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ECE606: Solid State Devices
Lecture 22: Non-ideal effects

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Outline

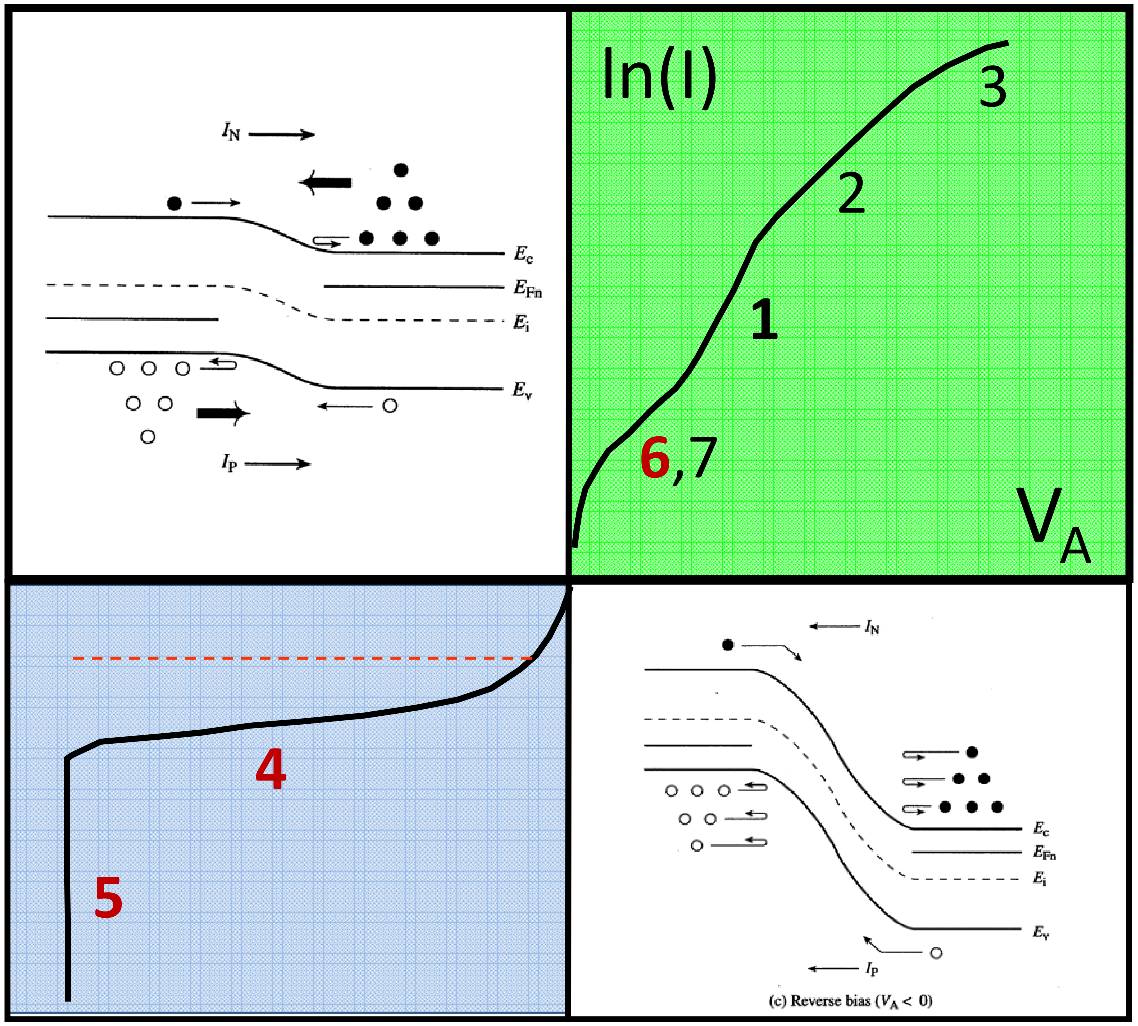
1) **Non-ideal effects: Junction recombination**
2) Non-ideal effects: Impact ionization
3) Conclusion

Ref. Semiconductor Devices Fundamentals, Chapter 6

Topic Map

	Equilibrium	**DC**	Small signal	Large Signal	Circuits
Diode		◆			
Schottky					
BJT/HBT					
MOSFET					

