Section 20
PN Diode I-V Characteristics

20.3 Forward Bias - Non-linear Regime

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PURDUE UNIVERSITY

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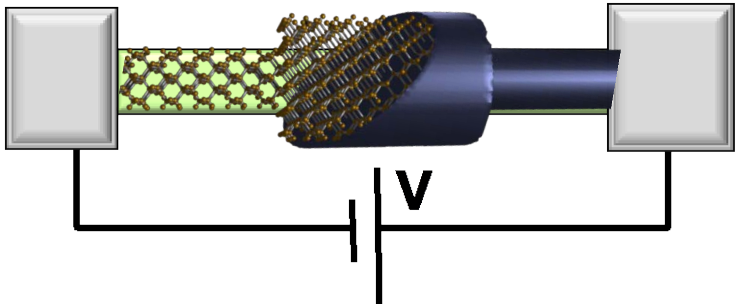
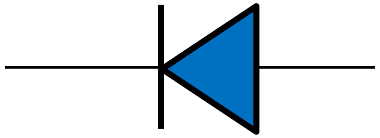


$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



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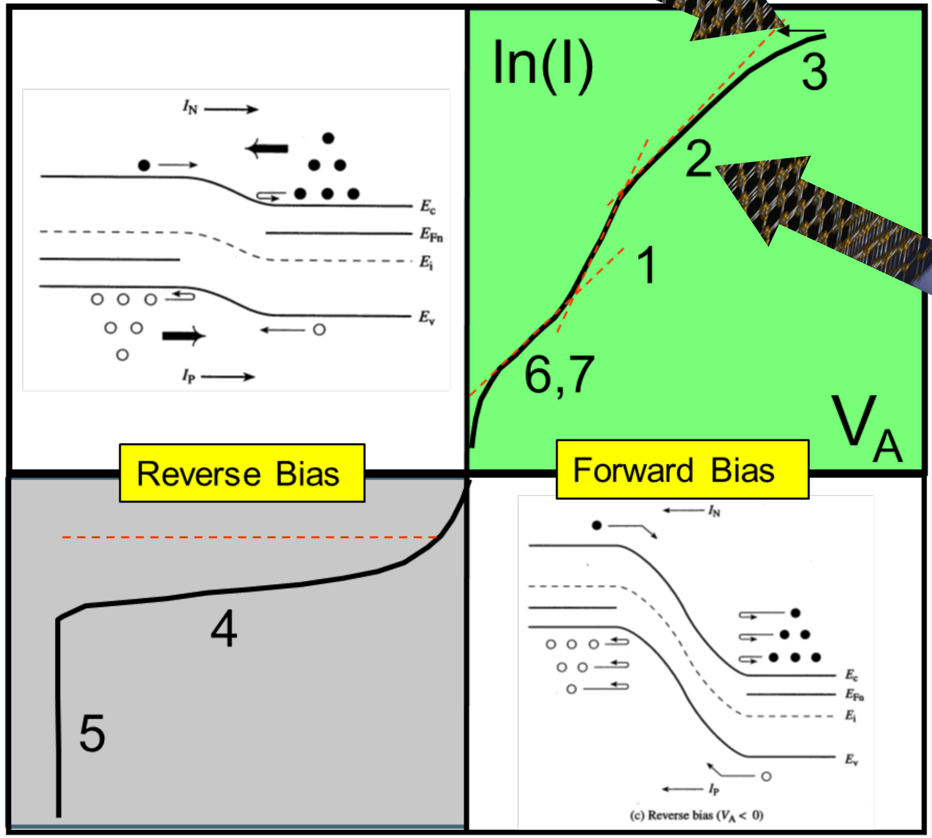
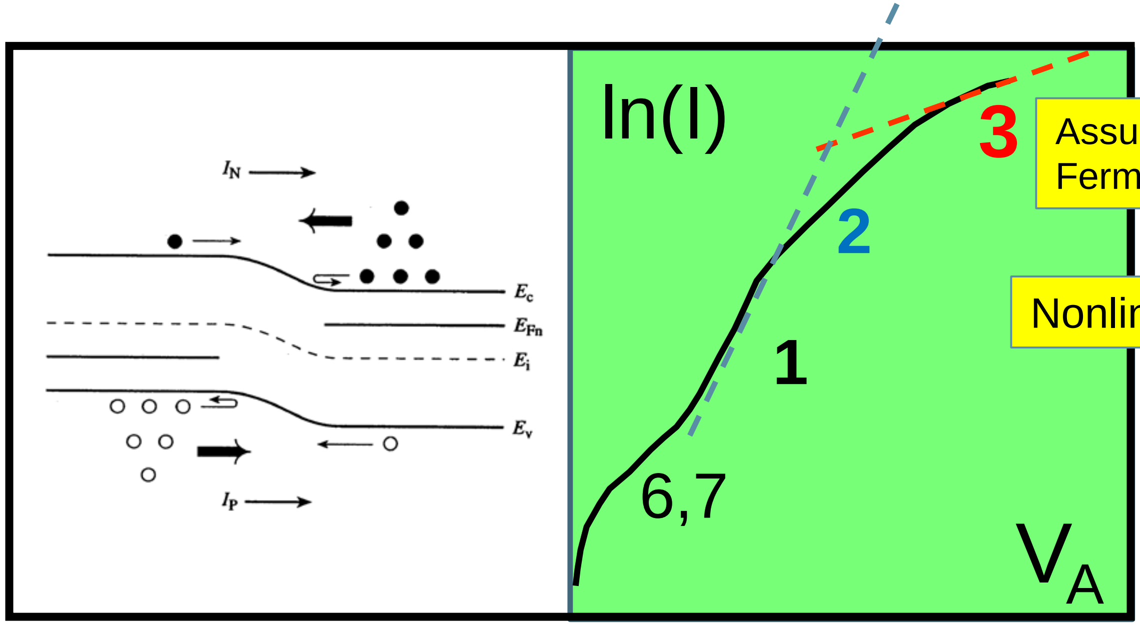
- »Resistive drop
- »Ambipolar regime

