

EEM 214

Lecture 3

Carrier Action

Drift, mobility and resistivity

Diffusion

Band bending

Non-uniform doping

Einstein relationship

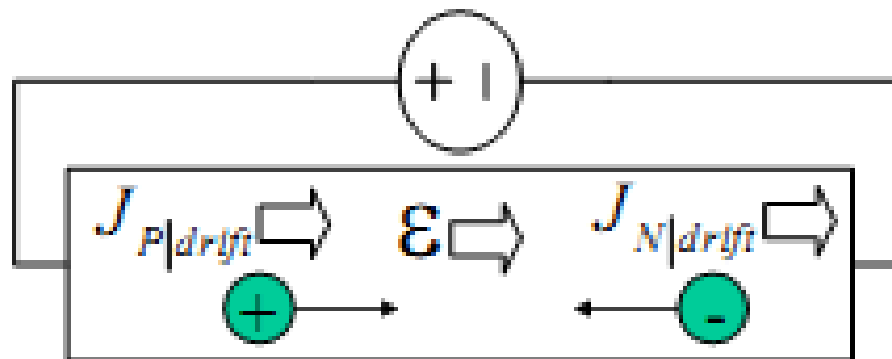
Diode behavior using E-band diagram

Recombination/generation

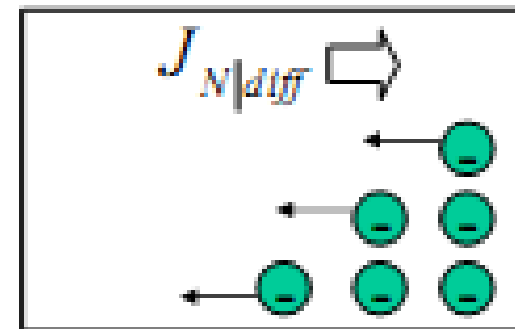
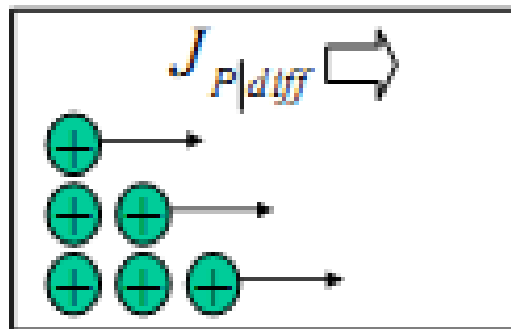
Minority carrier lifetimes

Causes of carrier motion

- Drift: Caused by electric field (or potential difference)

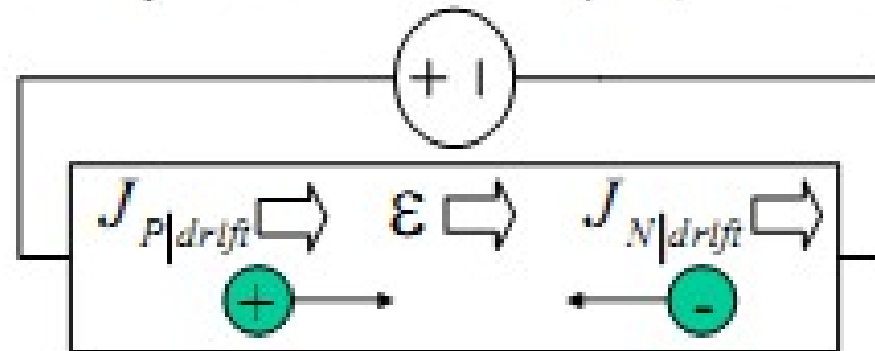


- Diffusion: Caused by difference in concentration of carriers



Drift currents

- Drift: Caused by electric field (or potential difference)



- Drift current density

$$J_{P|drift} = q\mu_p p\mathcal{E} \quad \text{for holes}$$

$$J_{N|drift} = q\mu_n n\mathcal{E} \quad \text{for electrons}$$

- Terminal velocity reached for high E-fields

Mobilities

Si at room temp (almost pure)

$$\mu_p \approx 460 \text{ cm}^2 / V - \text{sec} \quad (\text{at } N_A = 10^{14} / \text{cm}^3)$$

$$\mu_n \approx 1360 \text{ cm}^2 / V - \text{sec} \quad (\text{at } N_D = 10^{14} / \text{cm}^3)$$

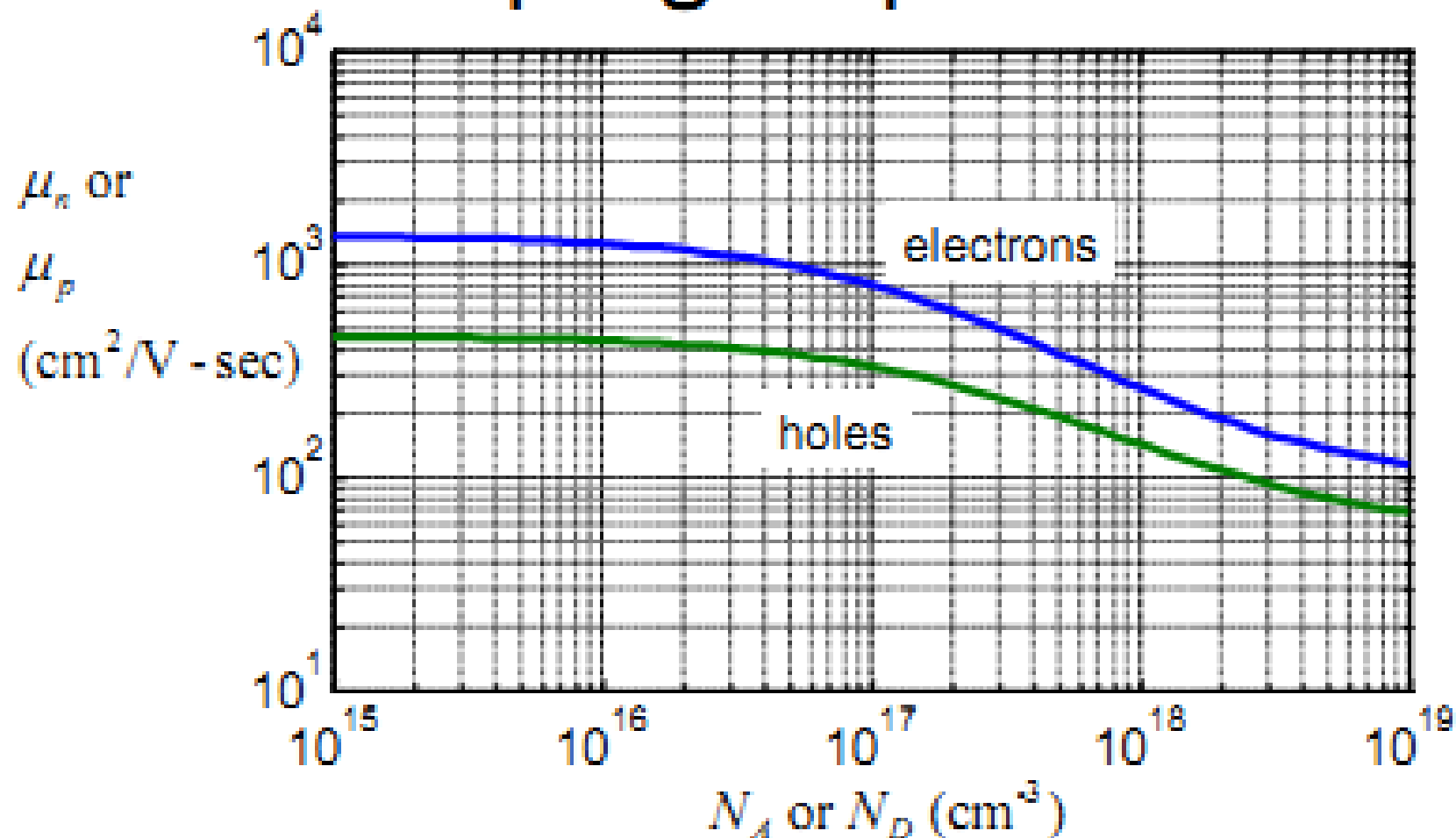
GaAs at room temp (high purity)

