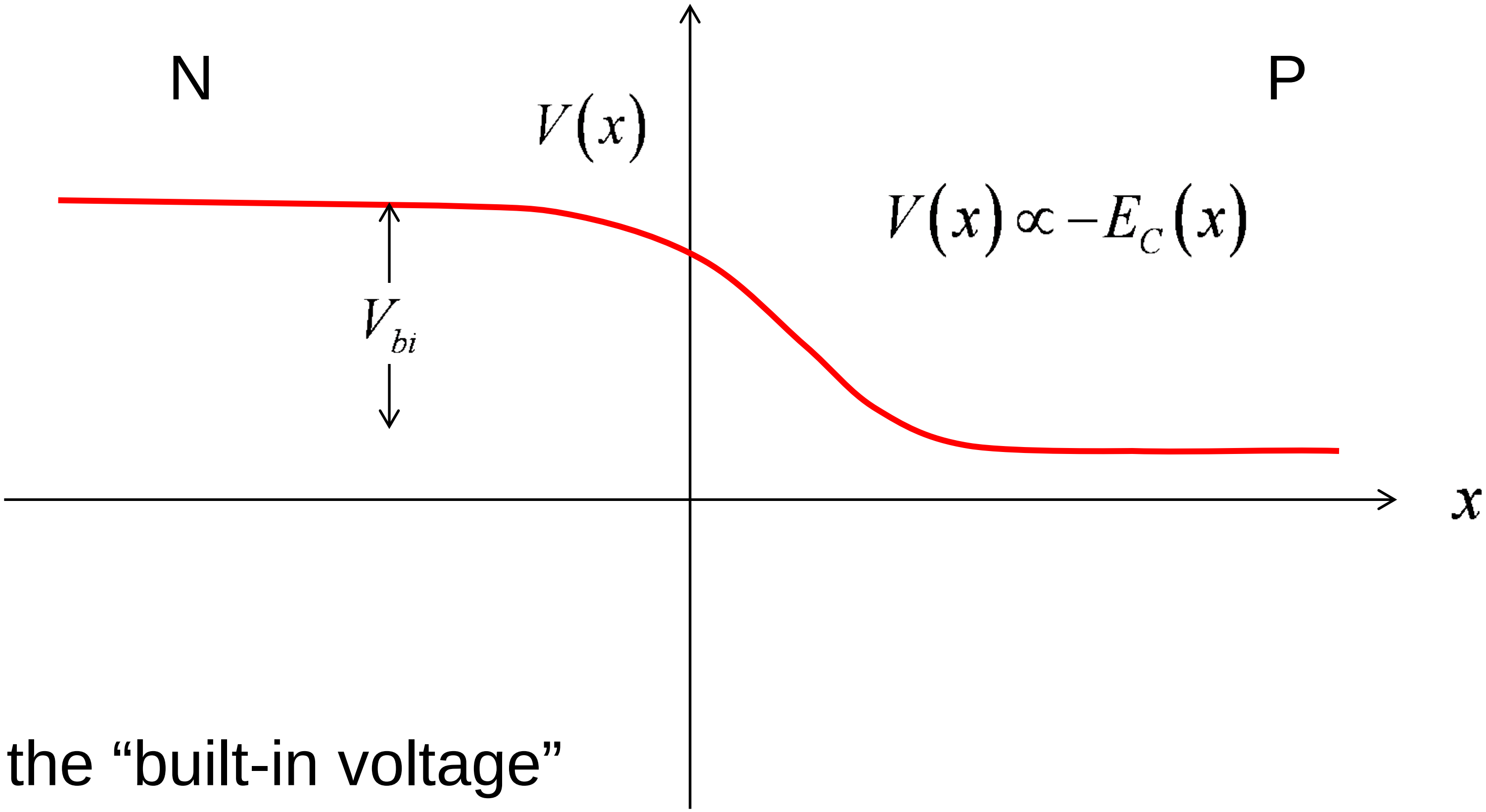
3) Electron and hole densities vs. position

4) Space-charge density vs. position

1) Electrostatic potential?