status

> • 20.4



Nonlinear Regime (3) …



Assumption of **flat** Quasi-Fermi levels invalid here

Nonlinear Regime (2,3)

$$J_T = -q\left[\frac{D_n}{W_p}\frac{n_i^2}{N_A} + \frac{D_p}{W_n}\frac{n_i^2}{N_D}\right]\left(e^{\left(qV_A - \Delta F_n - \Delta F_p\right)\beta} - 1\right) = I_0\left(e^{q\left(V_A - aJ_n - bJ_p\right)\beta} - 1\right) = J_n + J_p$$

Flat Quasi-Fermi Level up to Junction ?

$$\mathbf{J}_N = qn\mu_N \mathcal{E} + qD_N \frac{dn}{dx}$$

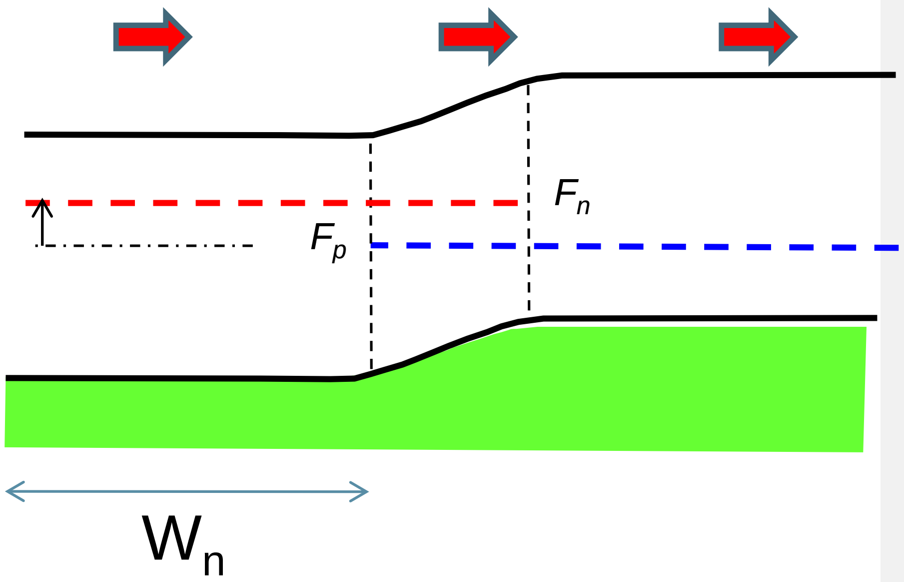
$$\vec{\mathcal{E}} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

Rewrite ***n*** into non-equilibrium form

$$n = n_i e^{\beta(F_n - E_i)}$$

Ignore variation in temperature in x

$$E_i(x), F_n(x)$$



$$\frac{dn}{dx} = \beta\left[\frac{dF_n}{dx} - \frac{dE_i}{dx}\right]\left[n_i e^{\beta(F_n - E_i)}\right] = \beta\left[\frac{dF_n}{dx} - \frac{dE_i}{dx}\right] n$$

$$qD_N \frac{dn}{dx} = qD_N \beta\left[\frac{dF_n}{dx} - q\mathcal{E}\right] n$$

$$\frac{D_N}{\mu_n} = \frac{k_B T}{q} \qquad D_N = \mu_n \frac{1}{\beta q}$$

$$qD_N \frac{dn}{dx} = \mu_n\left[\frac{dF_n}{dx} - q\mathcal{E}\right] n \quad = n\mu_n \frac{dF_n}{dx} - qn\mu_n\mathcal{E}$$

New diffusion component: Plug this into original $\mathbf{J}_n$ equation

$$J_n = n\mu_n \frac{dF_n}{dx}$$

$$\Rightarrow \Delta F_n = \frac{J_n W_n}{\mu_n N_D} = \tilde{R} J_n$$

Drop of Quasi-Fermi level across the junction **proportional** to current!

$$\tilde{R} = \frac{W_n}{\mu_n N_D}$$ resistivity

Forward Bias: Nonlinear Regime ...