$$\mu_p \approx 400 \text{ cm}^2 / V - \text{sec} \quad (\text{at } N_A \leq 10^{15} / \text{cm}^3)$$

$$\mu_n \approx 8000 \text{ cm}^2 / V - \text{sec} \quad (\text{at } N_D \leq 10^{15} / \text{cm}^3)$$

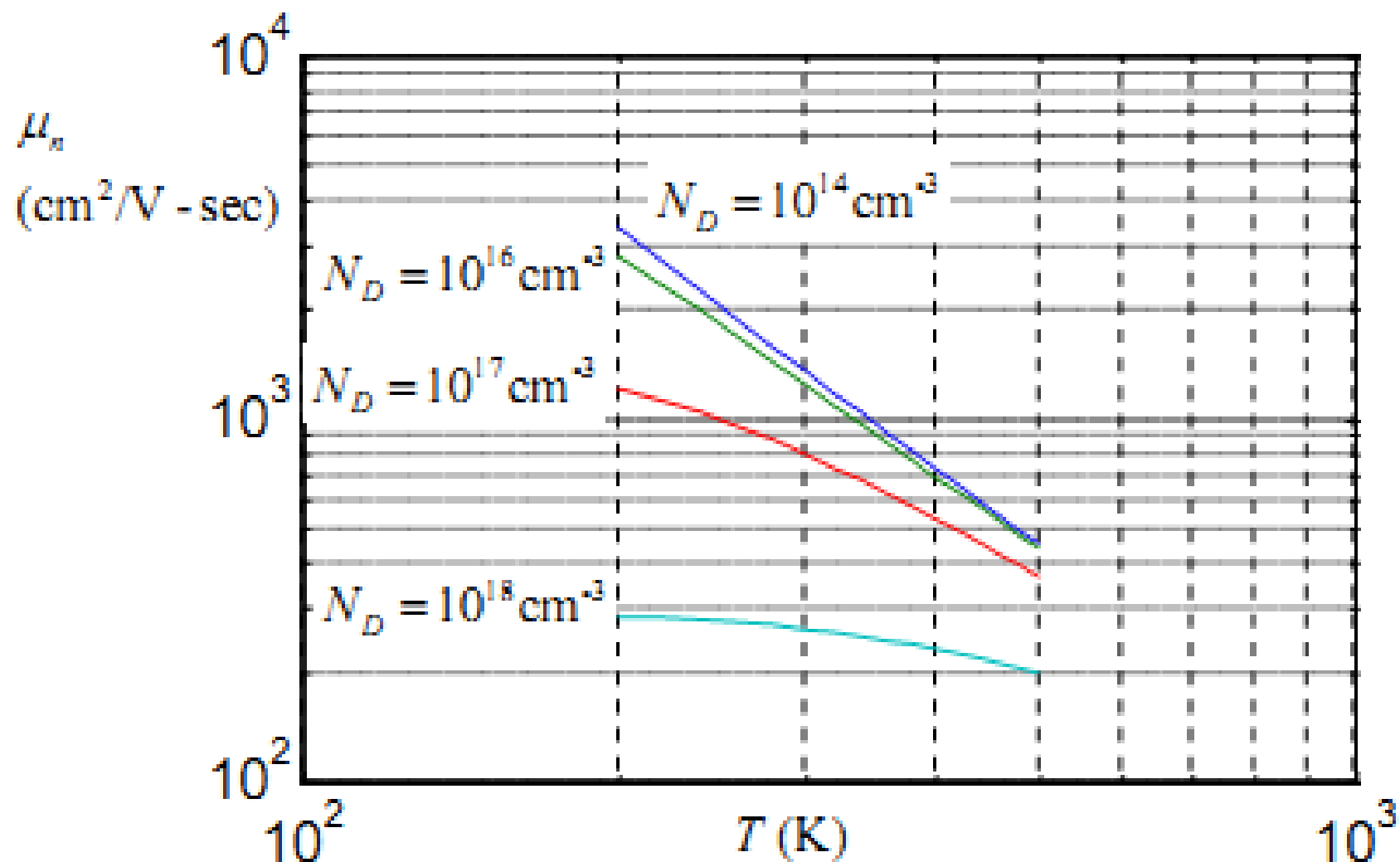
- Electrons faster than holes

Doping dependence



- Mobility decreases as result of increased scattering by ionized impurities

Temp dependence



Resistivity and doping

- Resistivity

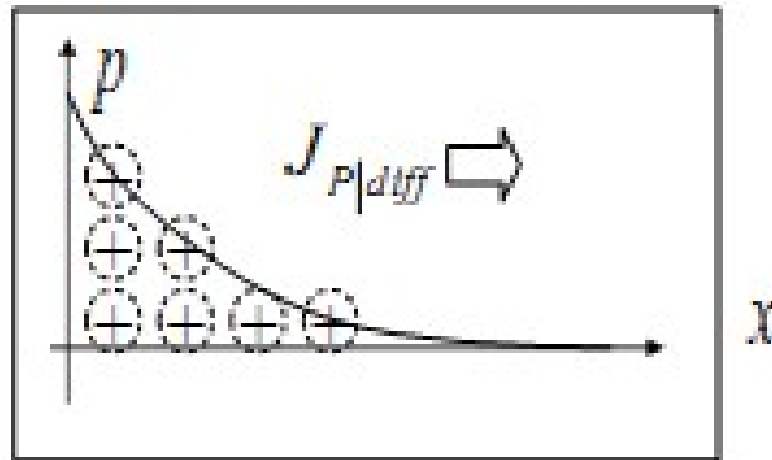
$$J = \frac{1}{\rho} \mathcal{E} \qquad \rho = \frac{1}{q(\mu_n n + \mu_p p)}$$

