ECE 340 Lecture 22
Semiconductor Electronics

Spring 2022
10:00-10:50am

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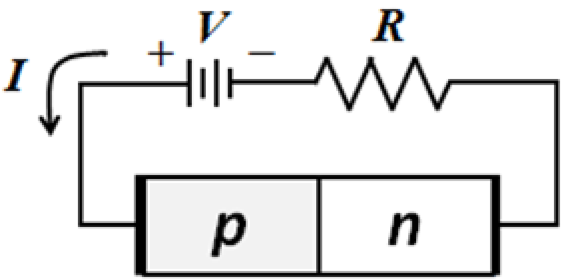
2062 ECE Building

Today's Discussion

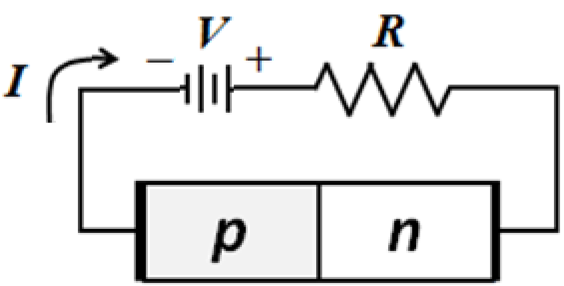
- **The p-n junction out of equilibrium -1**