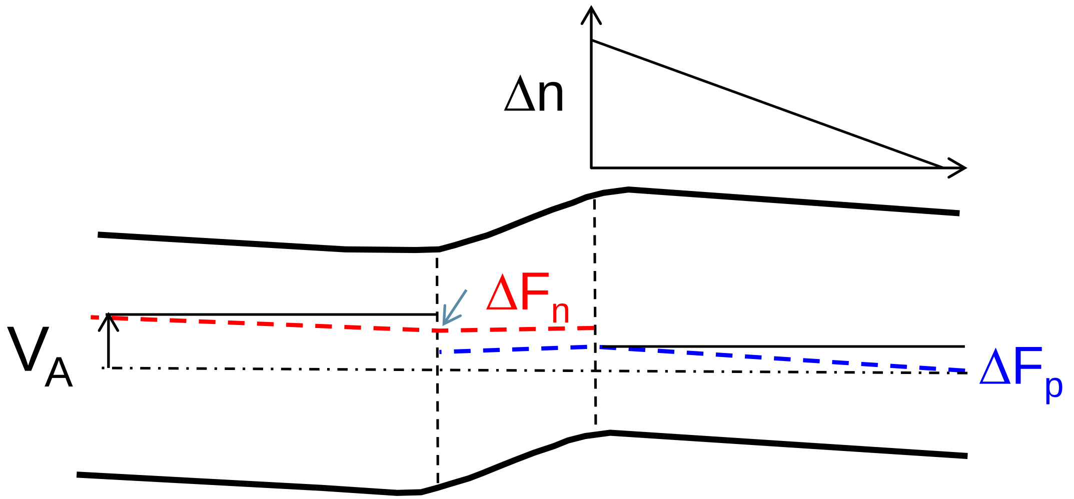
$$n(0^+) = \frac{n_i^2}{N_A} e^{(F_n - F_p)\beta}\Big|_{junction} = \frac{n_i^2}{N_A} e^{(qV_A - \Delta F_n - \Delta F_p)\beta} \Rightarrow \Delta n(0^+) = \frac{n_i^2}{N_A}\left(e^{(qV_A - \Delta F_n - \Delta F_p)\beta} - 1\right)$$

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

$$\Delta F_n = \frac{J_n W_n}{\mu_n N_D}$$

$$\Delta F_p = \frac{J_p W_n}{\mu_n N_D}$$

$$J_n = n\mu_n \frac{dF_n}{dx}$$



Still diffusion dominated transport? Since Quasi-Fermi levels are not flat in nonlinear regime (drift), this approximation becomes worse.

Current and Fermi Level Drop - A general concept

$$J_n = n\mu_n \frac{dF_n}{dx}$$

n can be derived from a complex quantum DOS

Opportunity to link Classical and Quantum Transport

Quantum and Semi-Classical Transport in NEMO 1-D

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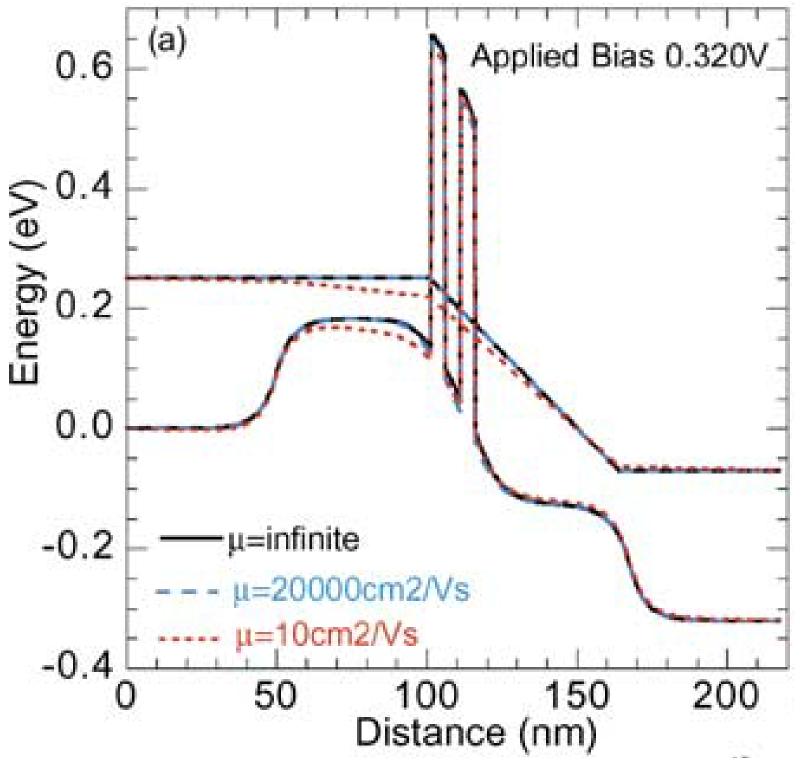

