Section 20
PN Diode I-V Characteristics

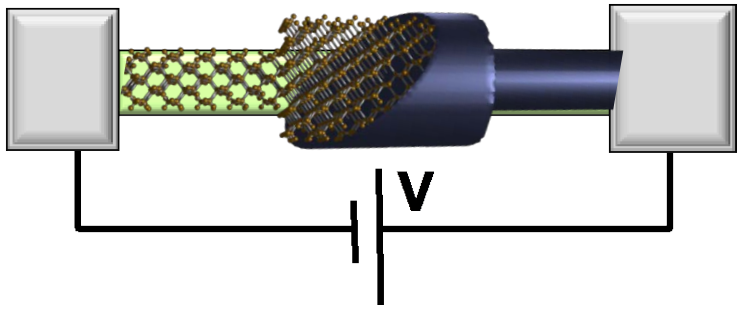
20.2 Derivation of the forward bias formula

Gerhard Klimeck
gekco@purdue.edu

PURDUE UNIVERSITY

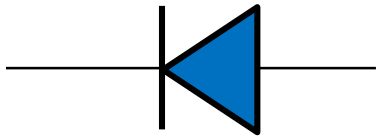
School of Electrical and Computer Engineering

Section 20
PN Diode I-V Characteristics

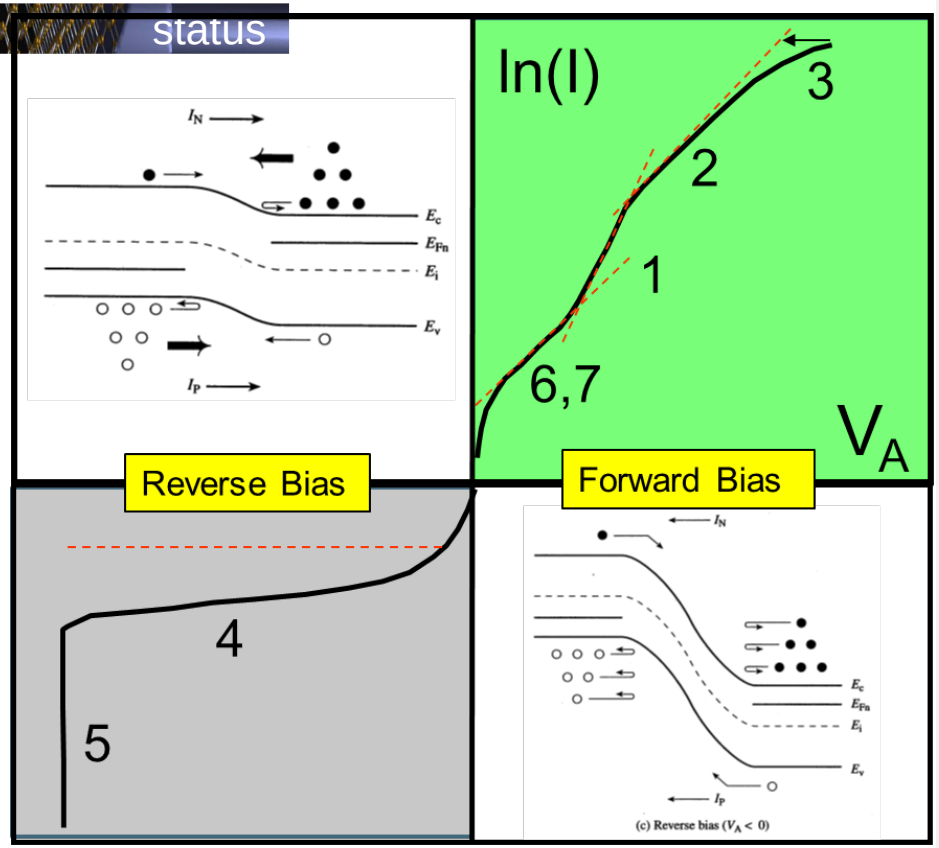


$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density, velocity, area

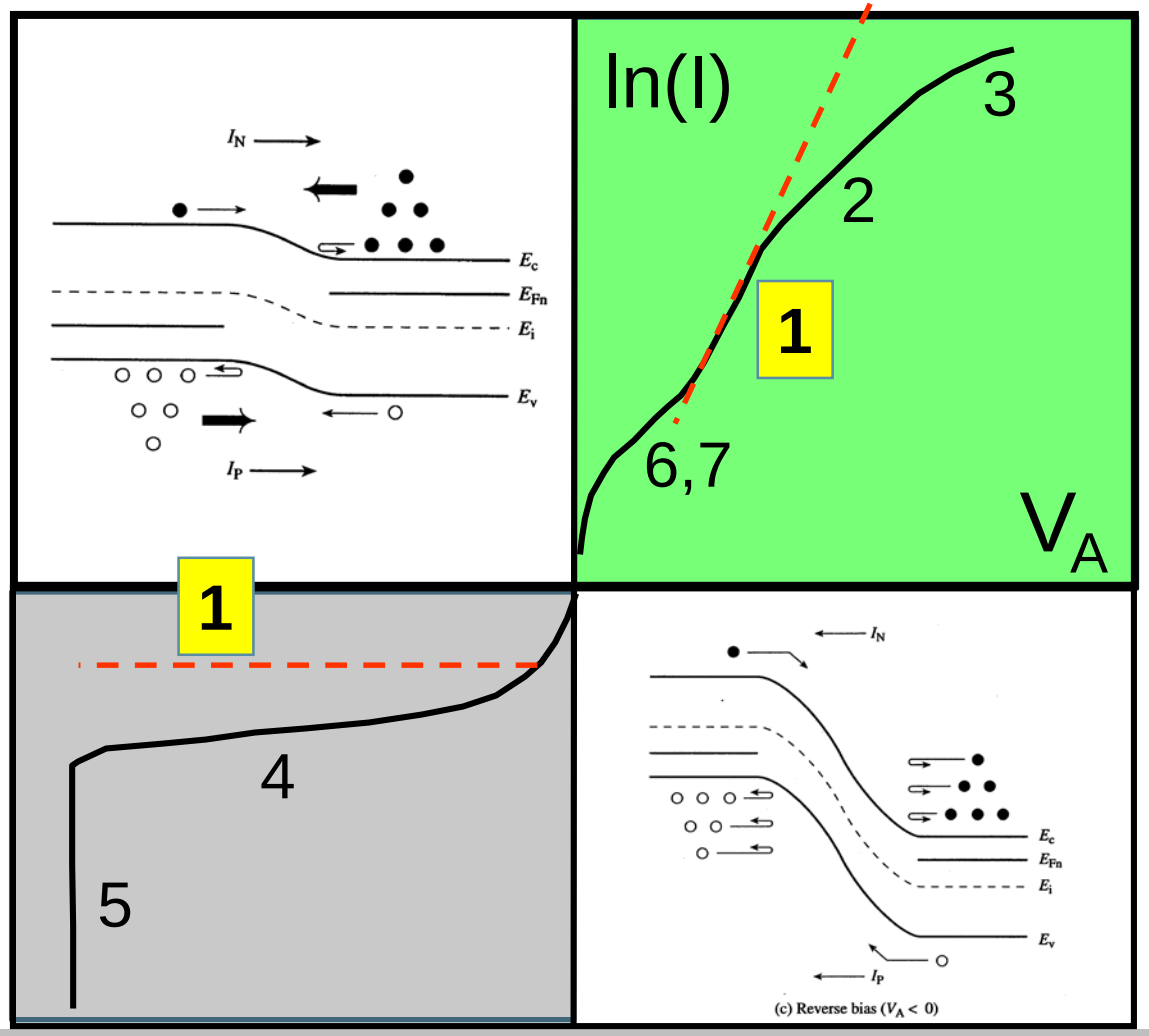


- 20.1 Band diagram with applied bias
- 20.2 Derivation of the forward bias formula
- 20.3
- 20.4