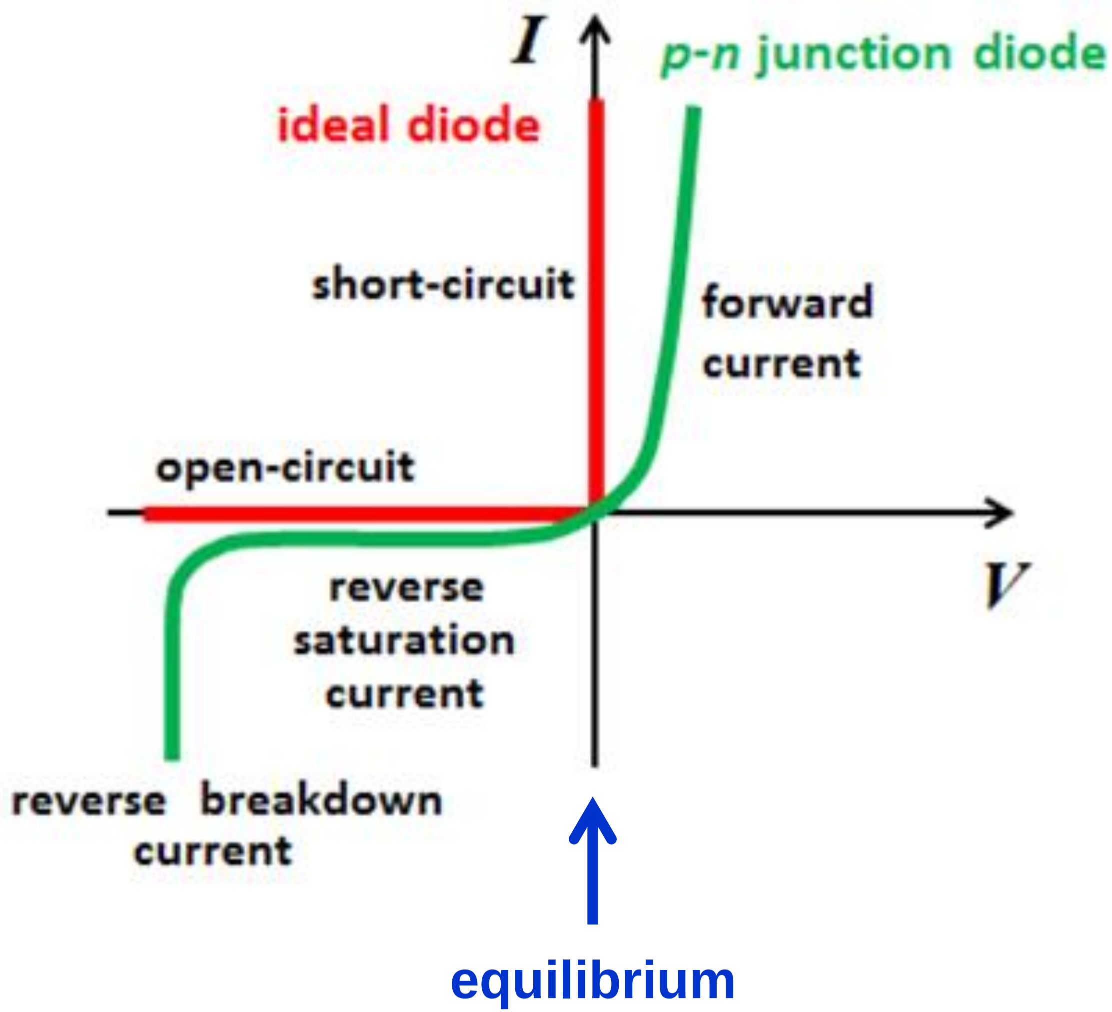
p-n junction *I-V* curve

Forward bias circuit

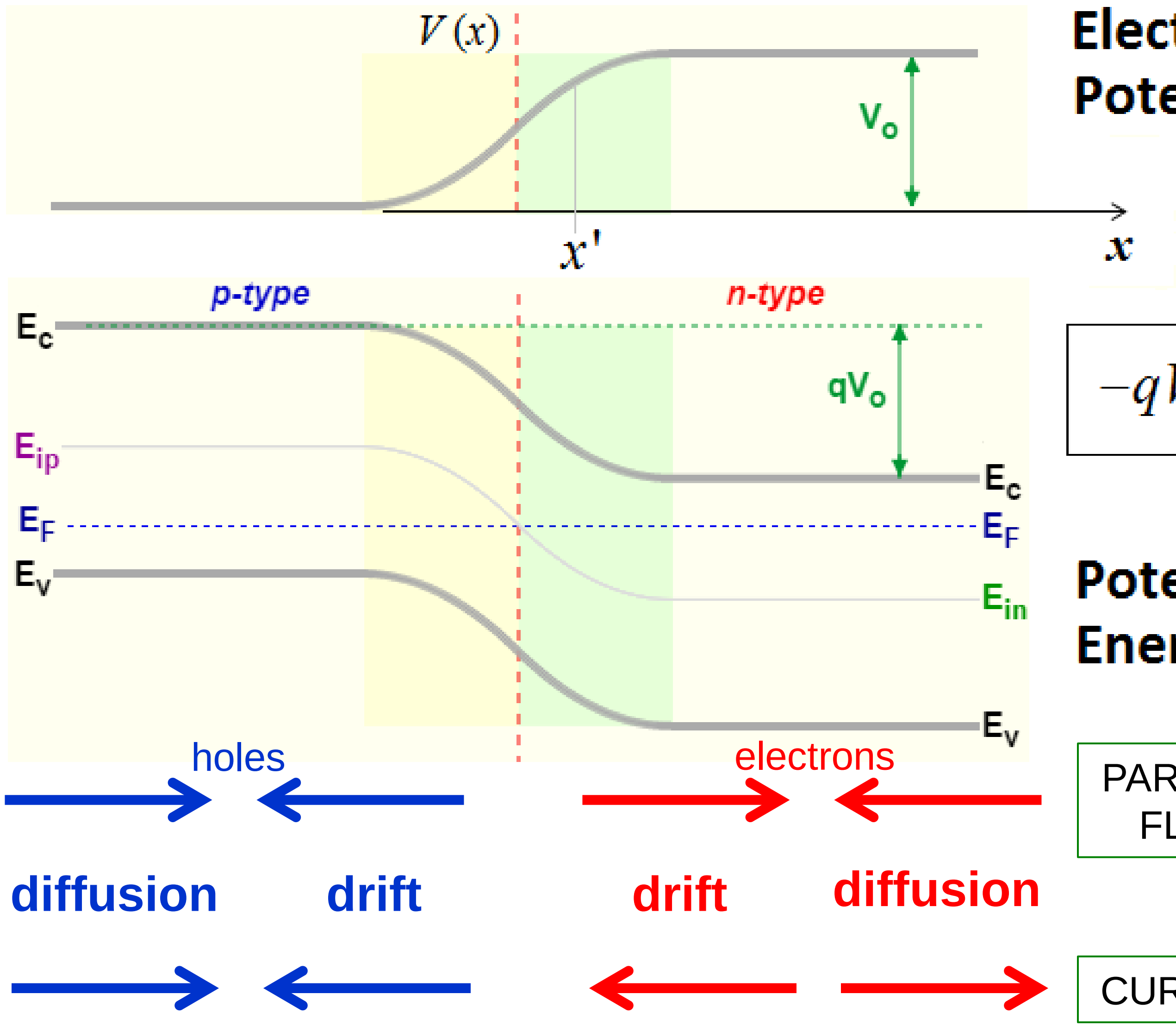


Reverse bias circuit





p-n junction in *equilibrium*



Electrostatic Potential

$$-qV(x) = \mathbf{E}$$

Potential Energy

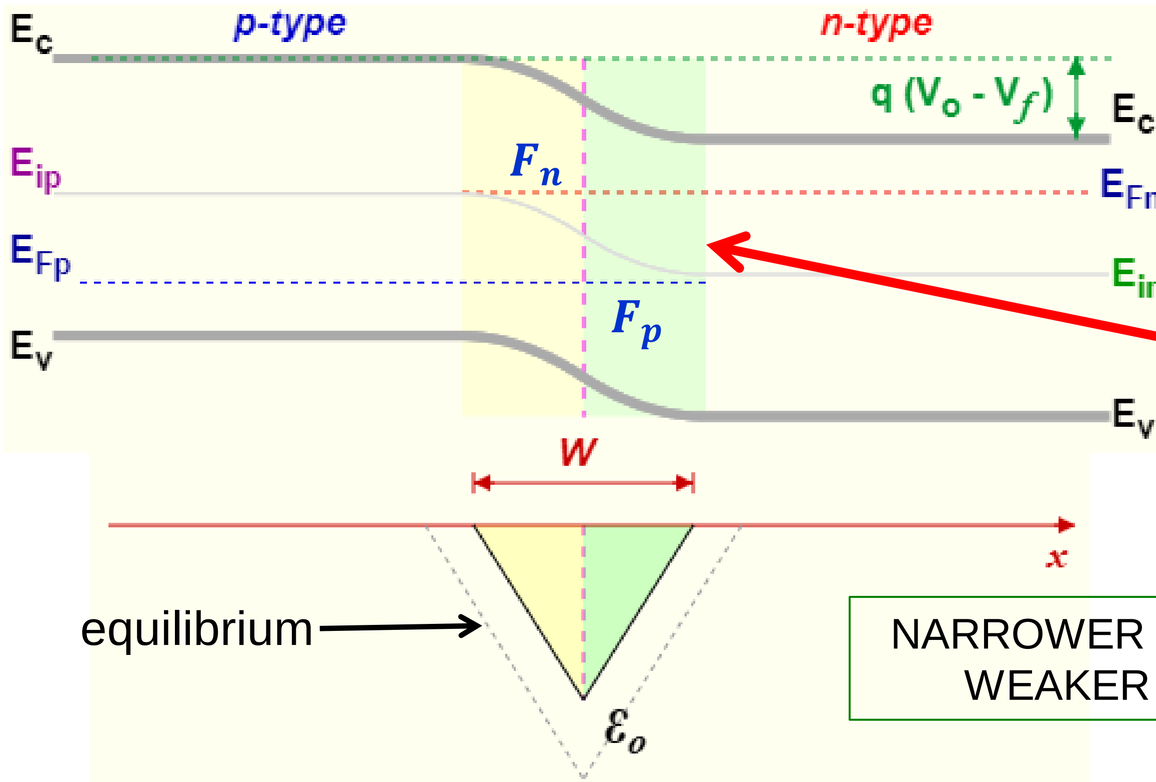
PARTICLE FLOW

net current = 0

CURRENT

p-n junction in *forward bias*

LOWER BARRIER



BIAS REDUCES CONTACT POTENTIAL

What about the details of quasi-Fermi levels?