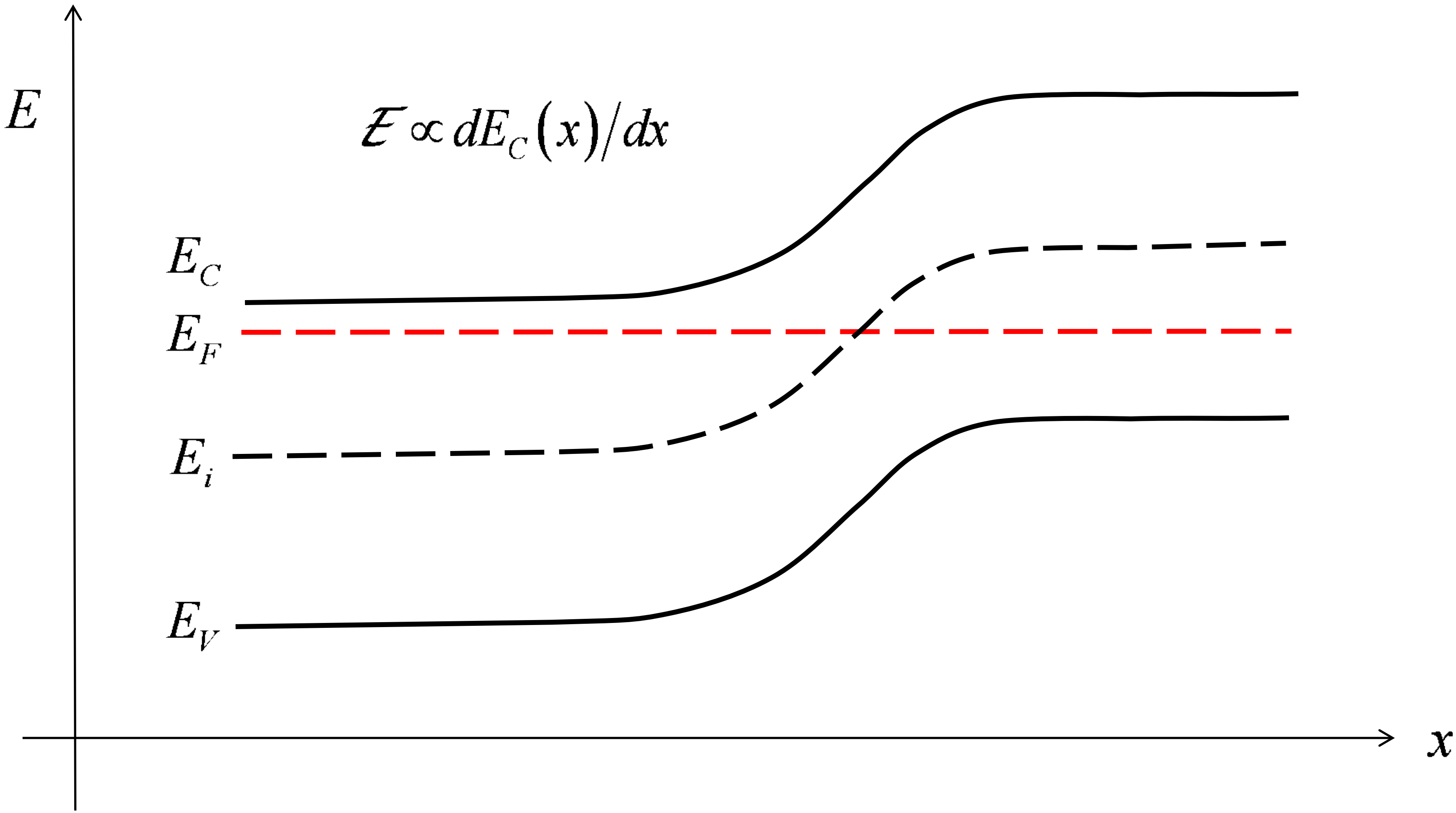


Electrostatics: *V*(*x*)