Various Regions of I-V Characteristics

$$\ln(I) \sim \frac{q}{k_B T} V_A$$

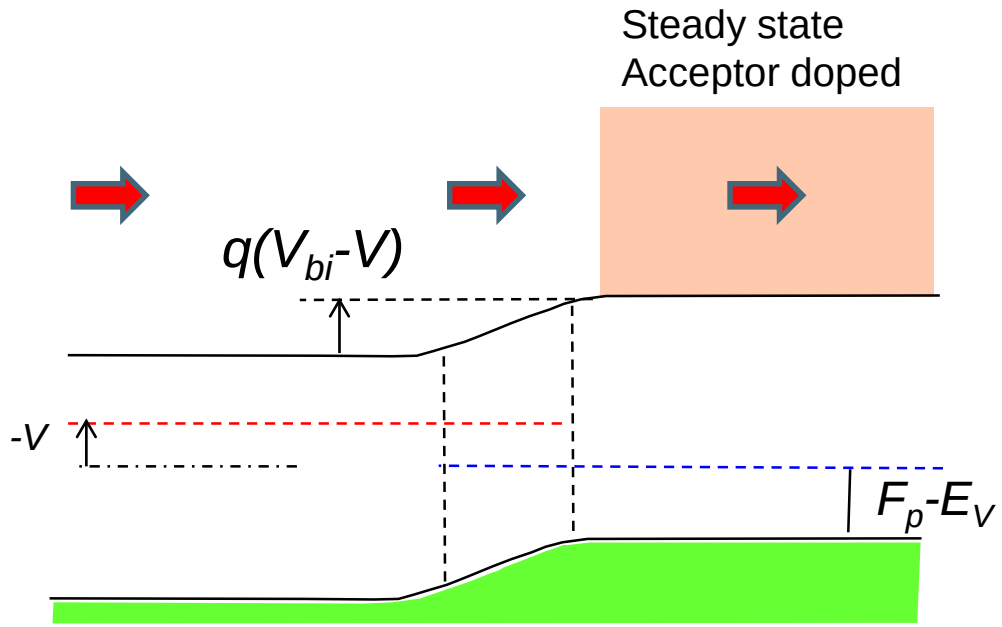


1. ***Diffusion limited***
2. *Ambipolar transport*
3. *High injection*
4. *R-G in depletion*
5. *Breakdown*
6. *Trap-assisted R-G*
7. *Esaki Tunneling*

Recall: One Sided Minority Diffusion

If current is continuous, one can calculate for the current anywhere. Position doesn't matter! Calculate at "easiest" position.

→Minority carrier current on p-side.
We know the solution from earlier
Assume steady state, no r_n, g_n



$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{dJ_n}{dx} - r_n + g_n$$

$$J_n = qn\mu_n\mathcal{E} + qD_n\frac{dn}{dx}$$

$$0 = D_n\frac{d^2n}{dx^2}$$

Boundary Conditions

Boundary Conditions

$$n(x=0^+) = n_i\, e^{(F_n - E_i)\beta}$$

$$p(x=0^+) = n_i\, e^{-(F_p - E_i)\beta}$$

Difference of Quasi-Fermi-levels equals applied voltage

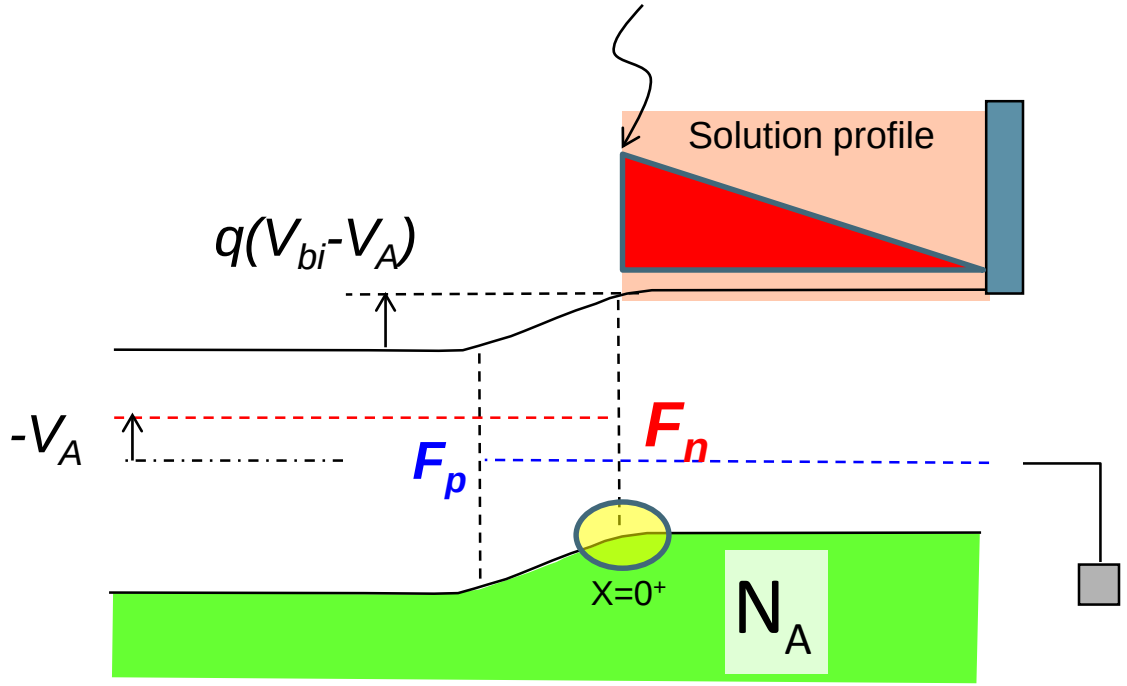
$$np = n_i^2 e^{(F_n - F_p)\beta} = n_i^2 e^{qV_A\beta}$$