NARROWER DEPLETION REGION
WEAKER ELECTRIC FIELD

holes → ← | electrons → ←

PARTICLE FLOW

diffusion **drift** **drift** **diffusion**

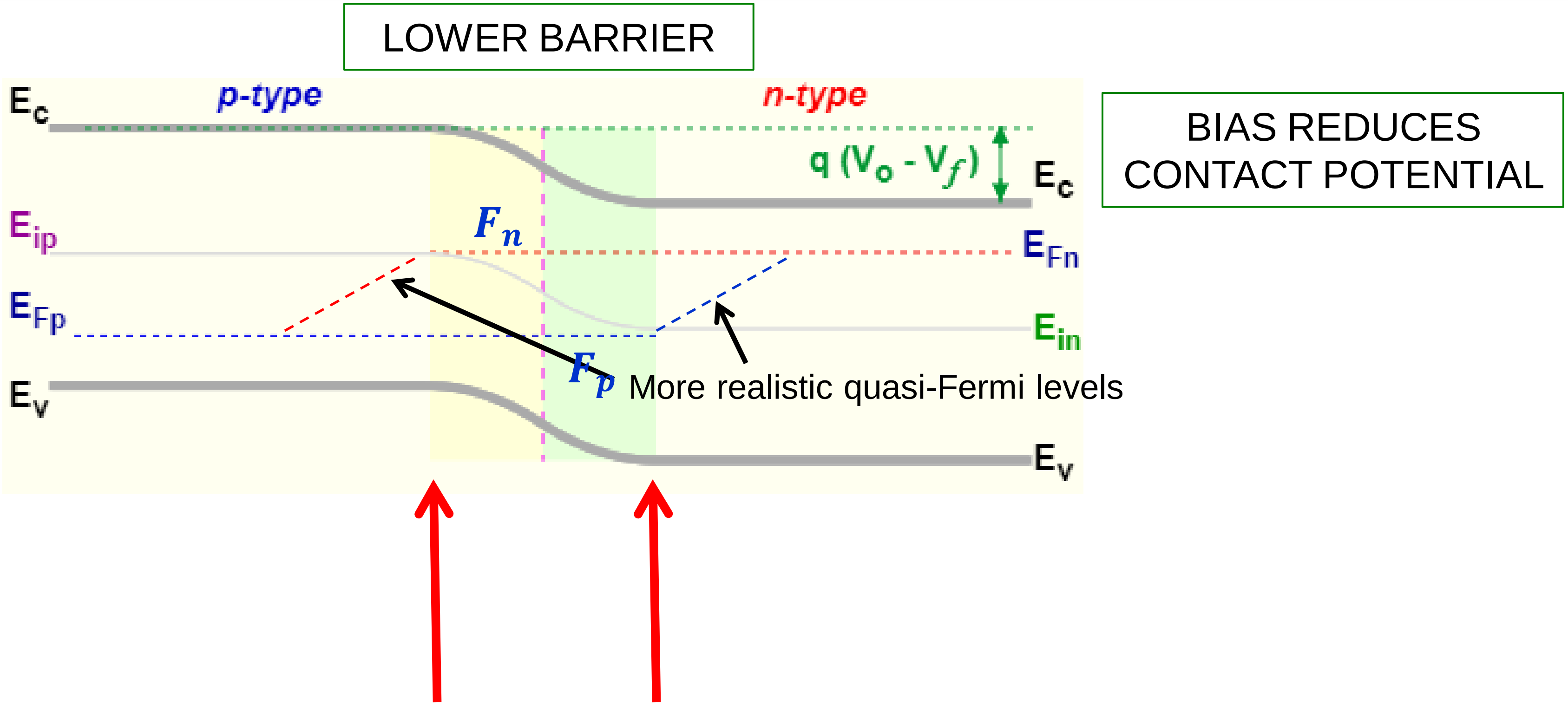
→ ← ← →

CURRENT

Limits of depletion approximation

- **The depletion approximation is sufficient to evaluate the electrostatic behavior of the junction reasonably well.**
- **However, it is insufficient to determine current flow.**
- ***No mobile charge*** **inside the depletion region would imply that there is never current flow.**

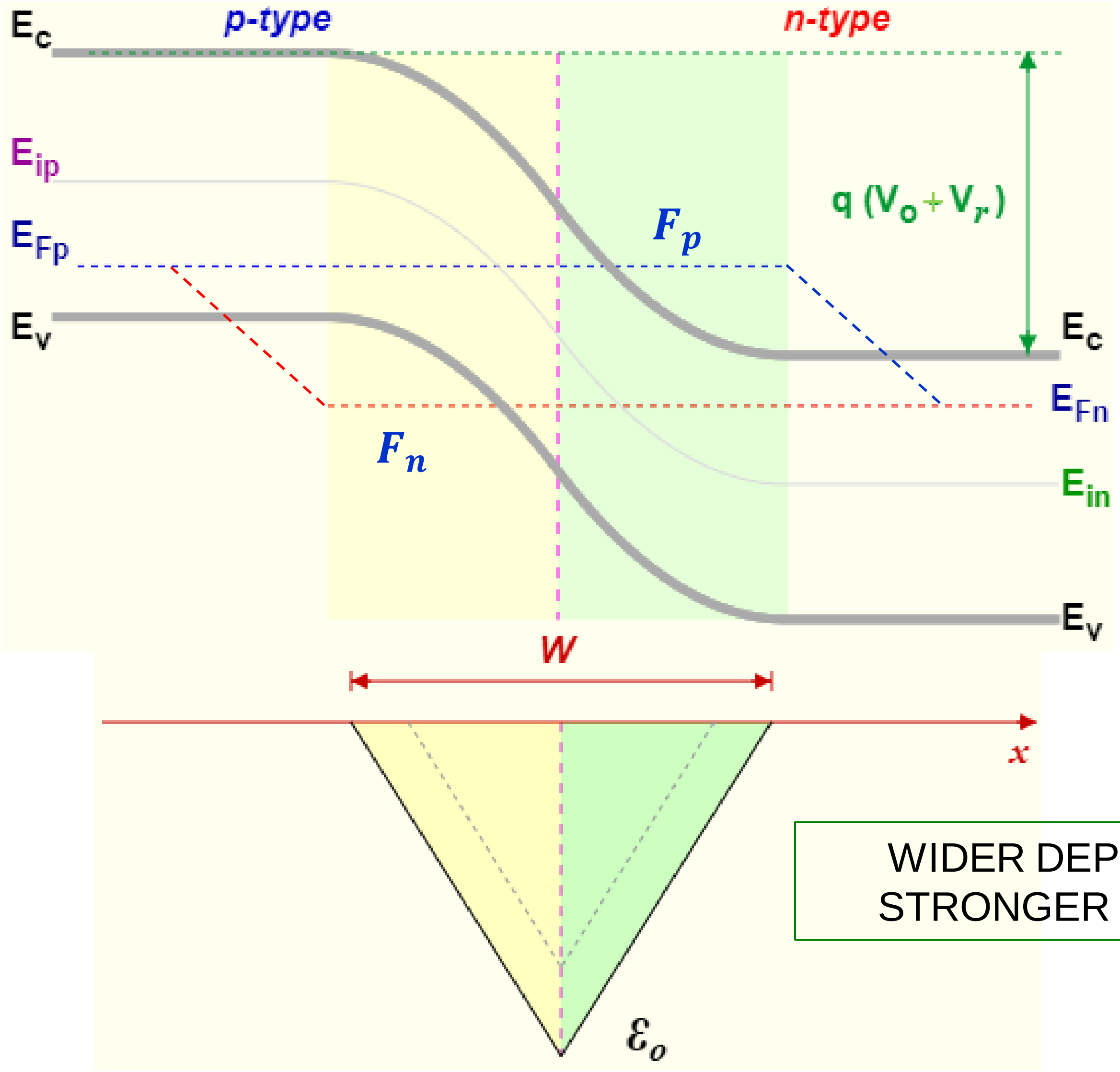
p-n junction in *forward bias*



The behavior of the quasi-Fermi levels indicates that there is excess minority carrier concentration at the “boundaries” of the depletion region.