- Effect of doping

$$\rho = \frac{1}{q\mu_n N_D} \quad \text{for n - type} \qquad \rho = \frac{1}{q\mu_p N_A} \quad \text{for p - type}$$

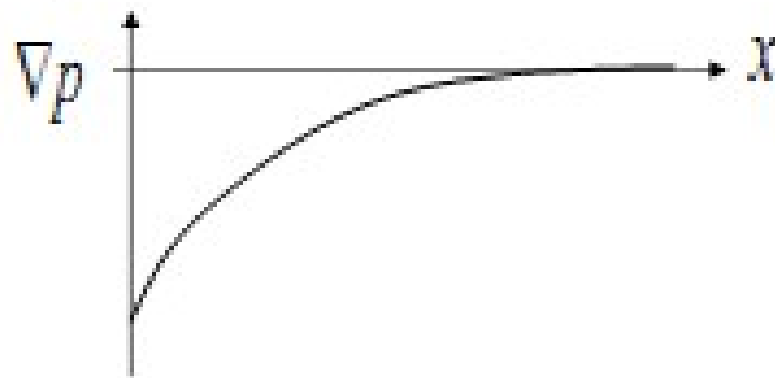
Diffusion current density

- Concentration gradient



$$J_{P|diff} = -qD_p \nabla p$$

$$J_{N|diff} = qD_n \nabla n$$



Einstein relationship (summary)

$$\frac{D_n}{\mu_n} = \frac{kT}{q}$$

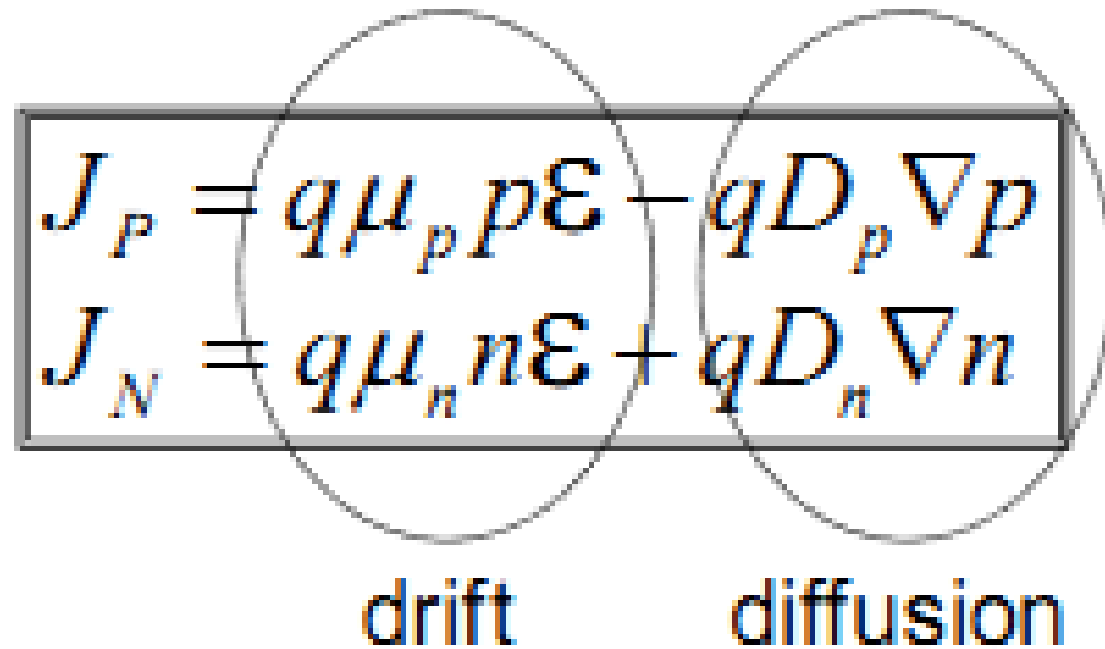
For electrons

$$\frac{D_p}{\mu_p} = \frac{kT}{q}$$

For holes

- Units of diffusion constant: cm²/sec

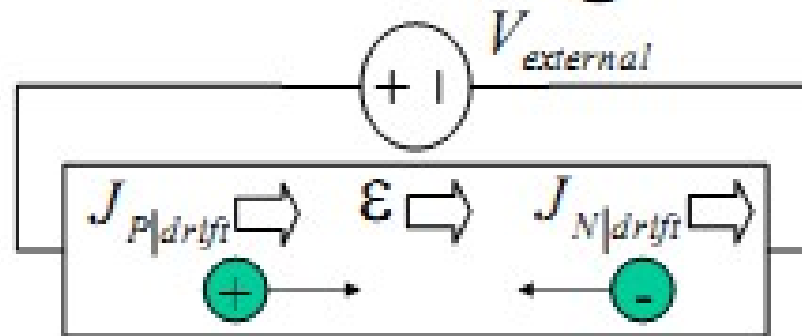
Total currents


$$\begin{aligned} J_P &= q\mu_p p \mathcal{E} - qD_p \nabla p \\ J_N &= q\mu_n n \mathcal{E} + qD_n \nabla n \end{aligned}$$

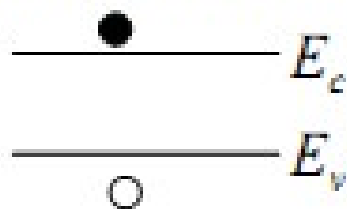
drift diffusion

$$J = J_P + J_N$$

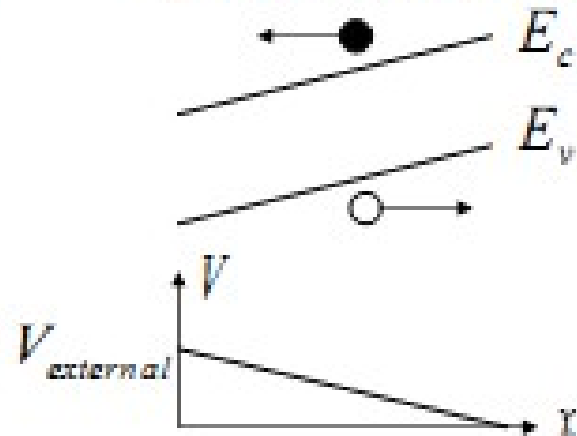
Band-bending



No external voltage



Applied voltage



Voltage increases
in direction opposite $\mathcal{E}$
since $\mathcal{E} = -\nabla V$