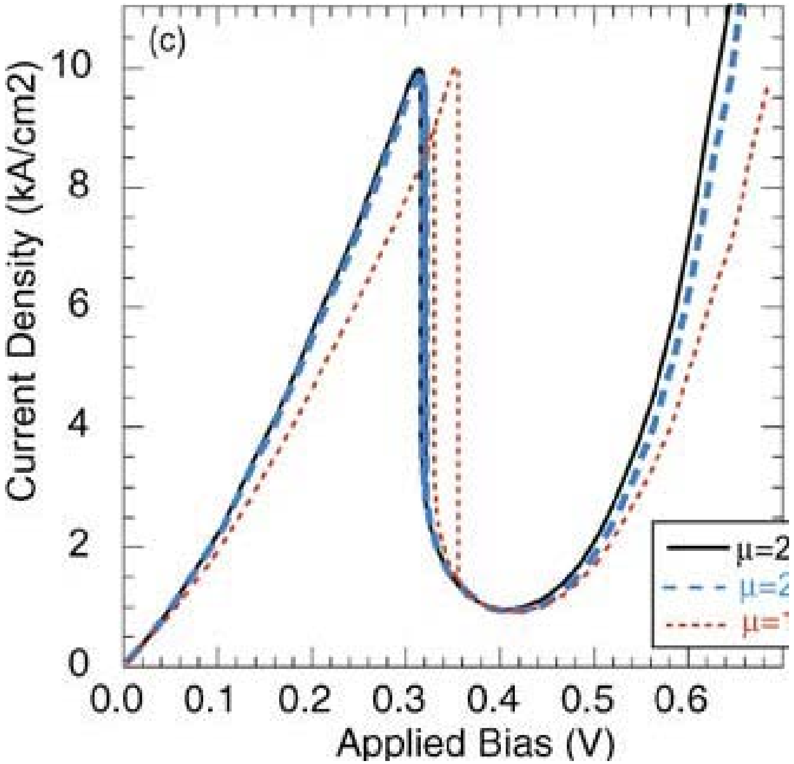

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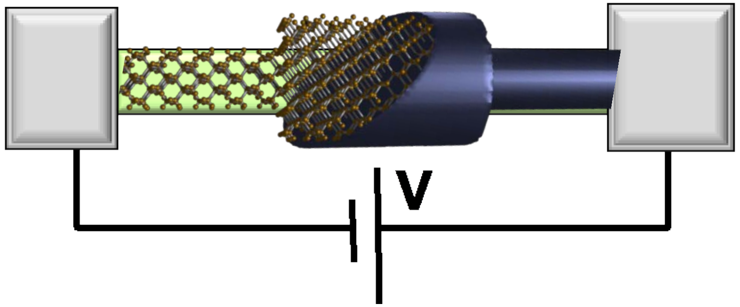

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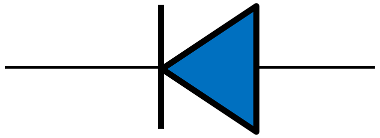
charge density velocity area



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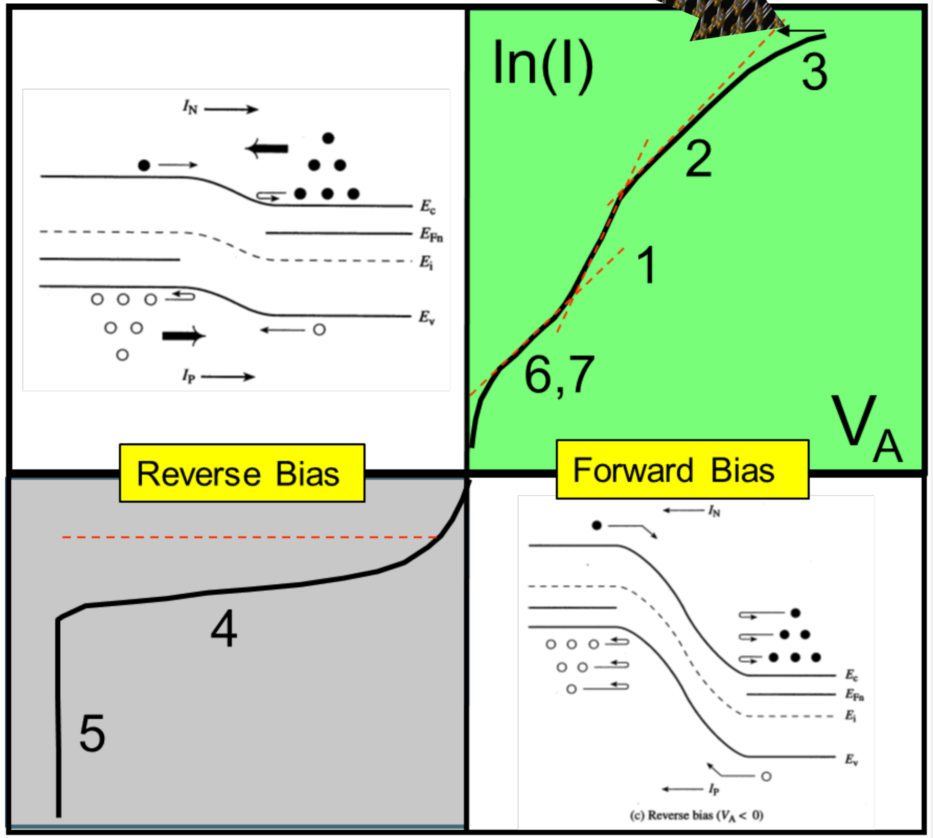
- 20.2 Derivation of the forward bias formula
- 20.3 Forward Bias - Non-linear Regime
  - »Resistive drop
  - »Ambipolar regime
- 20.4 Non-ideal effects:
  - »Junction recombination
  - »Impact ionization
  - »Tunneling