p-n junction in *reverse bias*

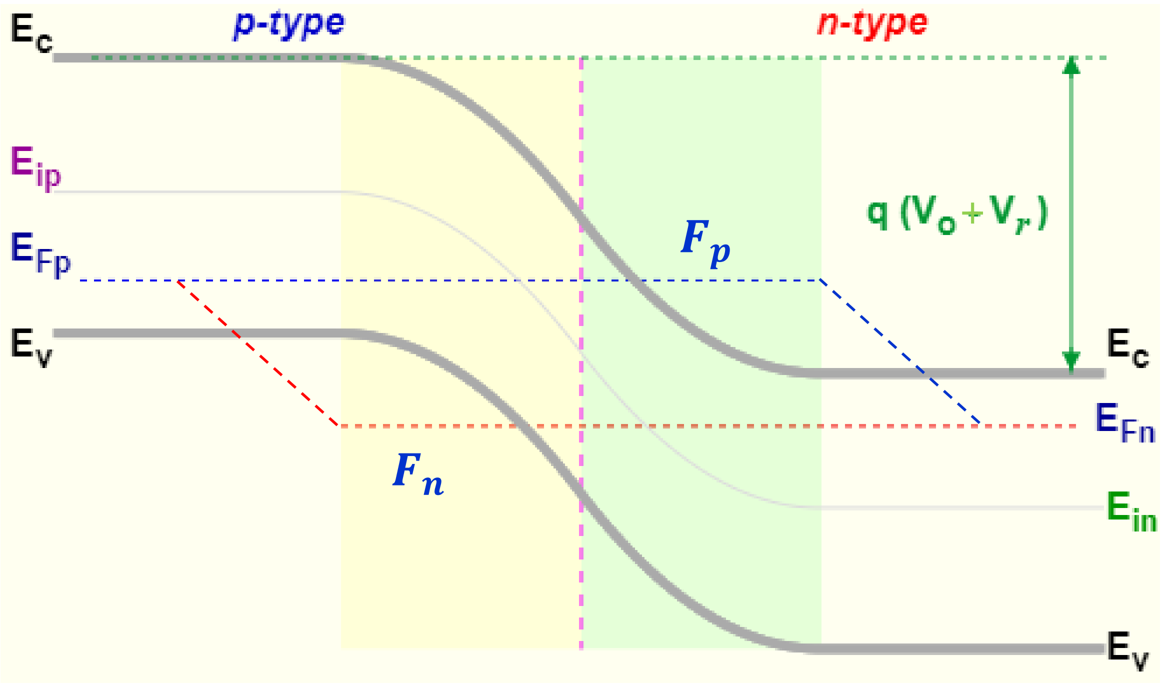
HIGHER BARRIER

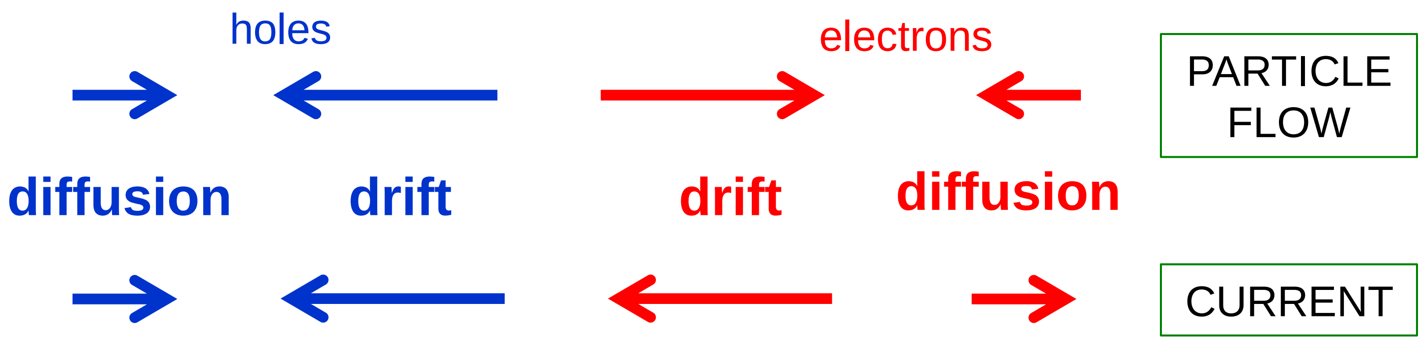


BIAS INCREASES CONTACT POTENTIAL

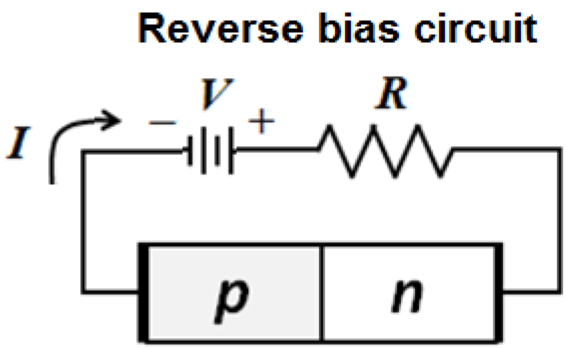
WIDER DEPLETION REGION
STRONGER ELECTRIC FIELD

p-n junction in *reverse bias*





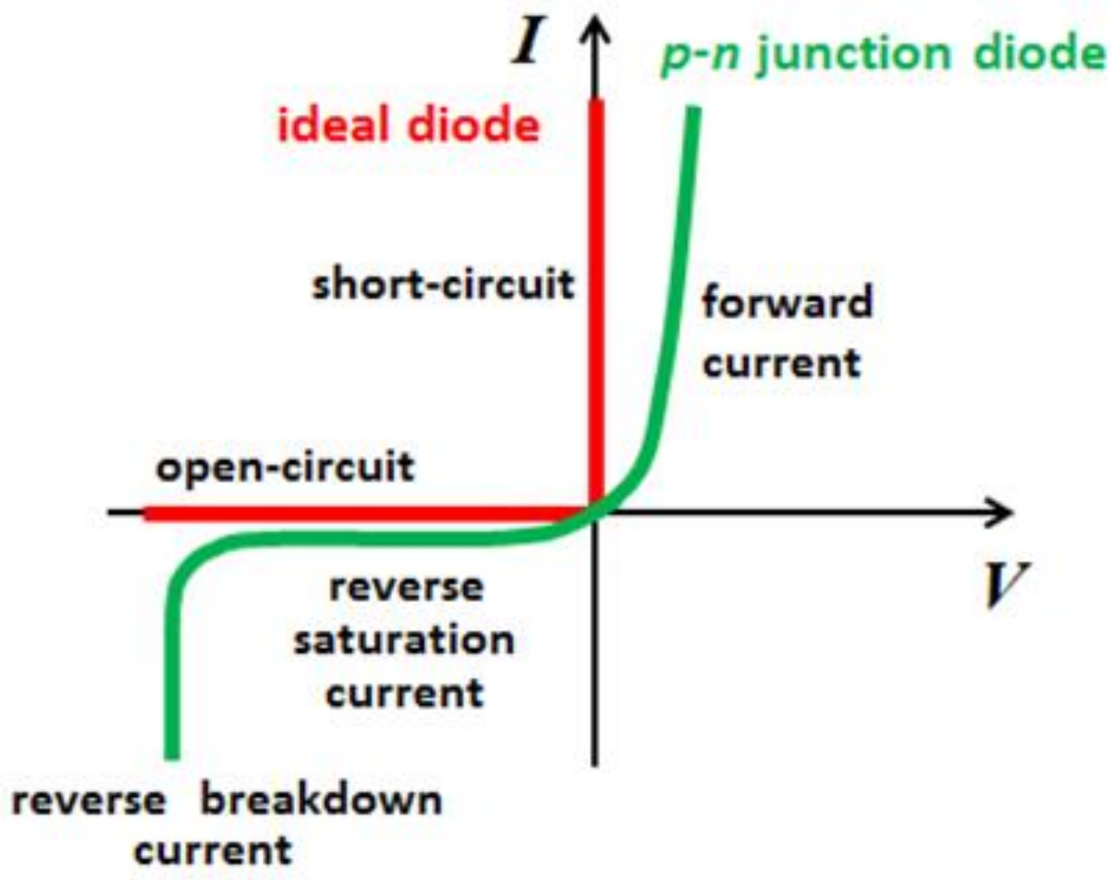
p-n junction in *reverse bias*



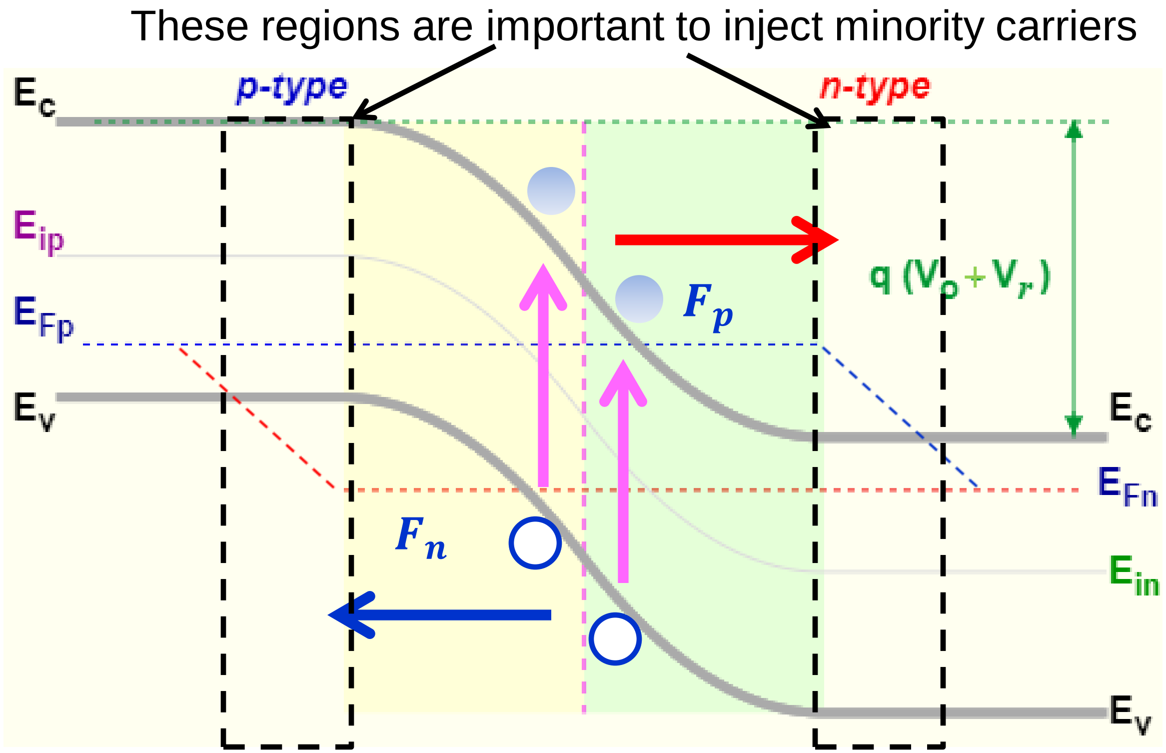
Reverse saturation current

$$I = I_0$$

Where does this current come from?