Energy-voltage relationship

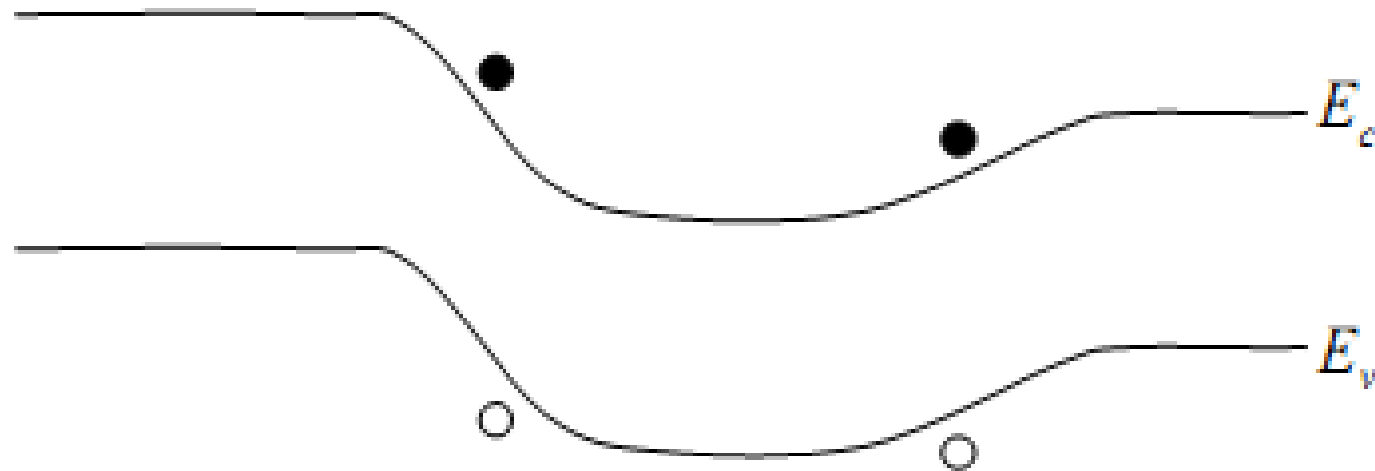
- Energy diagram is flipped graph of voltage

$$\begin{aligned} P.E. &= -qV \\ &= E_c - E_{ref} \end{aligned}$$

- Therefore, electric field proportional to slope of energy diagram

$$\begin{aligned} \mathcal{E} &= -\nabla V \\ &= \frac{1}{q} \frac{dE_c}{dx} = \frac{1}{q} \frac{dE_v}{dx} = \frac{1}{q} \frac{dE_i}{dx} \end{aligned}$$

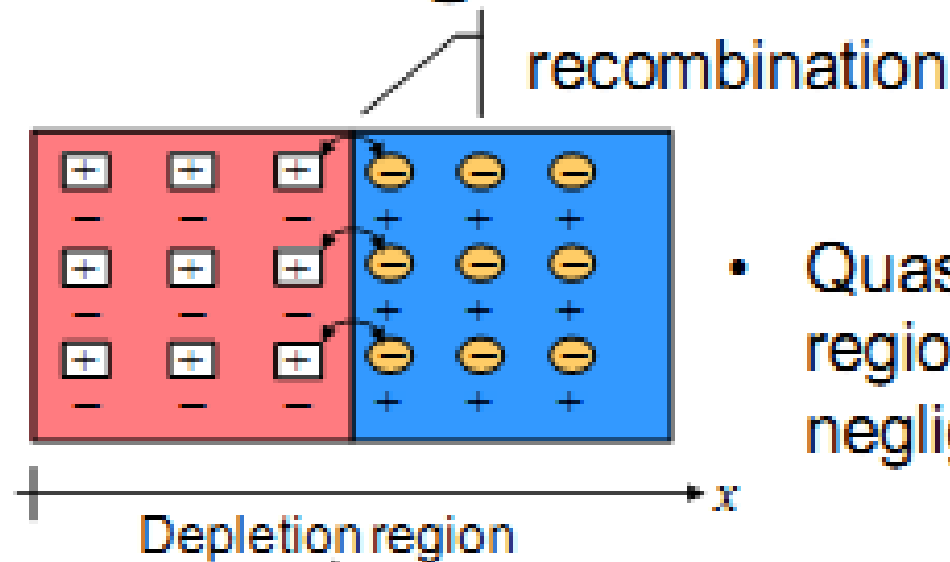
Band bending ...



- Q: Sketch the $\mathbf{E}$ of the material w/ above energy band diagram.
- Q: What is the direction of drift for each of the charge carriers shown?