$$p(0^+) = N_A$$

$$n(0^+) = \frac{n_i^2}{N_A} e^{qV_A\beta}$$

$$\Delta n(0^+) = n(0^+)_{V_G} - n(0^+)_{V_G=0}$$

$$= \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)$$

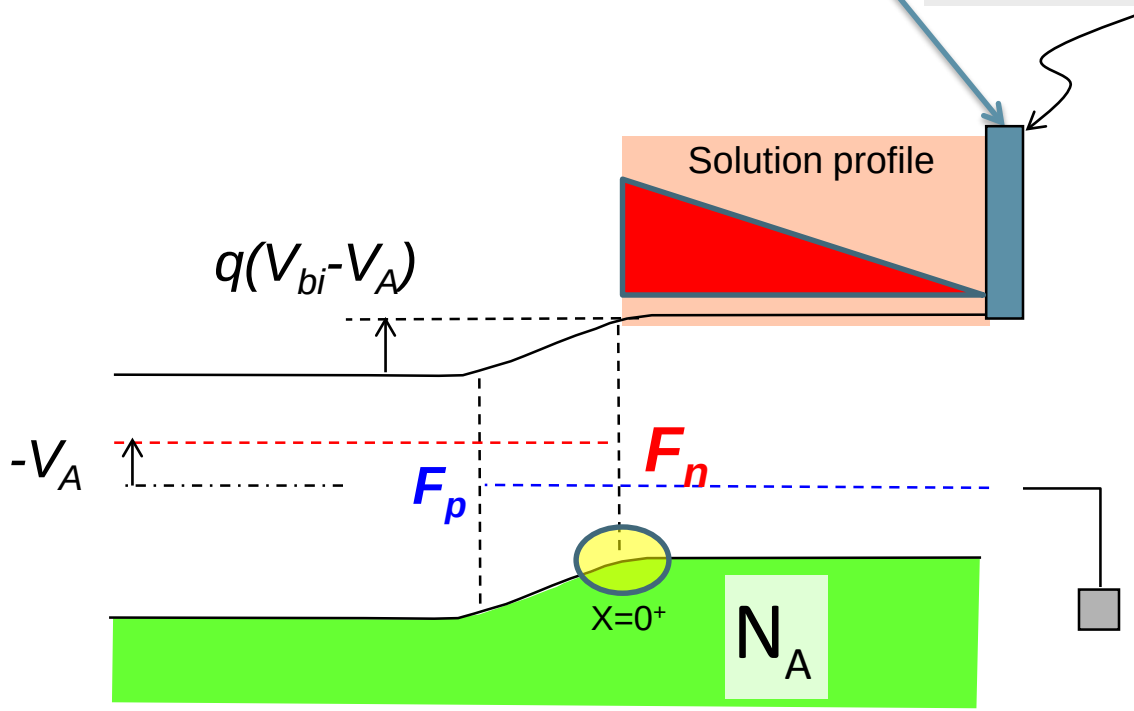


Right Boundary Condition

Infinite surface recombination velocity at metal → **excess** carrier concentration = 0