Why is it constant?



p-n junction in *reverse bias*



The field sweeps away the carriers generated in the depletion region

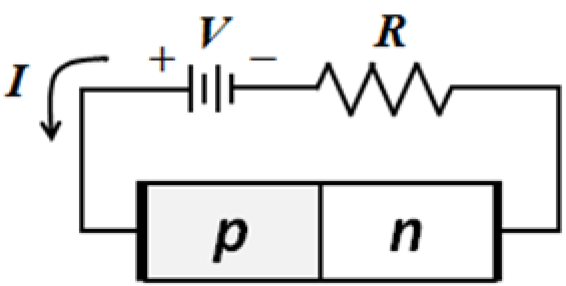
Thermal generation

At fixed temperature, thermal generation of EHP's is steady.
If the reverse bias is increased, carriers in the space charge region may be faster, but the number of available carriers per unit time stays the same.

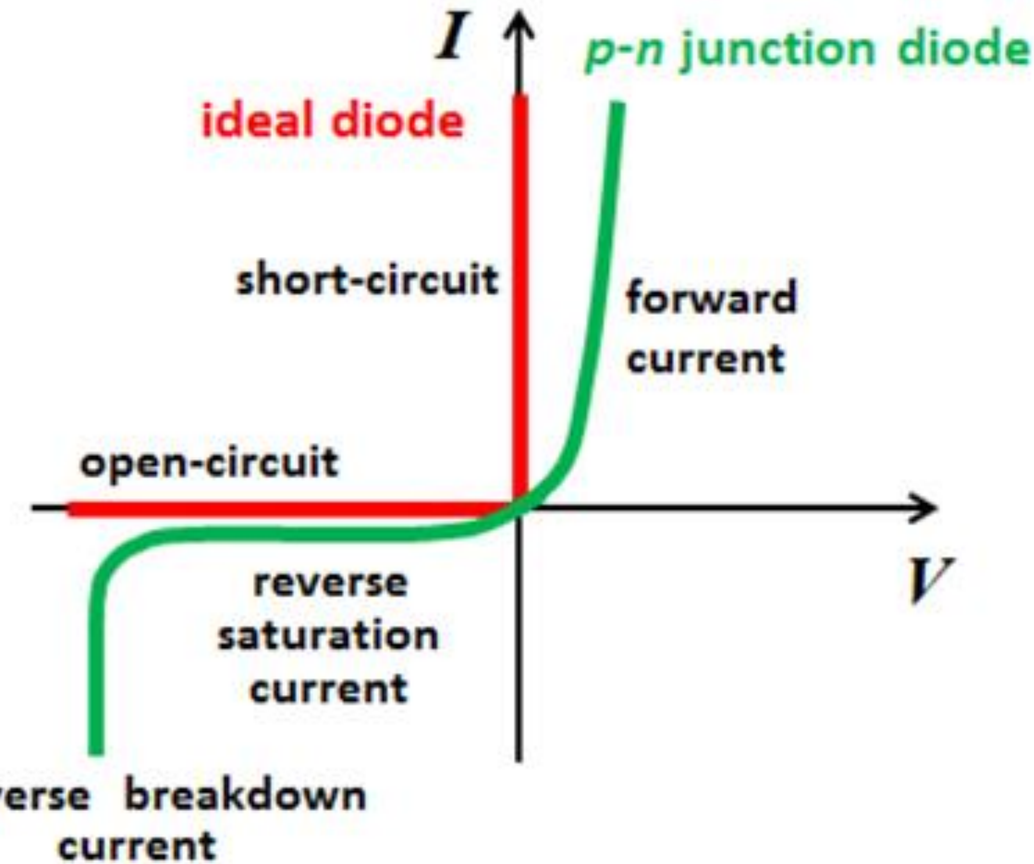
→ **The reverse saturation current remains constant.**