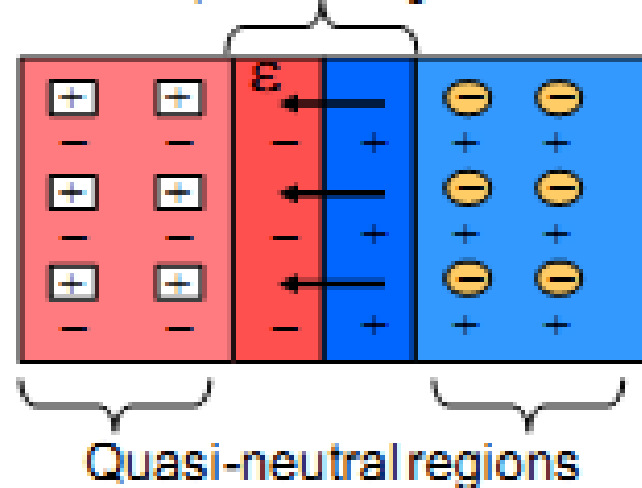
Depletion region formation

Before
equilibrium



- Quasi-neutral regions:
negligible ϵ -field

At
equilibrium

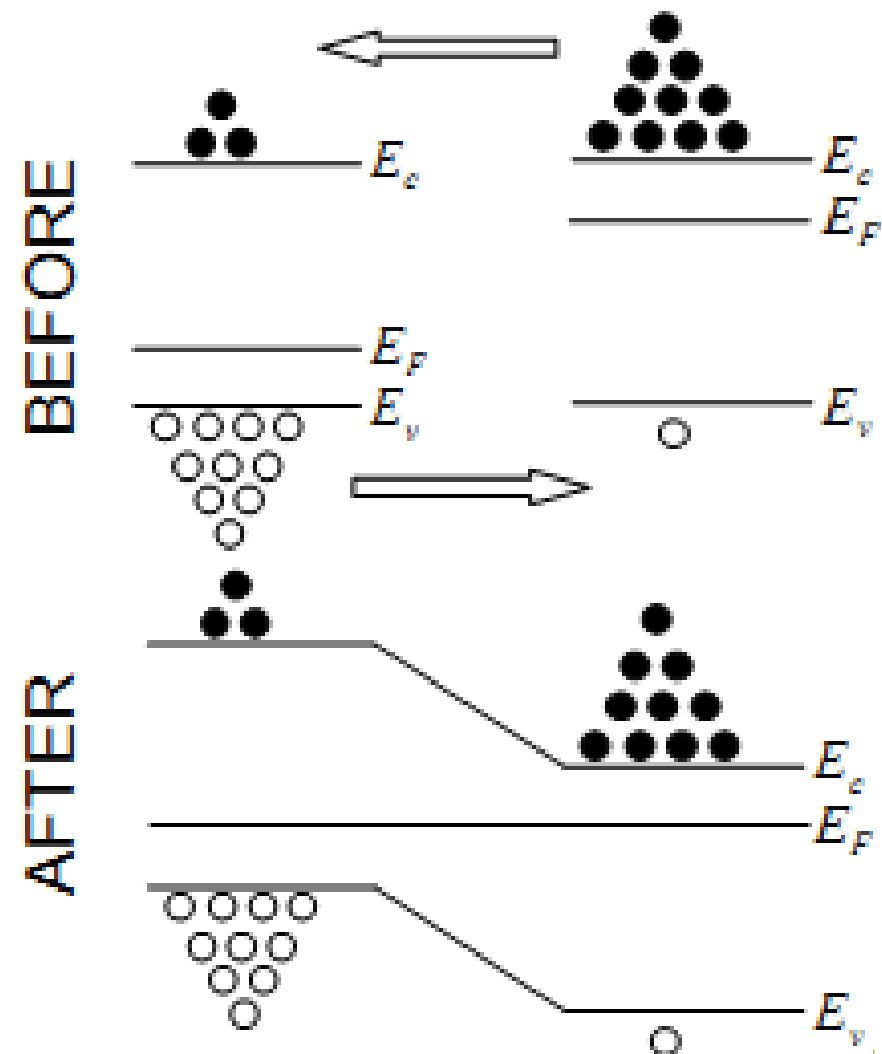


- Q: Sketch $V(x)$
using

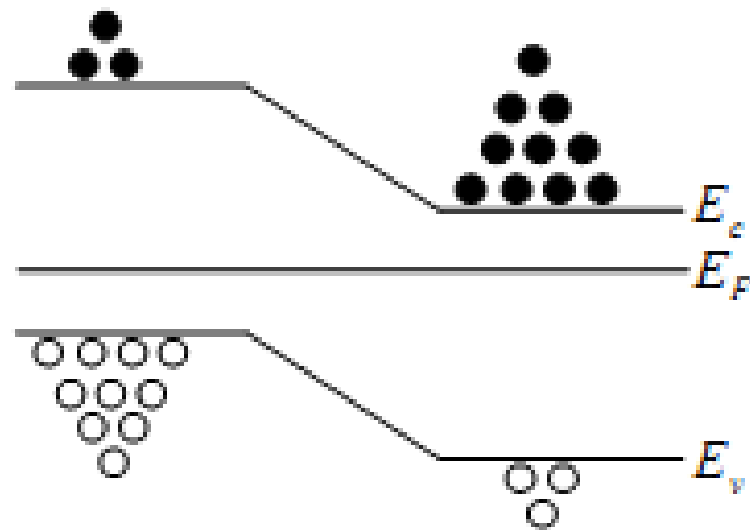
$$\epsilon = -\nabla V$$

Non-uniform doping ...

- Electrons diffuse from high N_D area to low N_D area ...
- Fermi level equalizes across the material ...
- But relative energy levels in each area (far from junction) remain constant