$$n(x = W_p) \approx \frac{n_i^2}{N_A}$$

$$\Delta n(x = W_p) = 0$$



Example: One Sided Minority Diffusion

$$D_N \frac{d^2 n}{dx^2} = 0$$

Ansatz

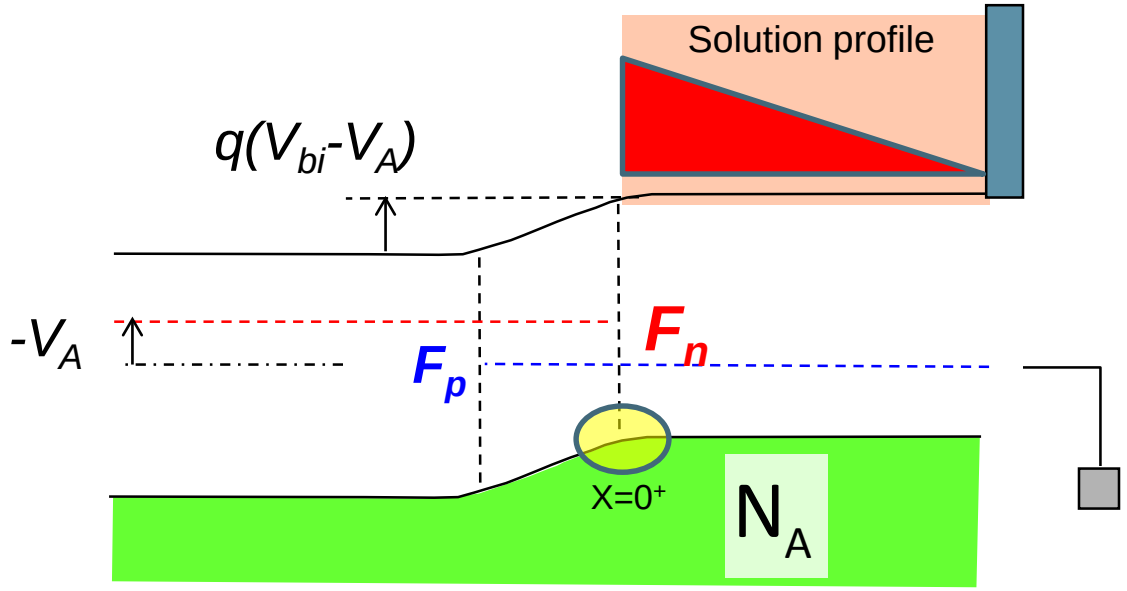
$$\Delta n(x,t) = C + Dx$$

Plug in B.C.

$$x = W_p, \quad \Delta n(x = W_p) = 0 \Rightarrow C = -DW_p$$

$$x = 0', \quad \Delta n(x = 0) = \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right) = C$$

$$\Delta n(x,t) = \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)\left(1 - \frac{x}{W_p}\right)$$



Final result: Excess electron carrier concentration (P-side) as function of position

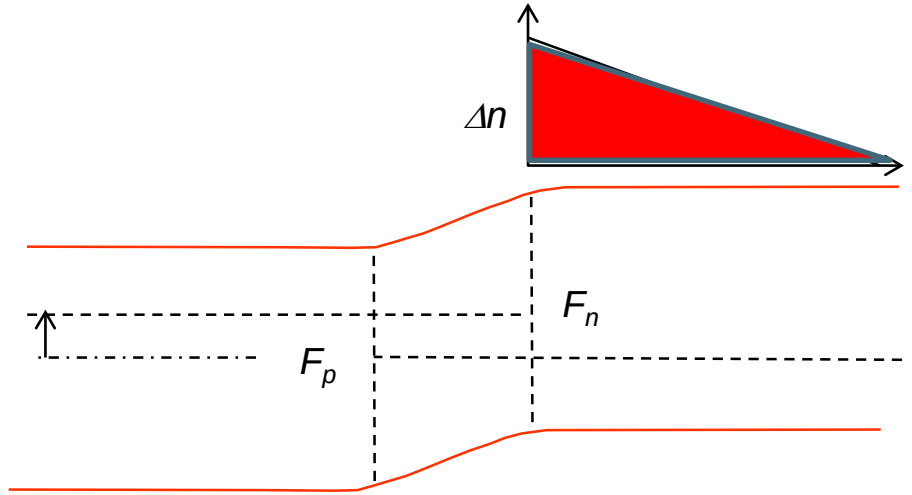
Electron & Hole Fluxes

$$\Delta n(x) = \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)\left(1 - \frac{x}{W_p}\right)$$

$$\mathbf{J}_N = qn\mu_N\boldsymbol{\mathcal{E}} + qD_N\nabla n$$

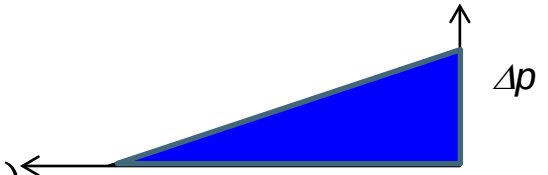
Current (electrons)

$$J_n = qD_n\left.\frac{dn}{dx}\right|_{x=0} = -\frac{qD_n}{W_p}\frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)$$



Current (holes)

$$J_p = -qD_p\left.\frac{dp}{dx}\right|_{x=0'} = -\frac{qD_p}{W_n}\frac{n_i^2}{N_D}\left(e^{qV_A\beta} - 1\right)$$