p-n junction in *forward bias*

Forward bias circuit

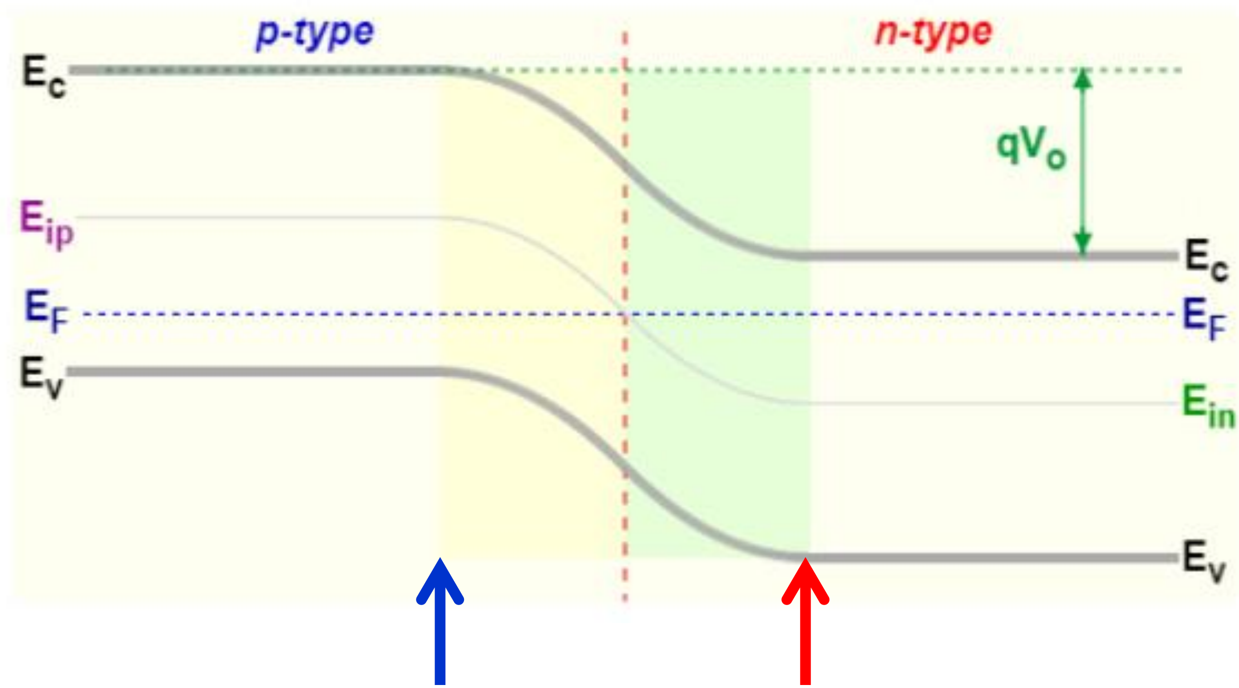


$$I = I_0\left(e^{qV/k_BT} - 1\right)$$
$$= I_0\, e^{qV/k_BT} - I_0$$



Thermal generation current is always there but it becomes negligible for $V \gg k_BT/q$

Obtained earlier: Relation between contact potential and carrier densities in equilibrium

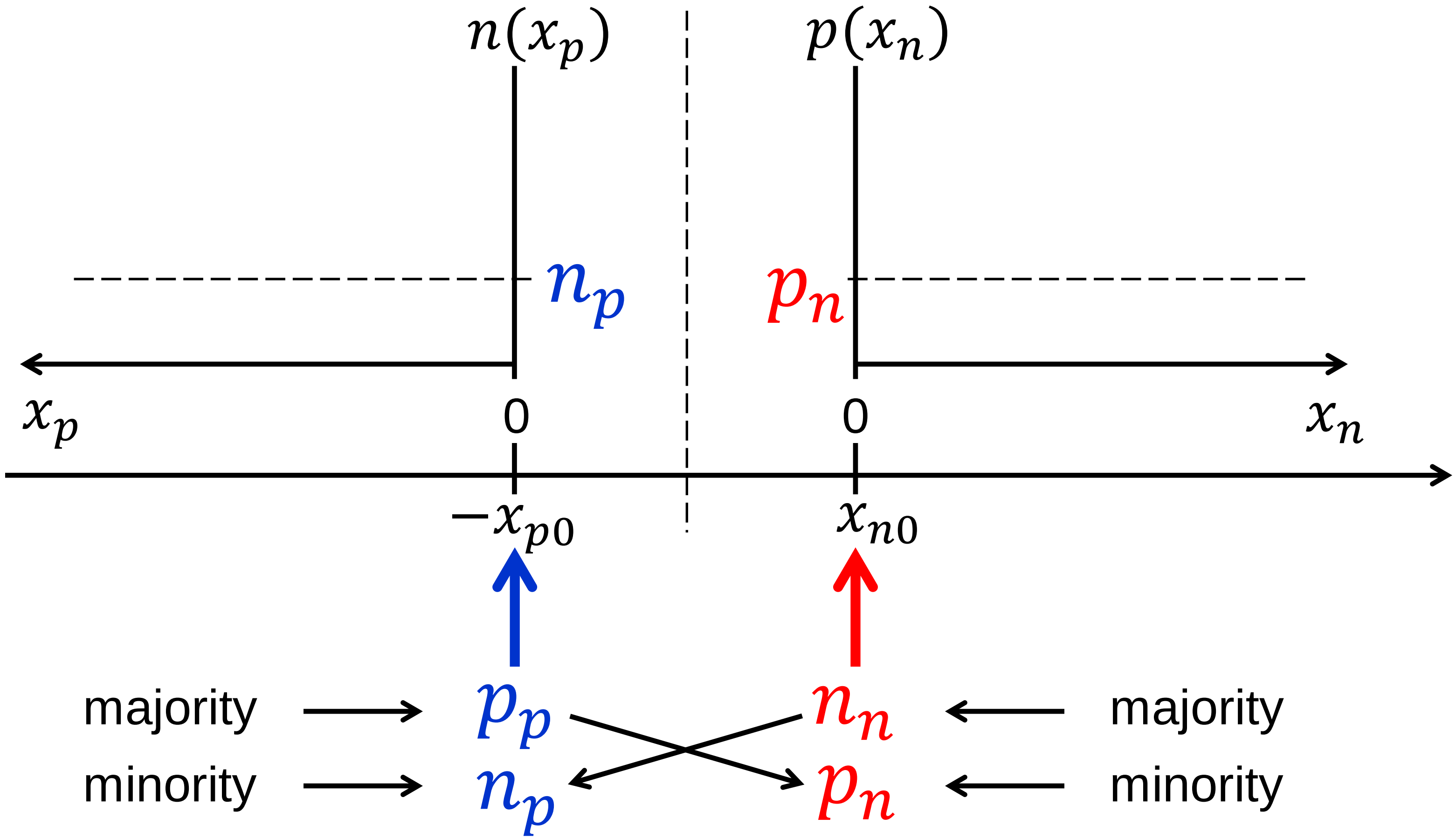


majority → p_p ↘ ↙ n_n ← majority

minority → n_p ↙ ↘ p_n ← minority

$$\frac{p_p}{p_n} = \exp\left(\frac{qV_0}{k_B T}\right) \qquad \frac{n_n}{n_p} = \exp\left(\frac{qV_0}{k_B T}\right)$$