... results in band-bending



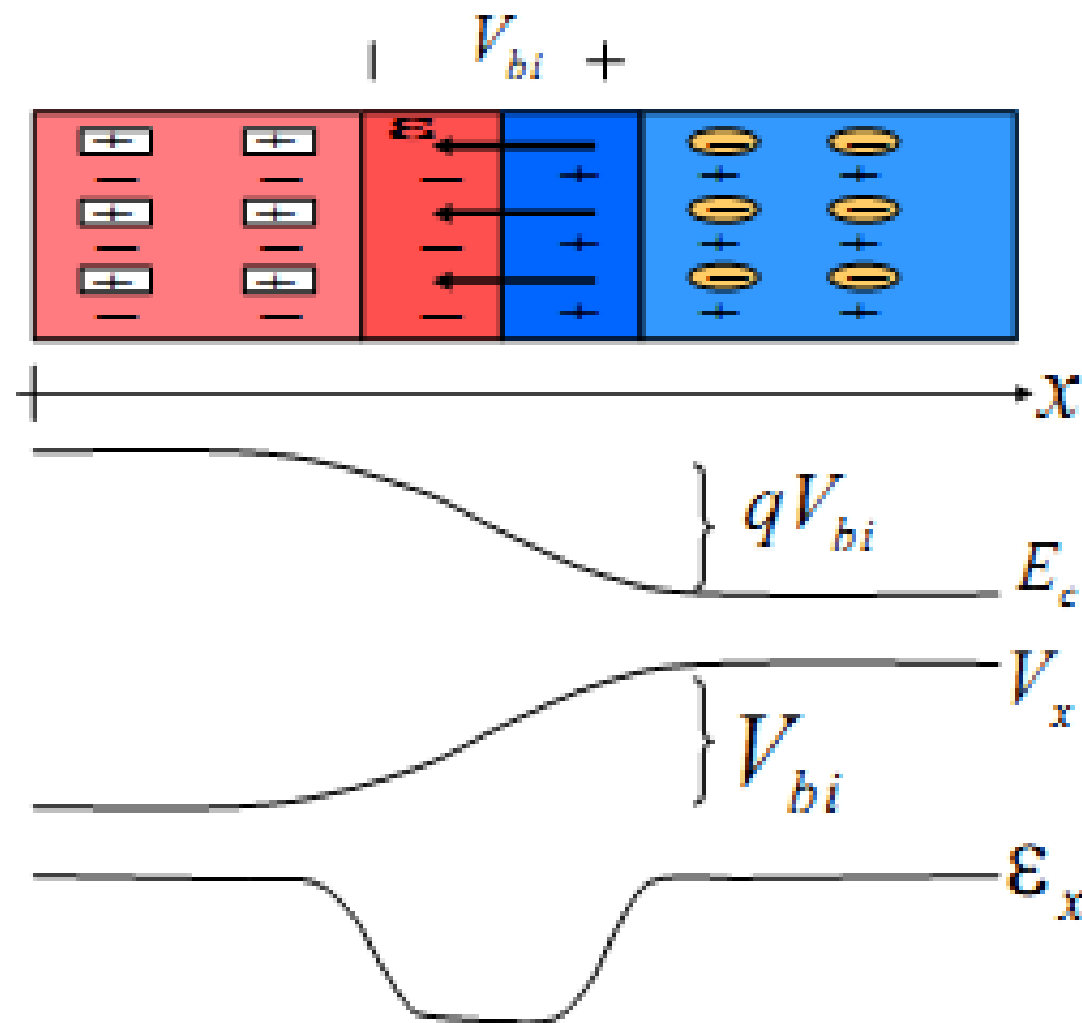
In equilibrium,

$$J_p = q\mu_p p\mathcal{E} - qD_p \nabla p = 0$$

$$J_n = q\mu_n n\mathcal{E} + qD_n \nabla n = 0$$

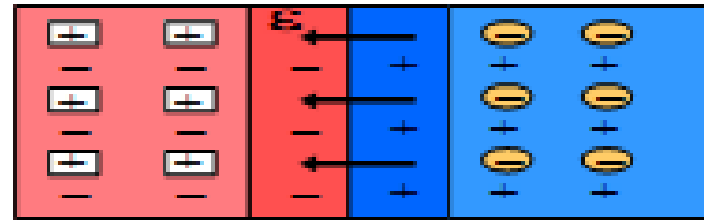
- Q: In which direction is the electric field caused by band bending?
- Band-bending sets up electric field stopping further diffusion

Built-in potential



- Internal potential V_j is sum of built-in potential V_{bi} plus any externally applied potential V_d

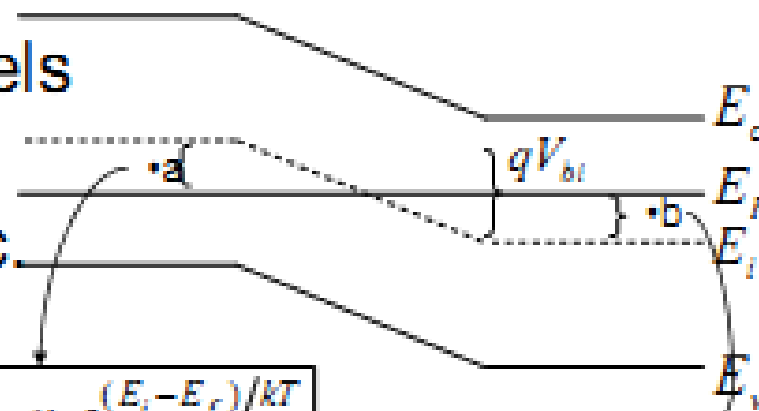
Built-in potential V_{bi}



- Energy levels related to charge conc. by ff eqns:

$$N_A \approx p = n_i e^{(E_i - E_f)/kT}$$

$$N_D \approx n = n_i e^{(E_f - E_i)/kT}$$



- From

$$qV_{bi} = a + b$$

- we get

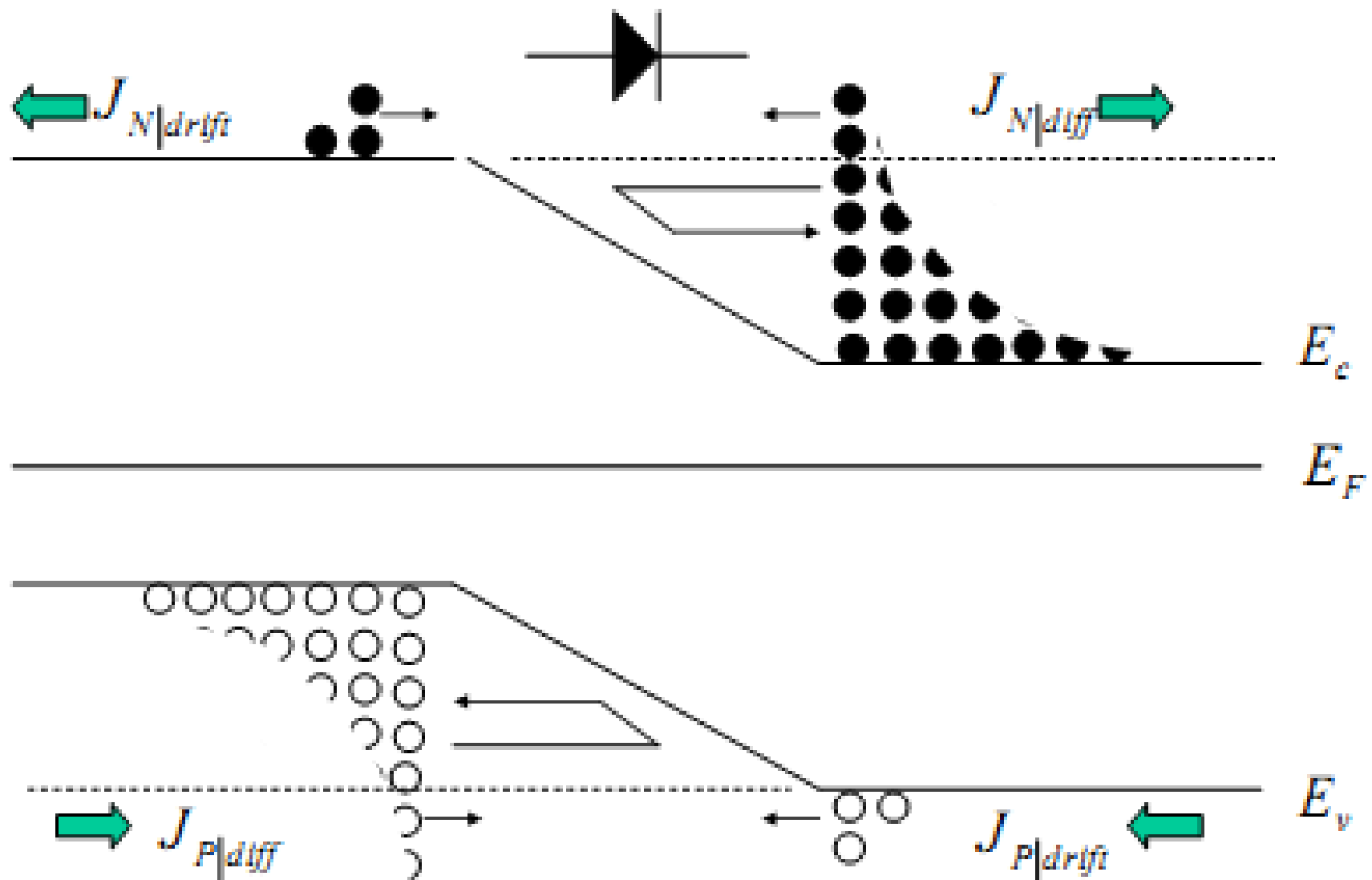
$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right)$$

Built-in potential V_{bi} ...