Total Current

Current (electrons)

$$J_n = qD_n \left.\frac{dn}{dx}\right|_{x=0} = -\frac{qD_n}{W_p}\frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)$$

Current (holes)

$$J_p = -qD_p \left.\frac{dp}{dx}\right|_{x=0'} = -\frac{qD_p}{W_n}\frac{n_i^2}{N_D}\left(e^{qV_A\beta} - 1\right)$$

$$J_T = -q\left[\frac{D_n}{W_p}\frac{n_i^2}{N_A} + \frac{D_p}{W_n}\frac{n_i^2}{N_D}\right]\left(e^{qV_A\beta} - 1\right)$$

Forward Bias

$$\ln J_T \approx qV_A/k_BT + \ln(const.)$$

Reverse Bias

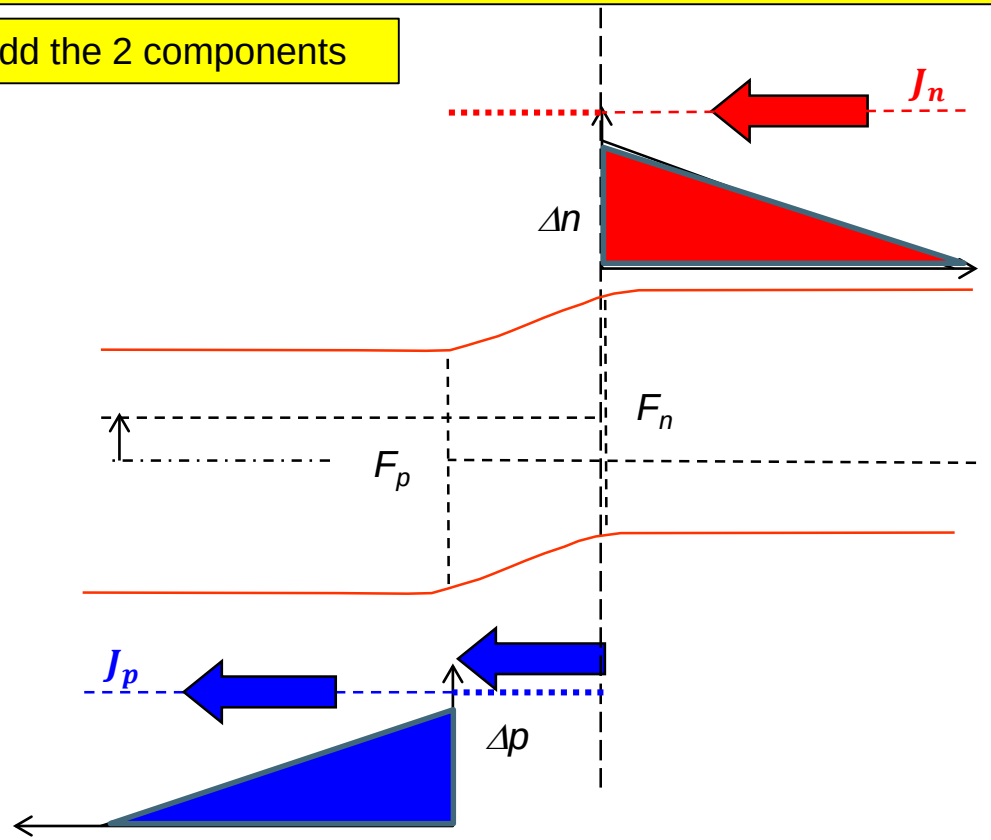
$J_T \approx const.$ Diffusion current

To get total current, add electron and hole current values at **identical** x-points.

But we have only expressions at different x-points

If there is no R-G in junction,
=> then the diffusion currents will be continuous

=> Add the 2 components



Ideal pn-junction current

$$J_T = -q\left[\frac{D_n}{W_p}\frac{n_i^2}{N_A} + \frac{D_p}{W_n}\frac{n_i^2}{N_D}\right]\left(e^{qV_A\beta} - 1\right)$$