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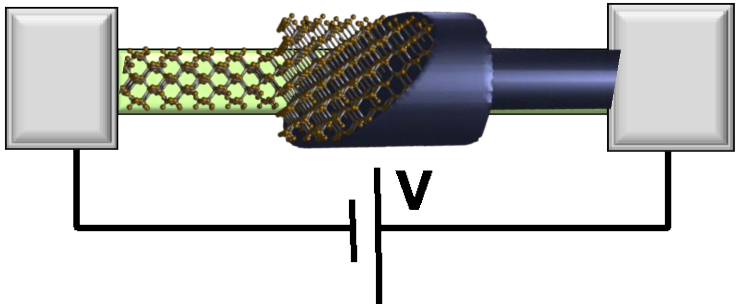

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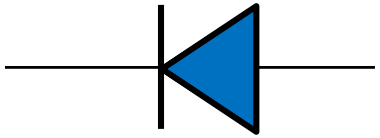

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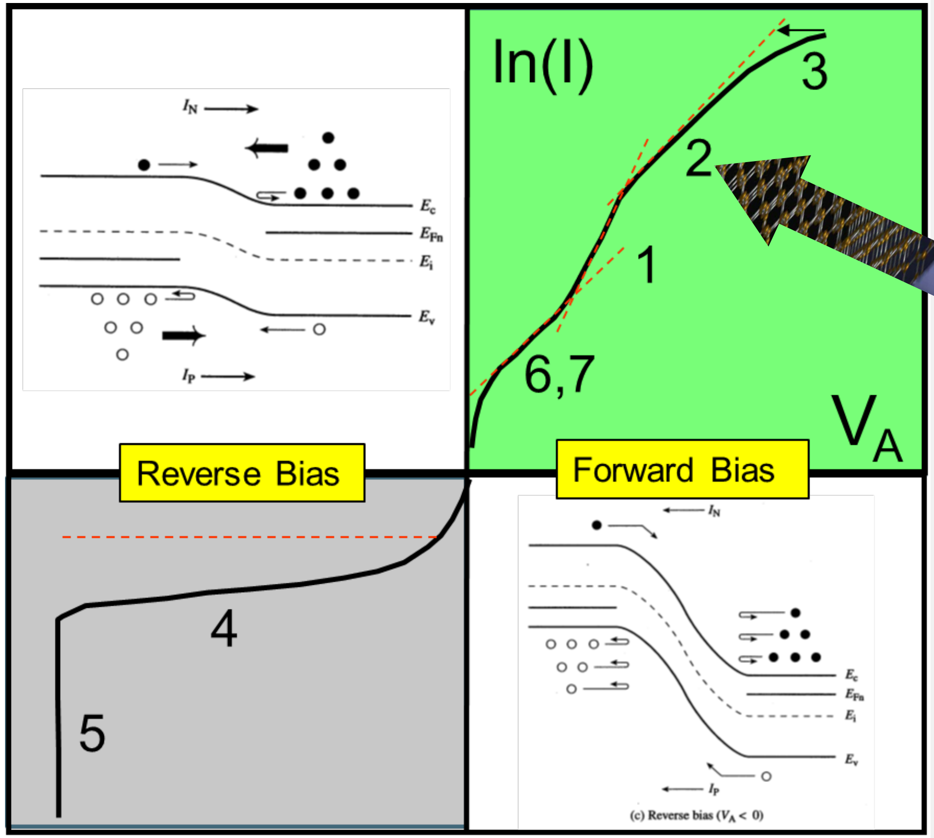