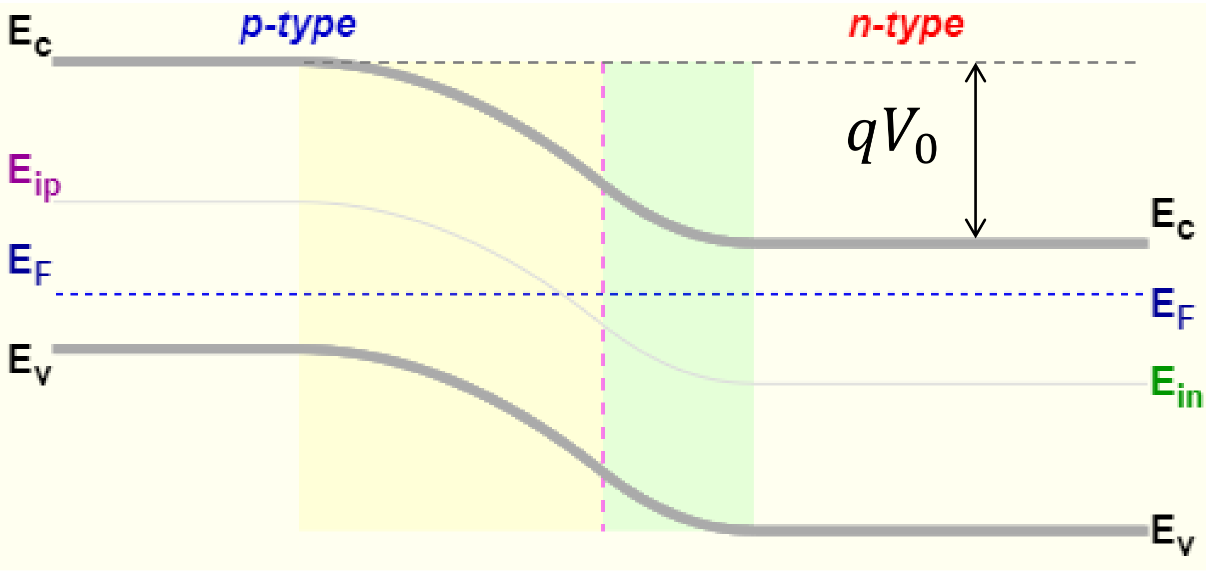
Use edges of depletion layer as space references



$$\frac{p_p}{p_n} = \exp\left(\frac{qV_0}{k_B T}\right)$$

$$\frac{n_n}{n_p} = \exp\left(\frac{qV_0}{k_B T}\right)$$

Asymmetric doping: $N_D > N_A$ (equilibrium)