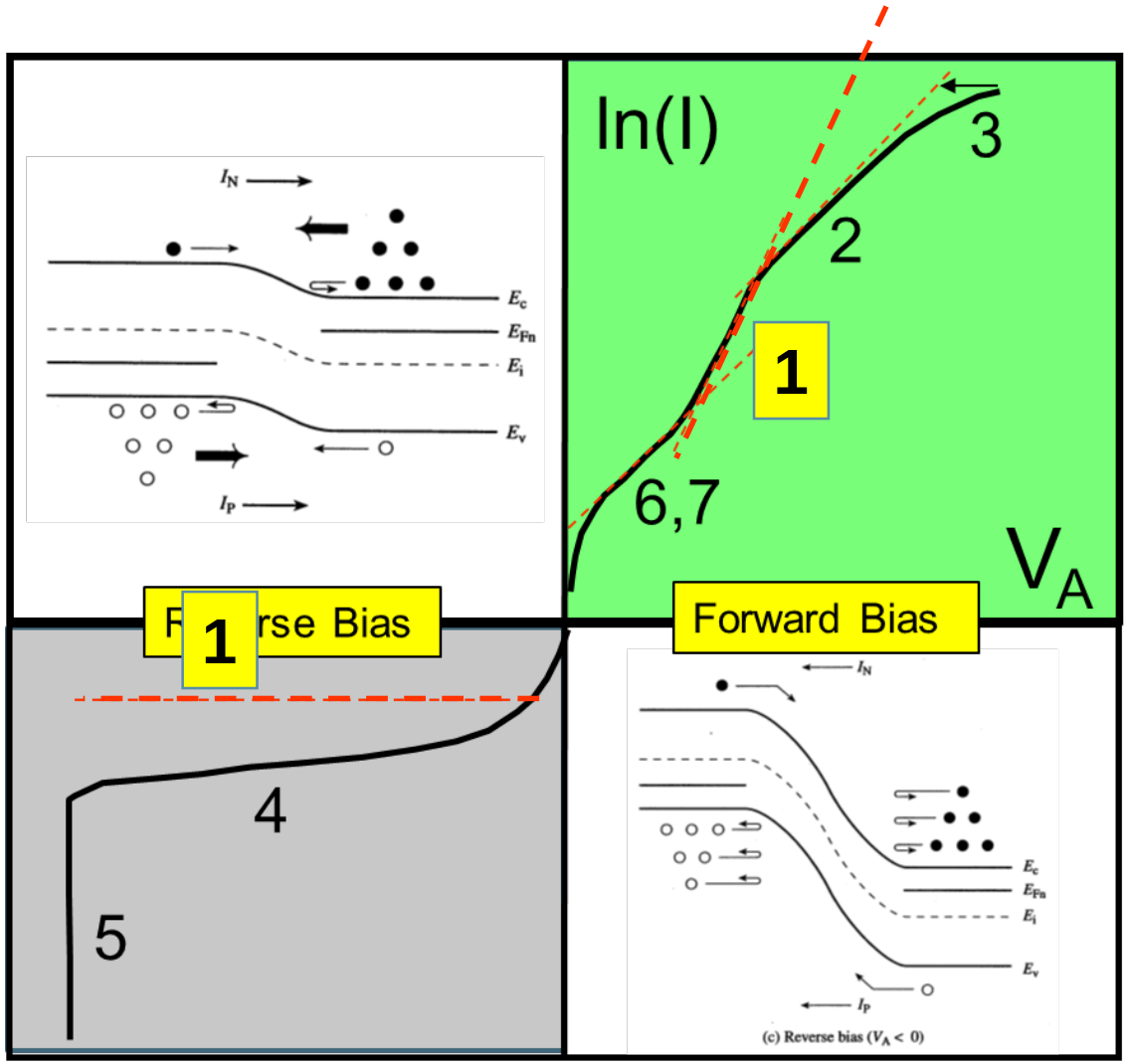
Forward Bias

$$\ln J_T \approx qV_A/k_BT + \ln(const.)$$

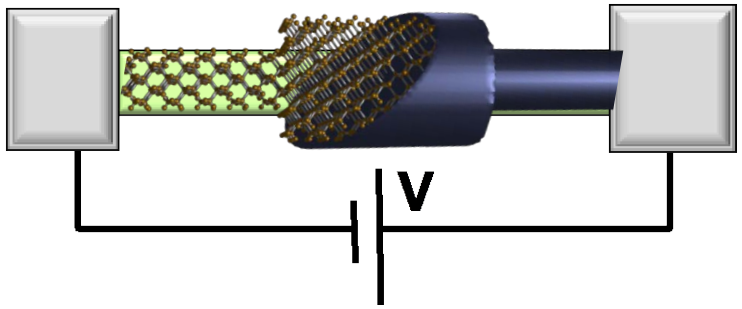
Slope = 1

Reverse Bias

$J_T \approx const.$ Diffusion current

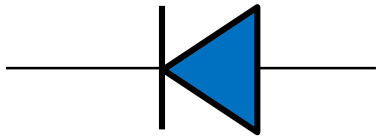


Section 20
PN Diode I-V Characteristics

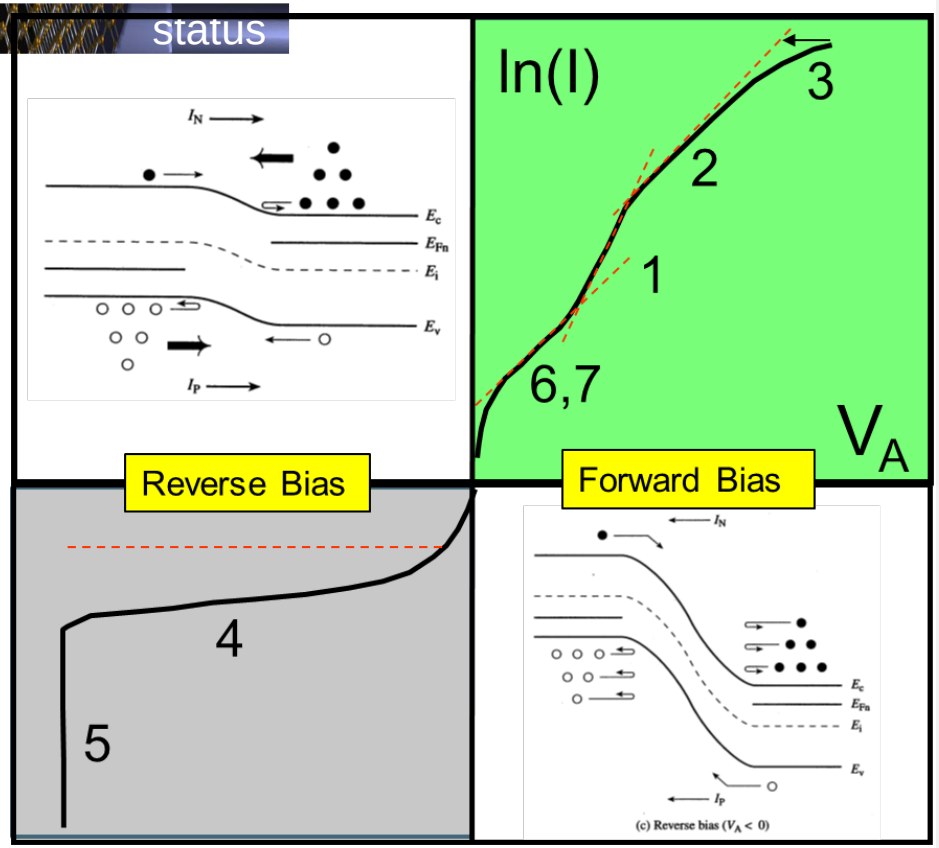


$$I = G \times V$$
$$= q \times n \times v \times A$$

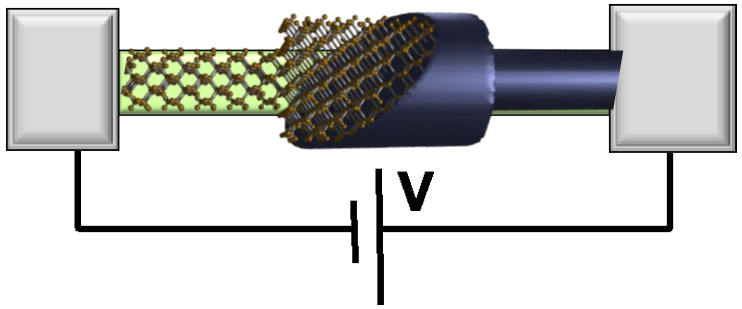
charge density, velocity, area



- 20.1 Band diagram with applied bias
- 20.2 Derivation of the forward bias formula
- 20.3
- 20.4

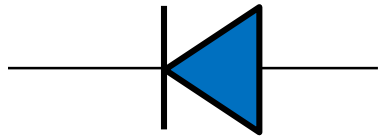


Section 20
PN Diode I-V Characteristics



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density, velocity, area



- 20.1 Band diagram with applied bias
- 20.2 Derivation of the forward bias formula
- 20.3 Forward Bias - Non-linear Regime
  - »Resistive drop
  - »Ambipolar regime
- 20.4

status