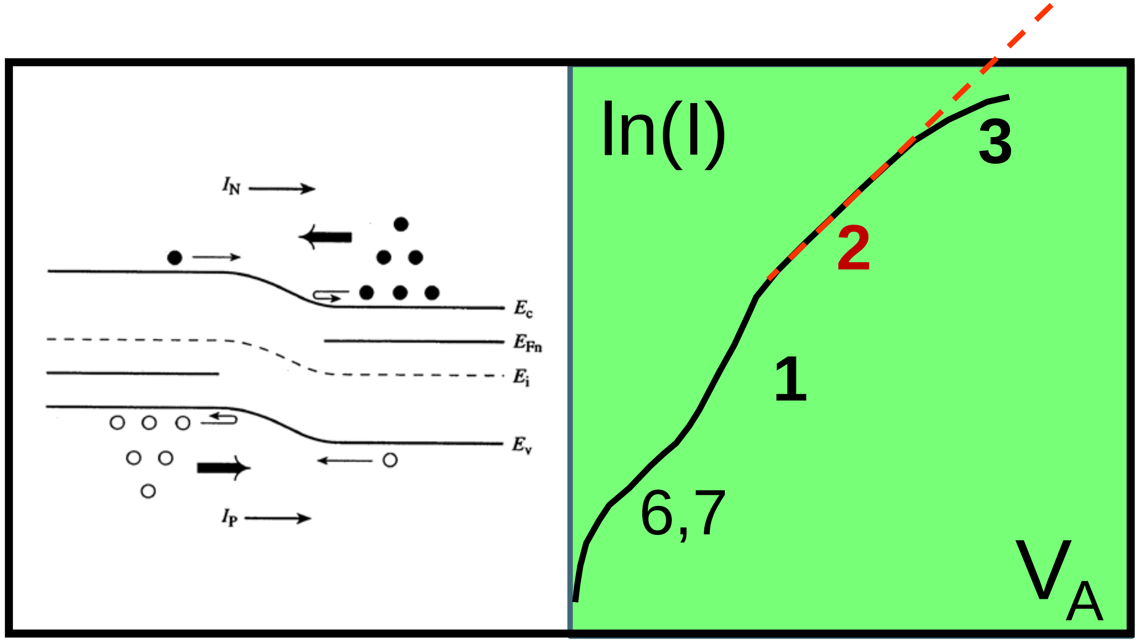
Region (2): Ambipolar Transport

$$J_T \approx -q\left[\frac{D_n}{W_p}+\frac{D_p}{W_n}\right] n_i e^{\left(qV_A-\Delta F_n-\Delta F_p\right)\beta/2}$$

$$\ln(J_T) \approx \frac{qV_A}{2k_BT}$$

Ambipolar Transport regime (2)

Question: Where does the 2 come from?



Nonlinear Regime: Ambipolar Transport

Previously considered: p-side: $\mathrm{N_A} = \mathrm{p_0} \gg \Delta p$

Here not negligibly small.
Ambipolar transport !

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

$$\left(\frac{n_i^2}{N_A} + \Delta n\right)(N_A + \Delta p) = n_i^2 \left(e^{(qV_A - \Delta F_n - \Delta F_p)\beta} - 1\right)$$

Excess carrier concentrations $\Delta p \gg p_0, N_A$ Thus…

$$\Delta n \approx \Delta p = n_i \sqrt{\left(e^{q(V_A - \Delta F_n - \Delta F_p)\beta} - 1\right)}$$

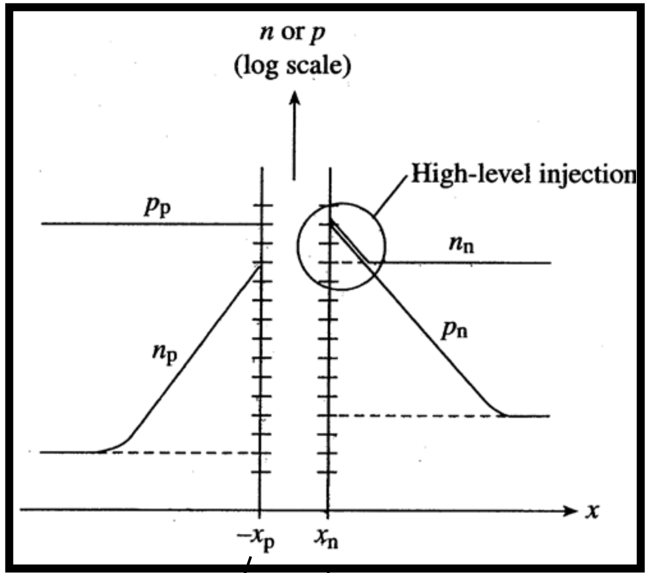
$$\approx n_i \, e^{q(V_A - \Delta F_n - \Delta F_p)\beta/2}$$

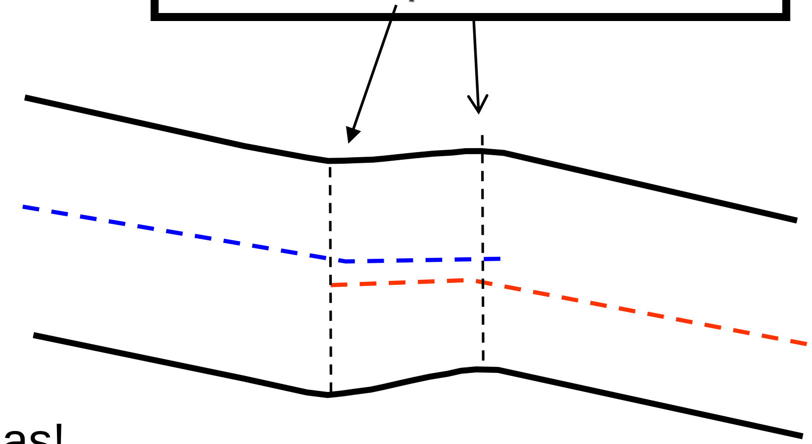
Currents

$$J_n = -qD_n \frac{\Delta n}{W_p} = \frac{qD_n n_i}{W_p} e^{(qV_A - \Delta F_n - \Delta F_p)\beta/2}$$

$$J_p = -qD_p \frac{\Delta n}{W_n} = \frac{qD_p n_i}{W_n} e^{(qV_A - \Delta F_n - \Delta F_p)\beta/2}$$

Ambipolar: minority AND majority carrier distribution is modified!