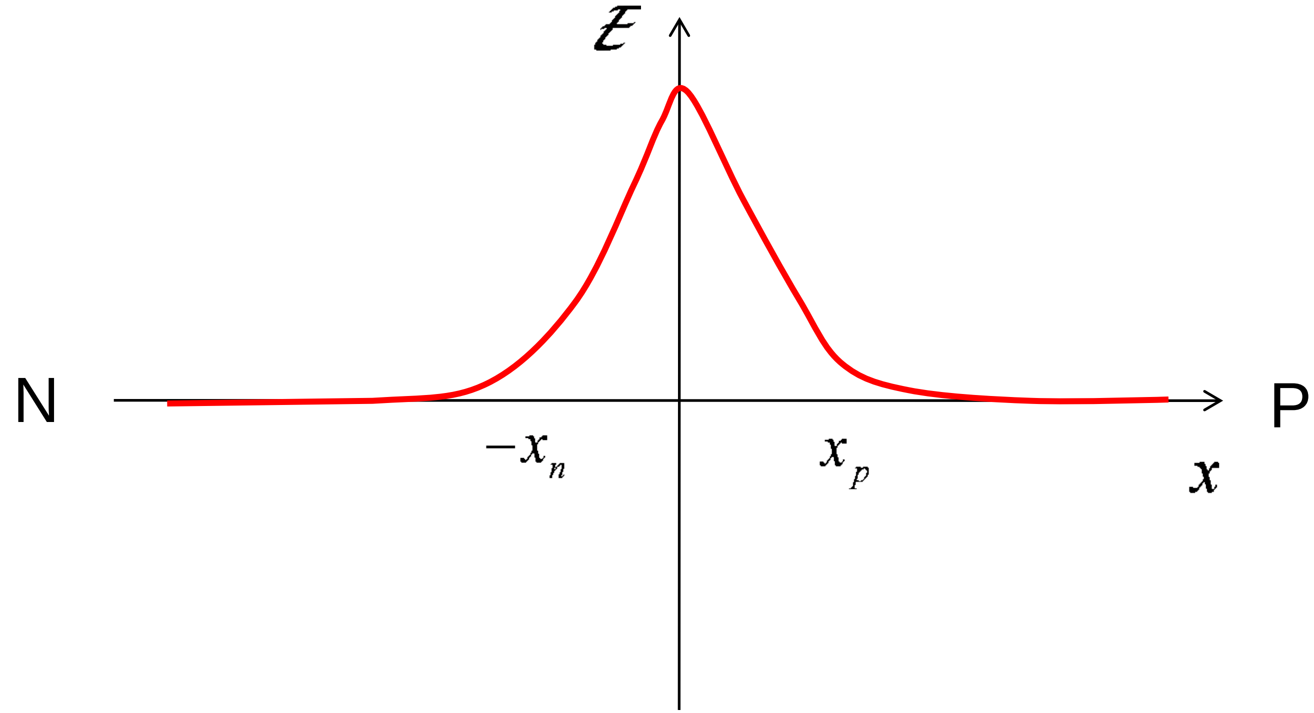


V_{bi} is the "built-in voltage"