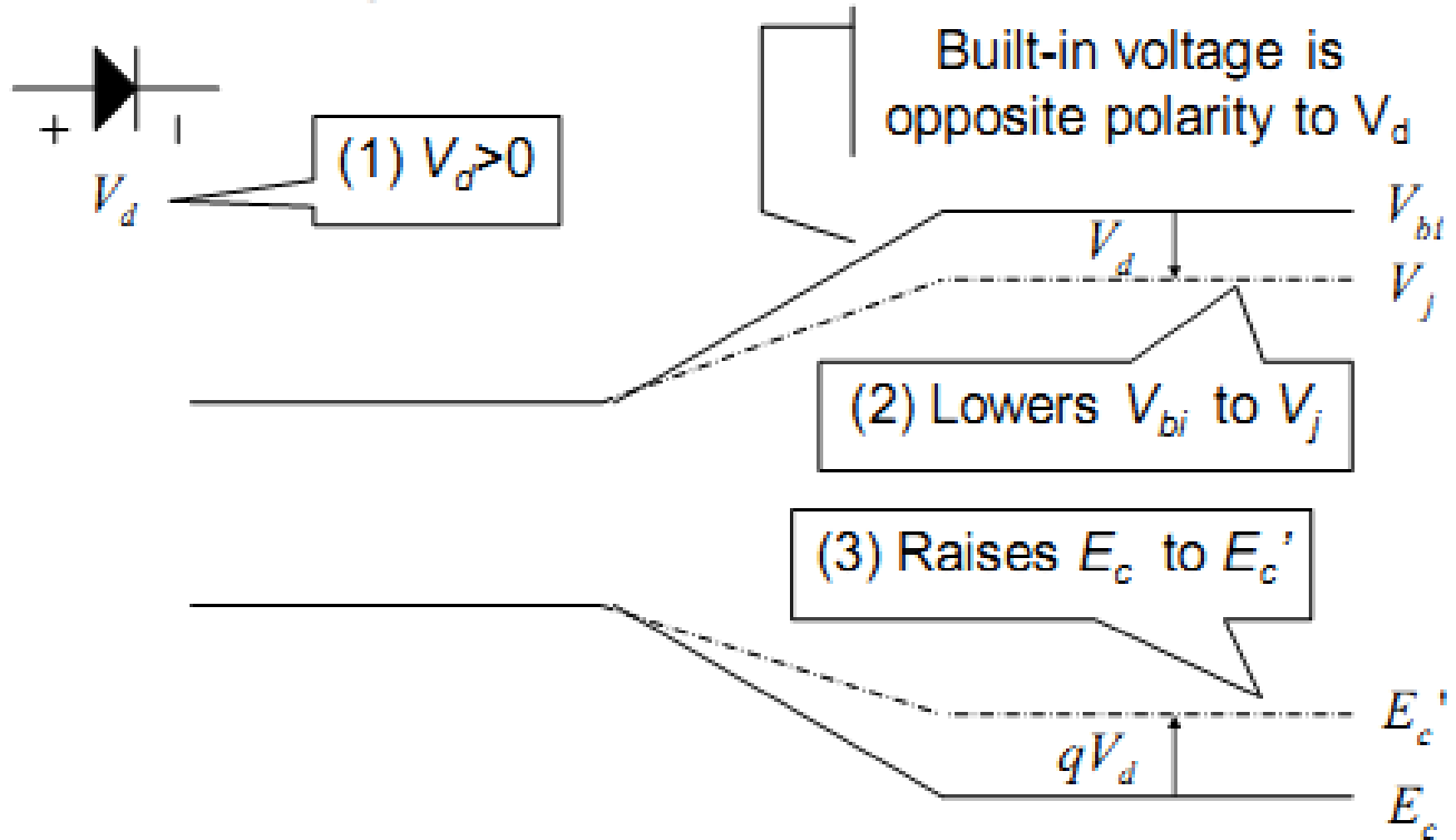
$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right)$$

- Q: Suppose $N_A = N_D = 10^{14}/\text{cm}^3$ for Si at 300K.
 - Compute V_{bi} .
 - Sketch the energy band diagram of the diode.
Compute the spacings between E_F and E_i at both ends of the diode.