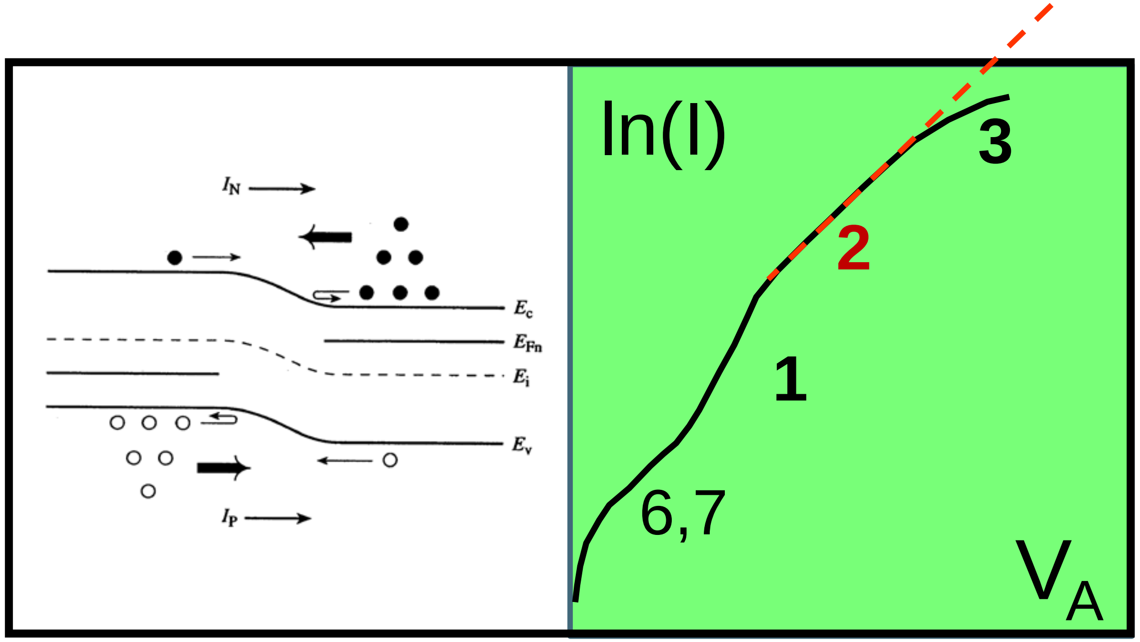


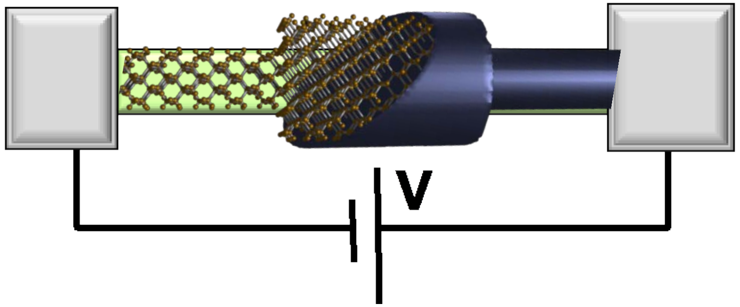
Note: junction never disappears, even for large forward bias!
Electric field is not really negligible, but we do it anyhow….

Region (2): Ambipolar Transport

$$J_T \approx -q\left[\frac{D_n}{W_p}+\frac{D_p}{W_n}\right] n_i e^{(qV_A-\Delta F_n-\Delta F_p)\beta/2} \qquad \ln(J_T) \approx \frac{qV_A}{2k_BT}$$

Ambipolar Transport regime (2)





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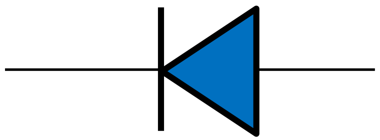
charge density, velocity, area



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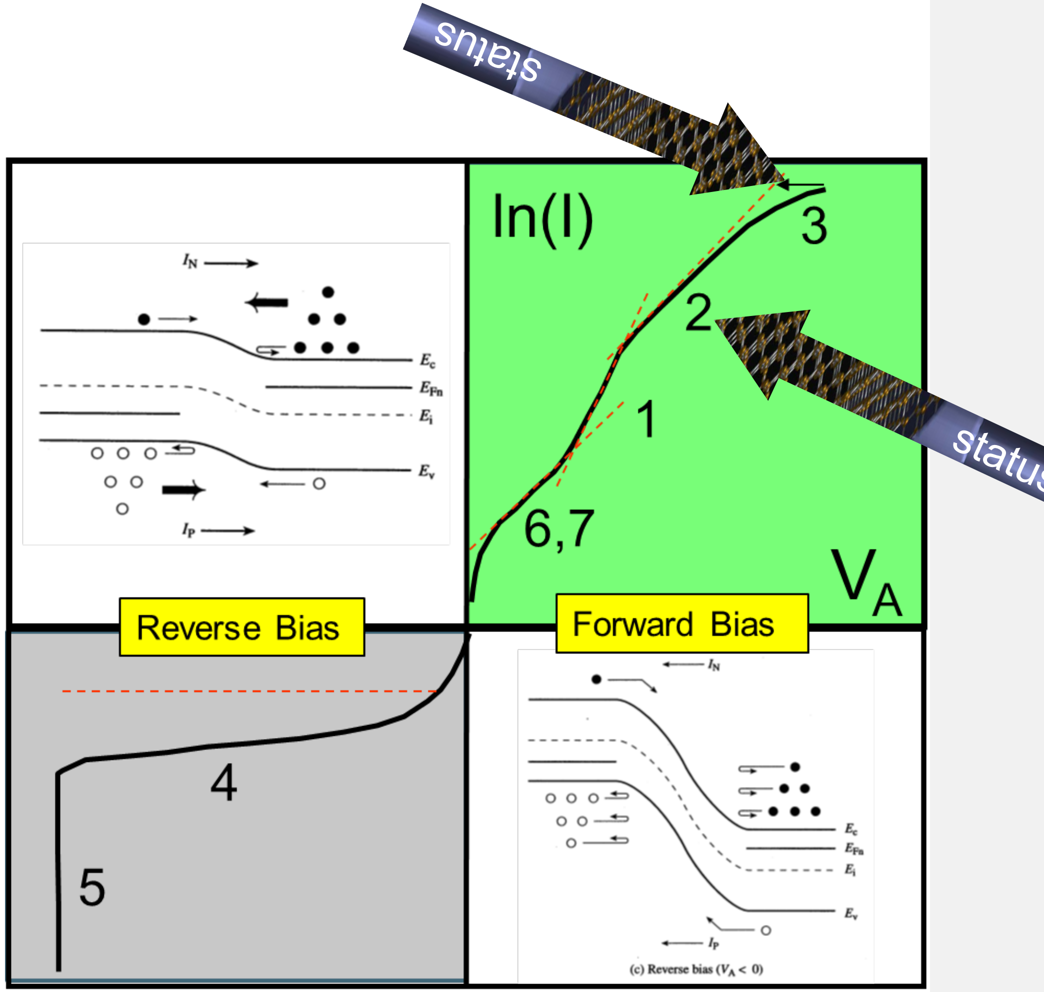