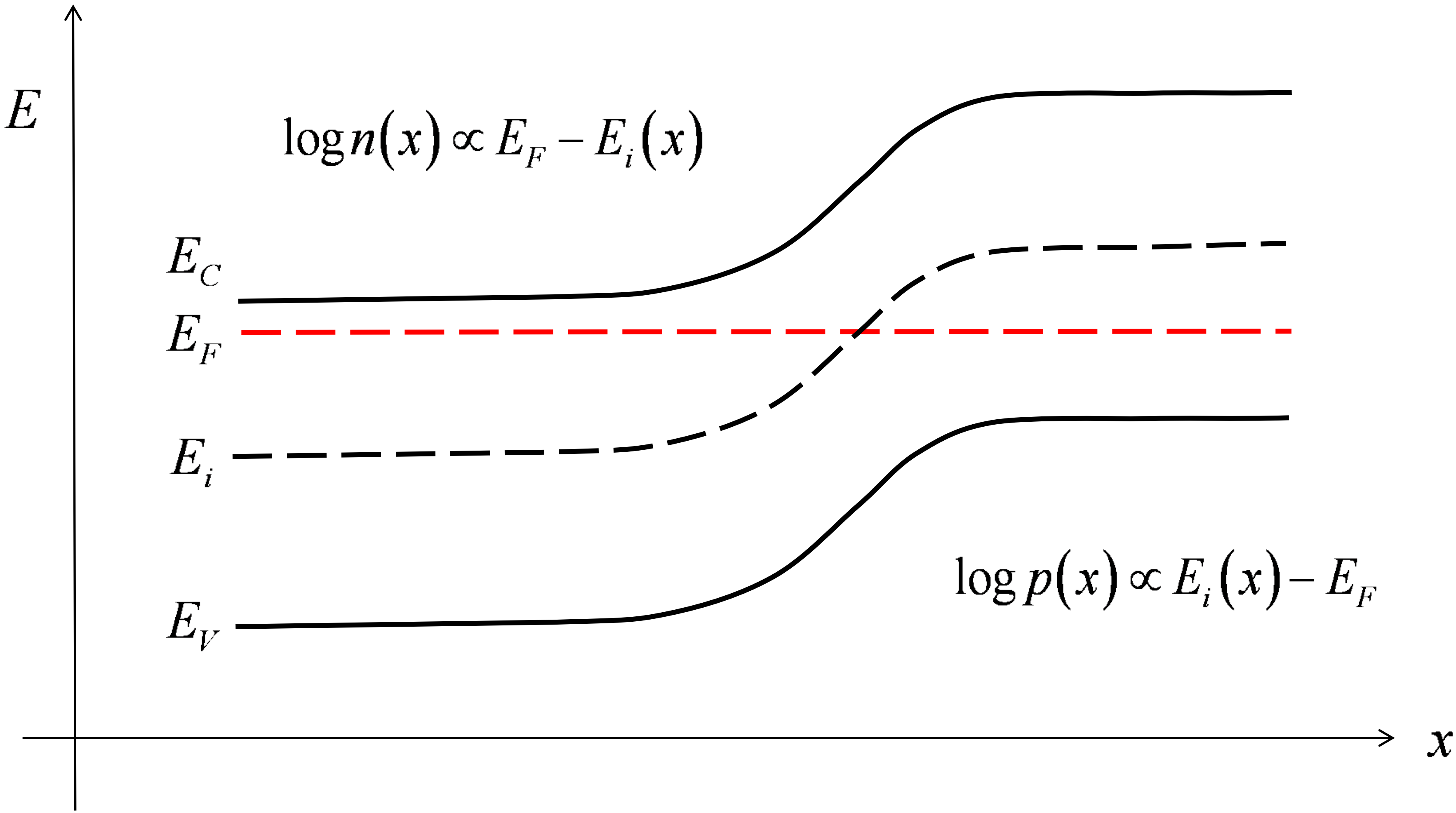
2) Electric field?