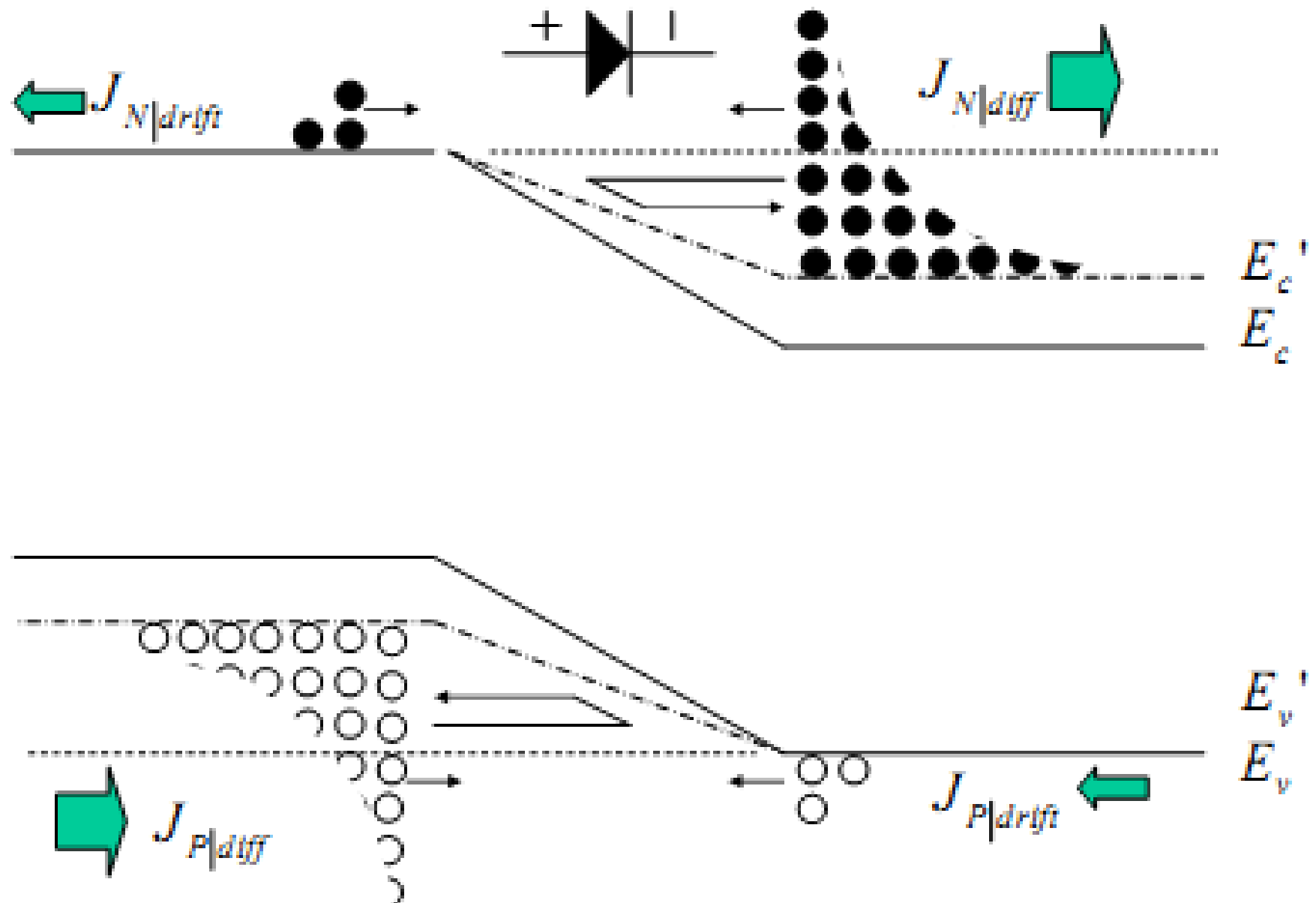
P-N junction at $V_d=0$



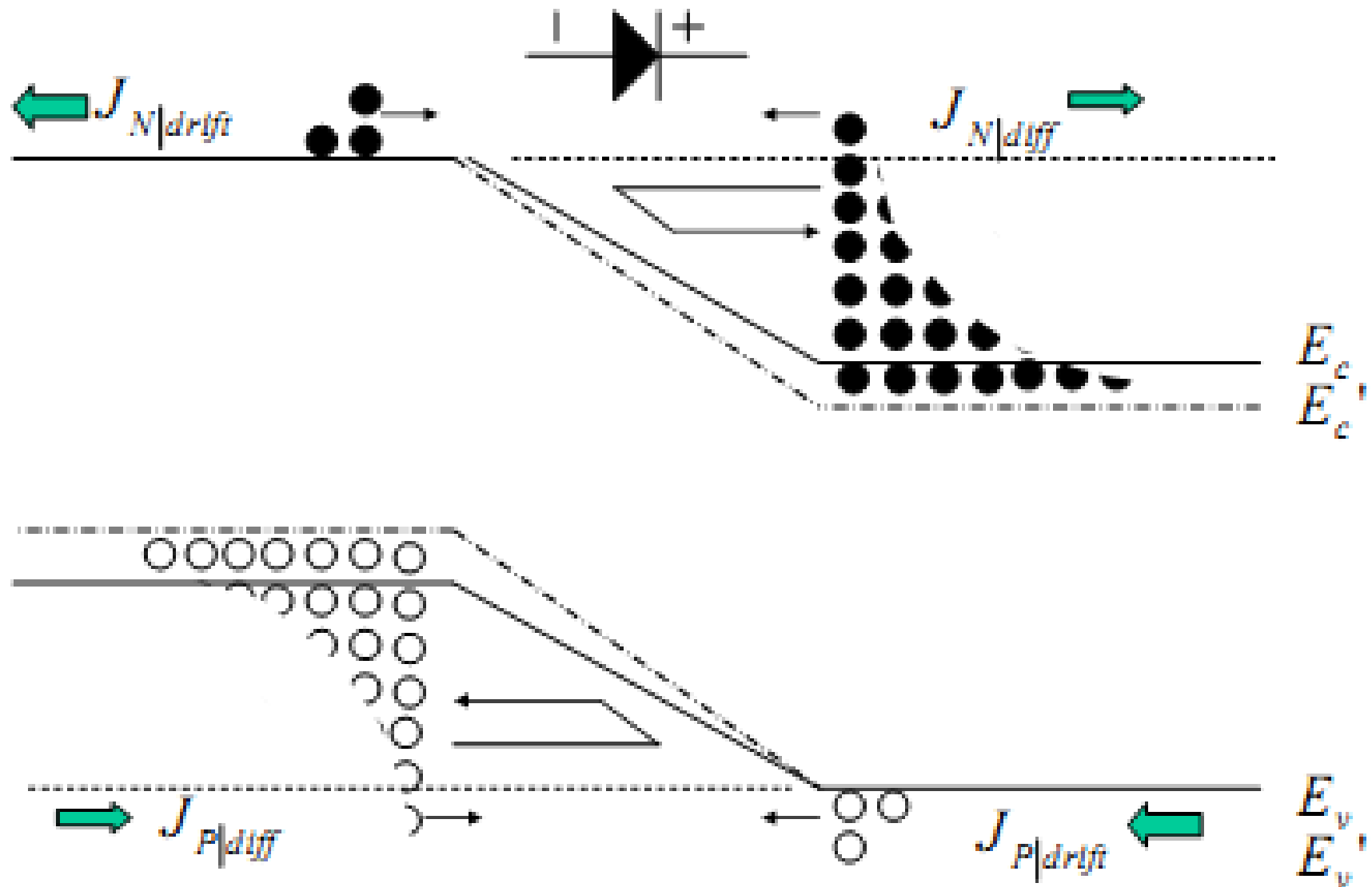
P-N junction electrostatics



Forward-biased P-N junction



Reverse-biased P-N junction



Summary of qualitative diode behavior

- Fermi level no longer flat when net currents flow
 - Use quasi-fermi levels
- When diode is forward-biased
 - “ON” current is mainly **diffusion** current
 - electrons diffuse from N to P region, where they become **minority carriers**
 - similarly, holes diffuse from P to N ...
- Minority carrier diffusion dynamics are important!
 - Leads to ideal diode equation