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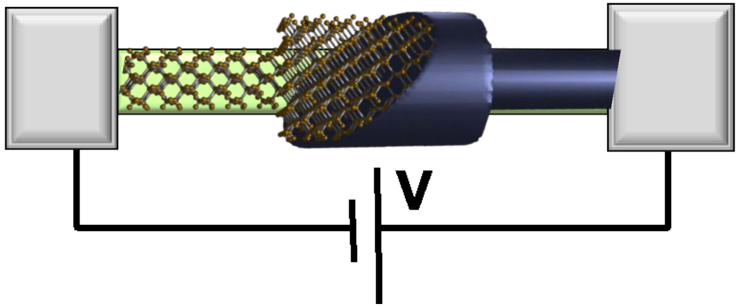

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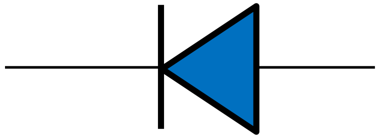

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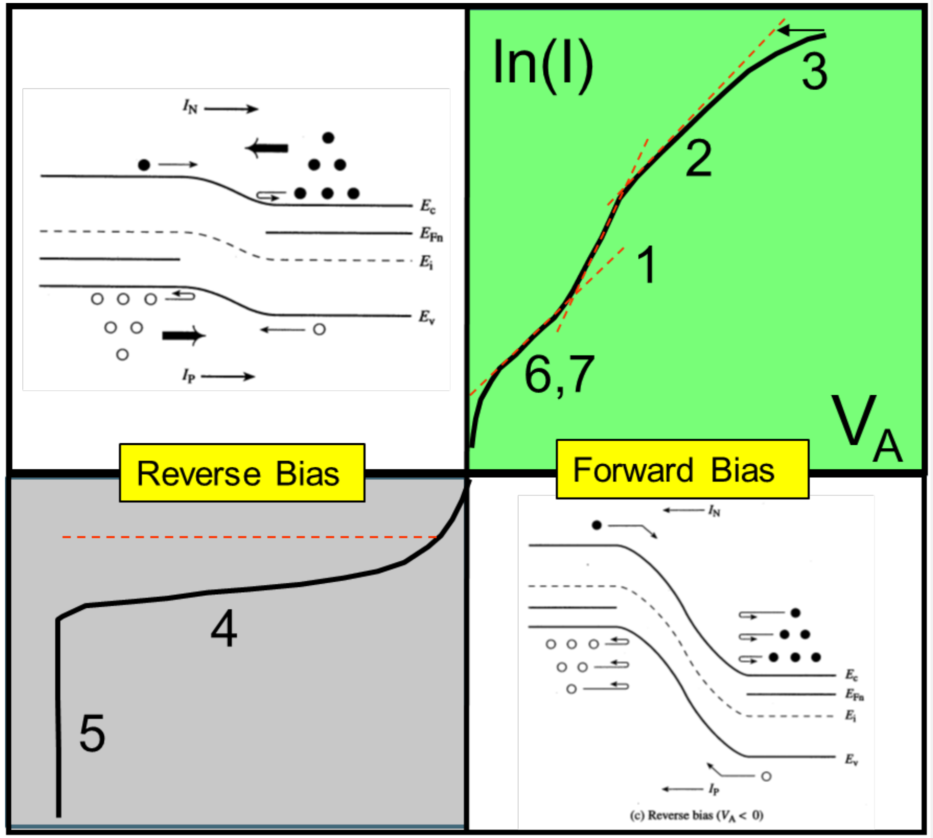

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Video

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