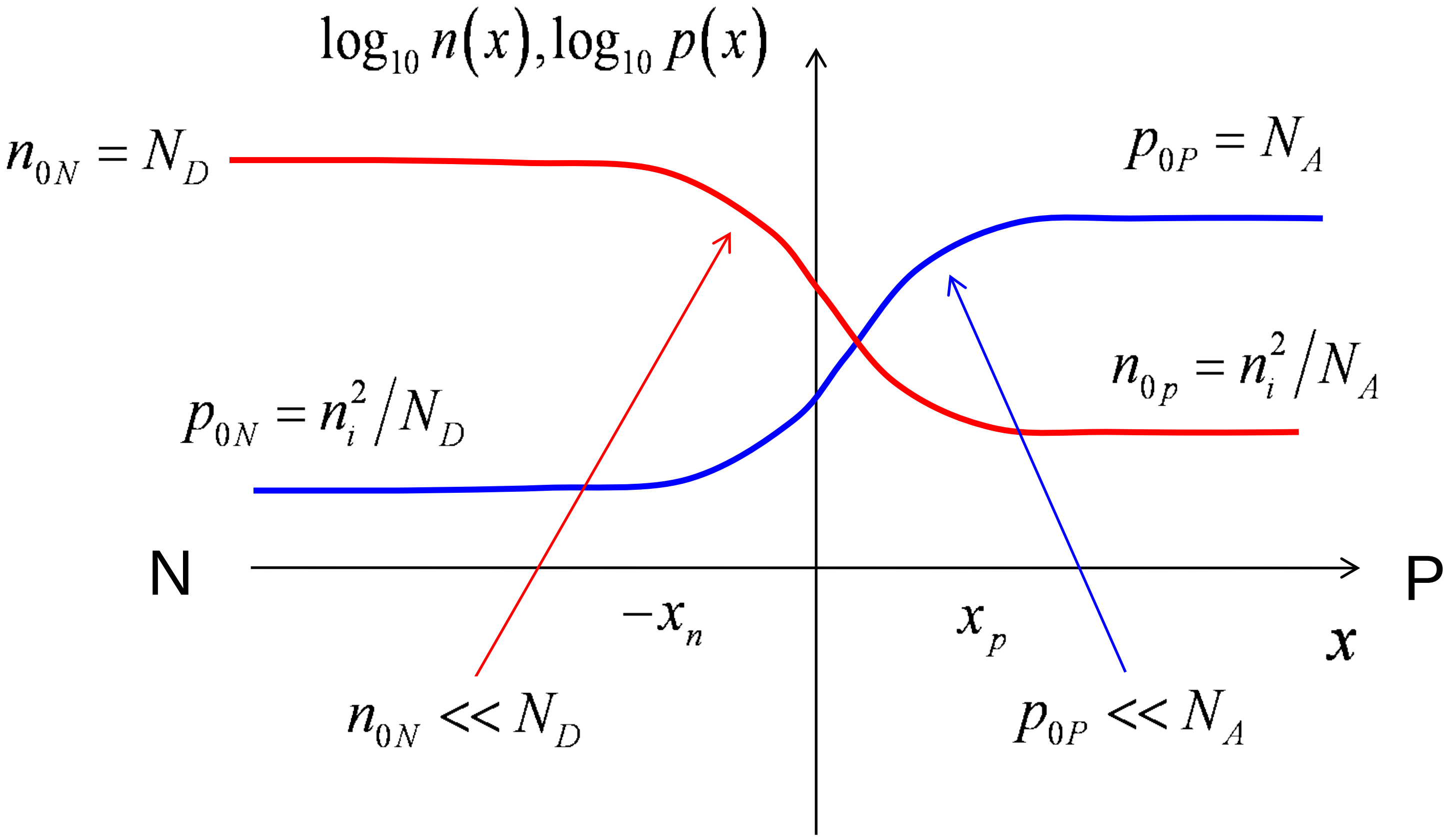
Electric field: $\mathcal{E}$ (x)