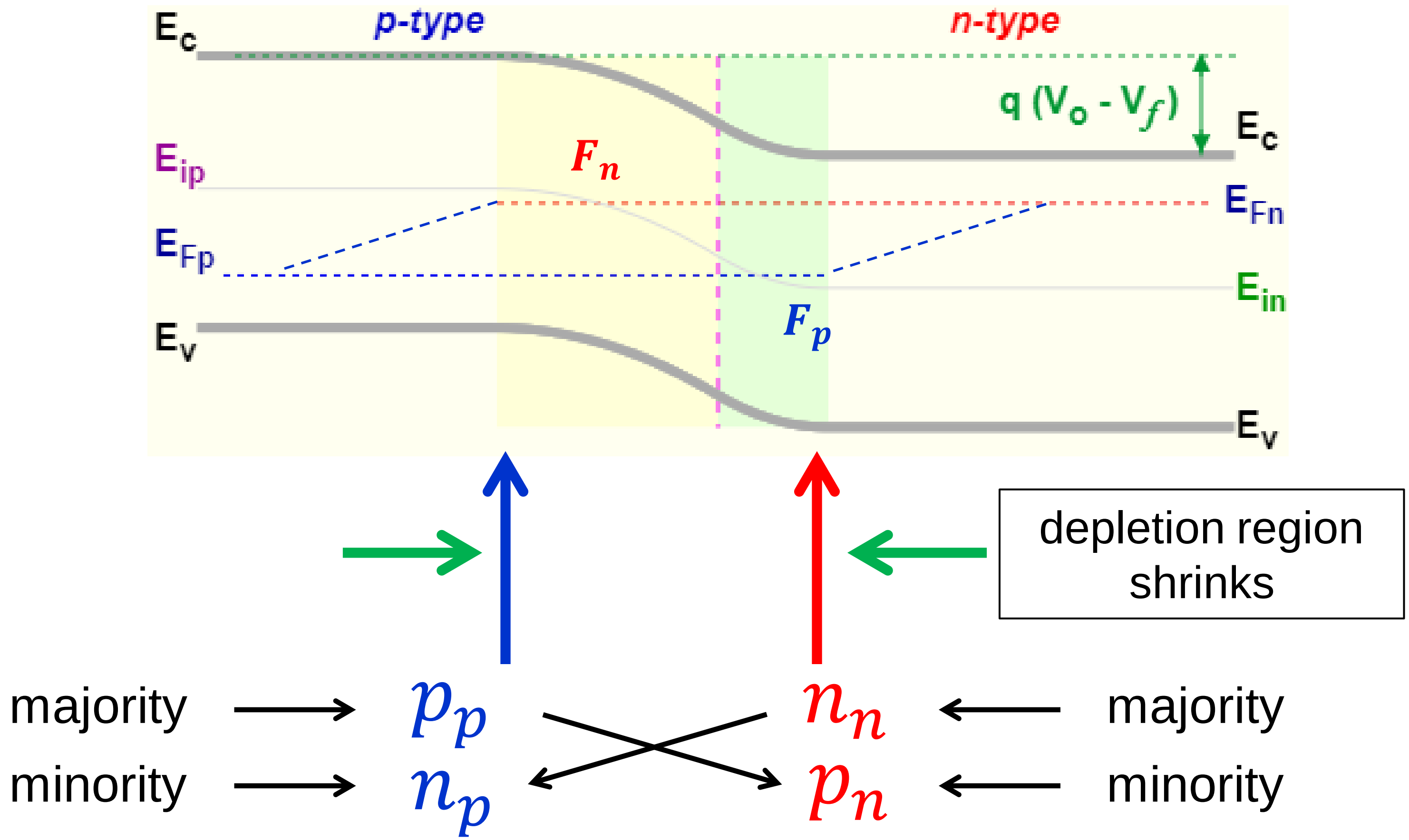


majority → p_p n_n ← majority

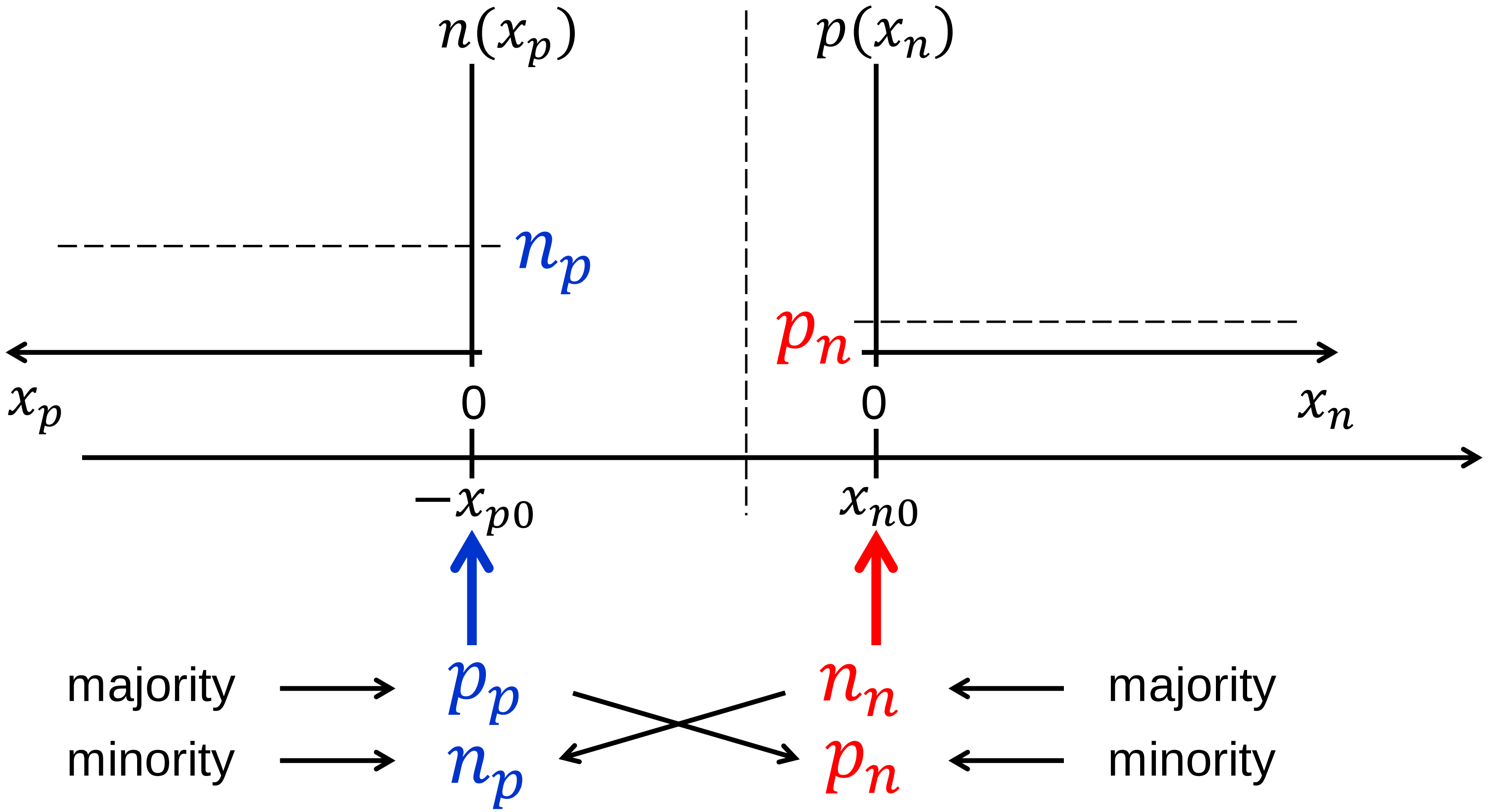
minority → n_p p_n ← minority

$$\frac{p_p}{p_n} = \exp\left(\frac{qV_0}{k_B T}\right) \qquad \frac{n_n}{n_p} = \exp\left(\frac{qV_0}{k_B T}\right)$$

Asymmetric doping: $N_D > N_A$ (forward bias)

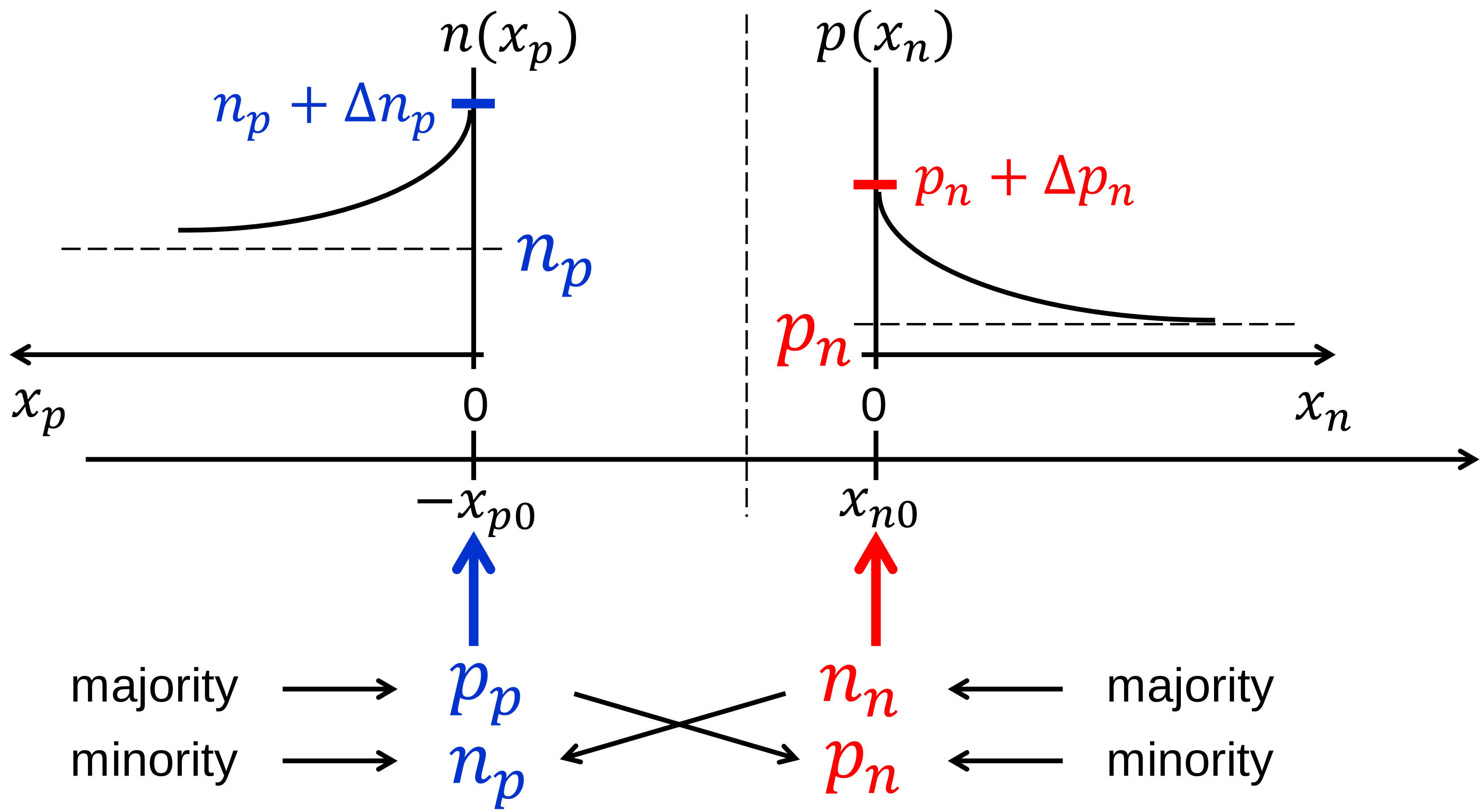


Asymmetric doping: $N_D > N_A$ (forward bias)



Reference minority carrier densities up to the edges of the depletion layer

Asymmetric doping: $N_D > N_A$ (forward bias)



Excess carriers as boundary conditions for the two sides

→ We do not model in detail the space-charge region