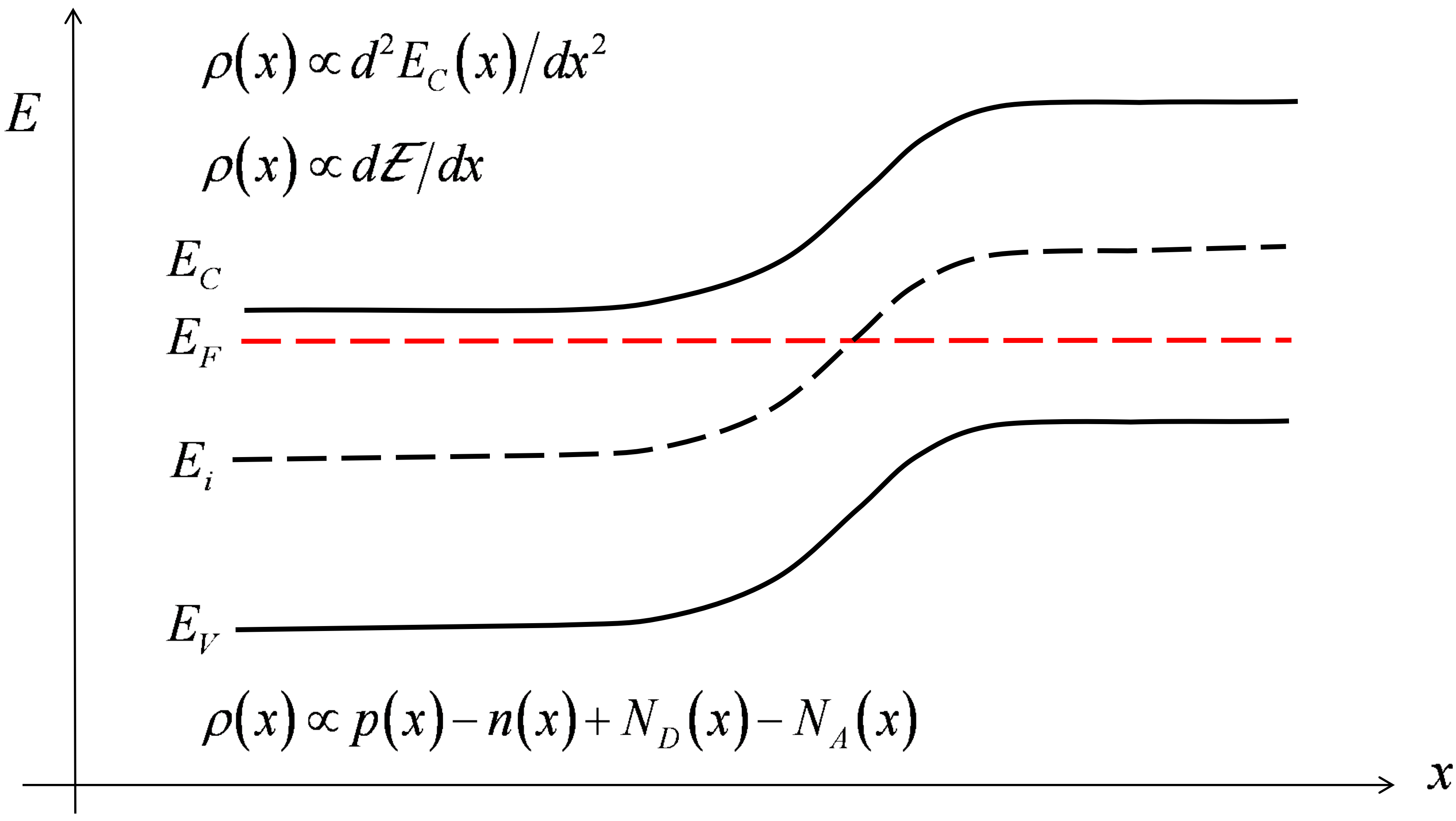
3) Carrier densities?



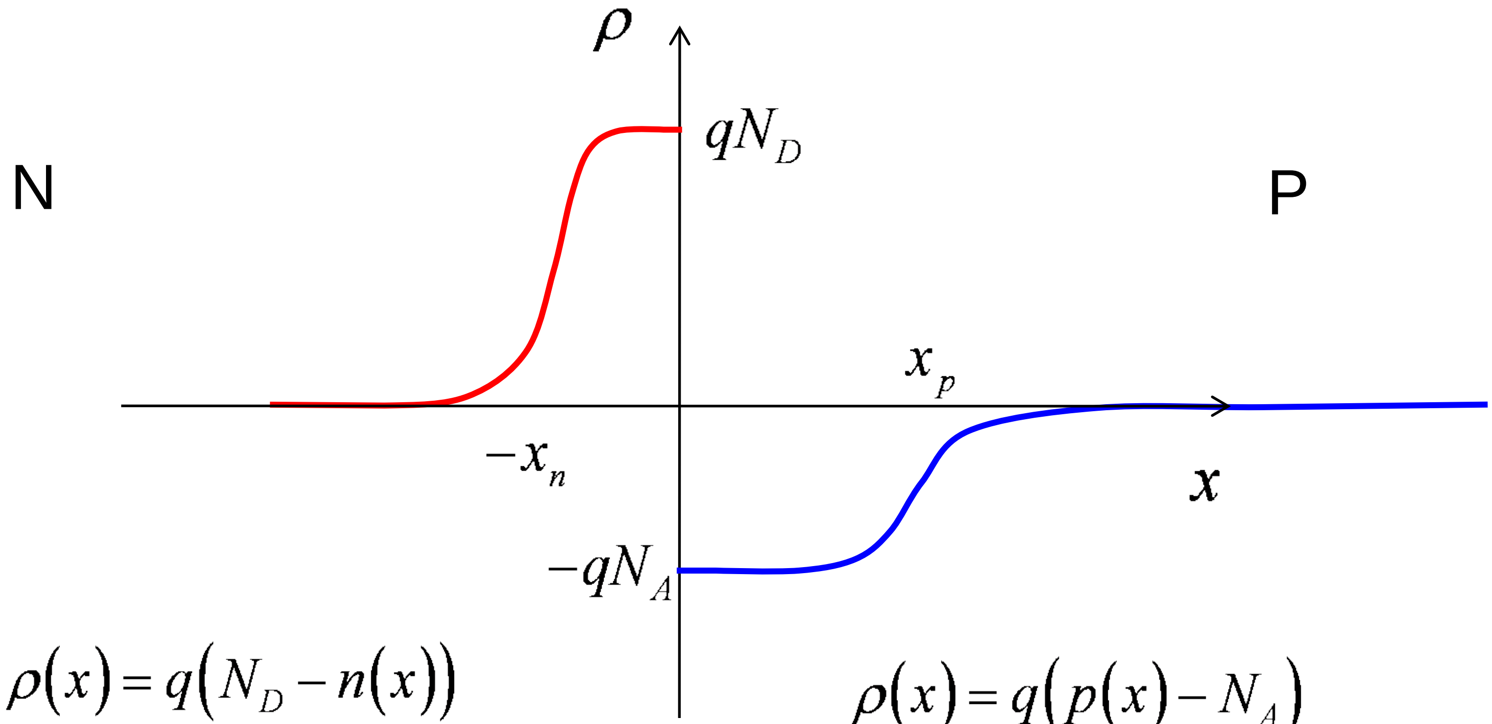
Carrier densities vs. *x*



4) Space charge density?



Electrostatics: $\rho(x)$



$$\rho(x) = q\left(N_D - n(x)\right)$$

$$\rho(x) = q\left(p(x) - N_A\right)$$

Summary

$$\frac{\partial p}{\partial t} = -\nabla \bullet \left(\frac{\vec{J}_p}{q} \right) + G_p - R_p$$

$$\frac{\partial n}{\partial t} = -\nabla \bullet \left(\frac{\vec{J}_n}{-q} \right) + G_n - R_n$$

$$\nabla \bullet \left(K_S \varepsilon_0 \vec{\mathcal{E}} \right) = \rho$$

Three coupled, nonlinear PDE's in three unknowns:

$$p\left(\vec{r}\right), n\left(\vec{r}\right), V\left(\vec{r}\right)$$

Drawing and then reading an E-band diagram gives us a qualitative solution to these equations.

Next topic:

In the next lecture, we will use energy band diagrams to develop a qualitative understanding of MOSFET IV characteristics.