Various Regions of I-V Characteristics



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

Slide 4

MAA1 Asad: We should redraw the figure ...
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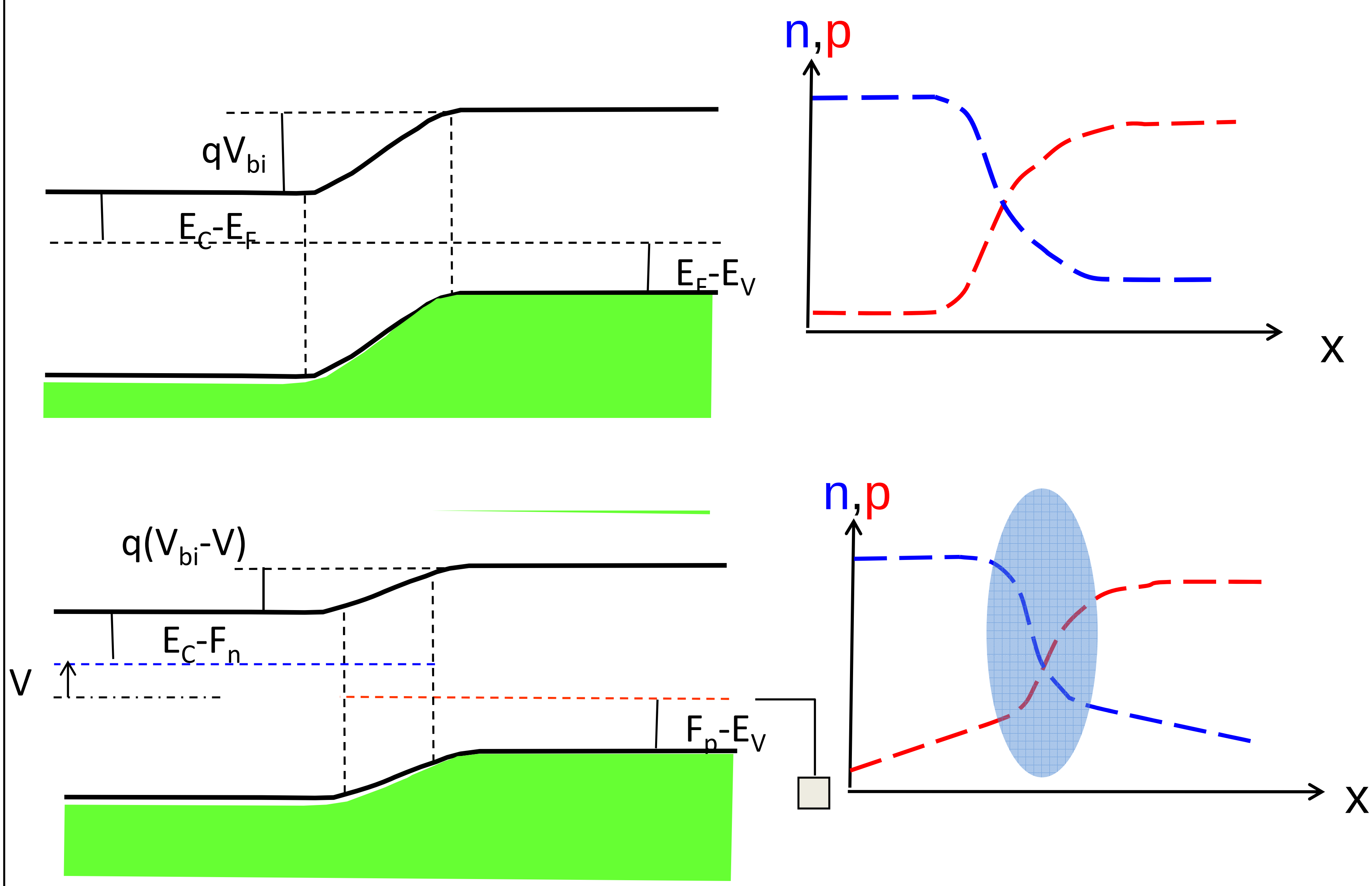
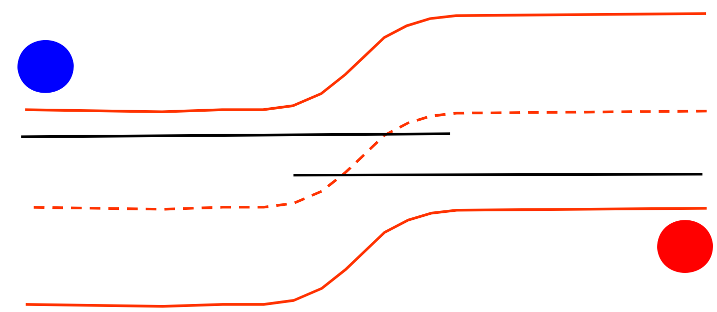
Applying Bias



(4,6) Junction Recombination

$$I_R = -qA\int_0^W \frac{\partial n}{\partial t}dx$$



$$\frac{\partial n}{\partial t} = -\frac{[n(x)p(x) - n_i^2]}{\tau_p[n(x)+n_1] + \tau_n[p(x)+p_1]}$$

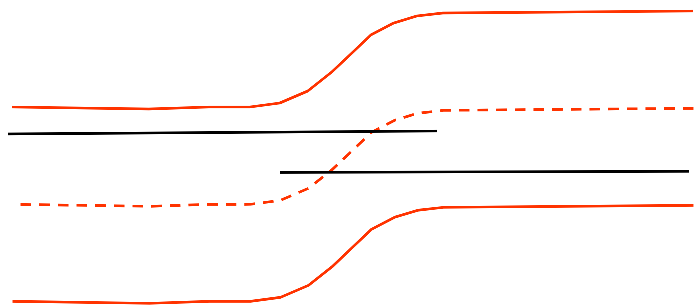
Assume $\tau_n = \tau_p$ $E_i = E_T$ $n_1 = p_1 = n_i$

$$\frac{\partial n}{\partial t} = -\frac{n_i^2(e^{qV_A/kT} - 1)}{\tau[n(x)+p(x)+2n_i]}$$

Note: Do you remember this HW ?

(np) Product within the Junction

Mass action in non-equilibrium

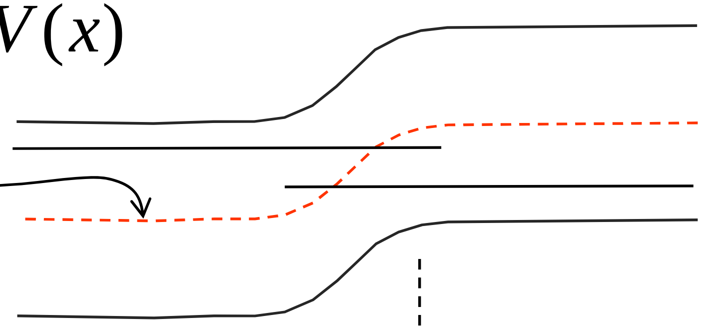


$$n(x)\,p(x) = n_i^{\,2} e^{(F_N - F_P)/kT}$$

$$= n_i^{\,2} e^{qV_A/kT}$$

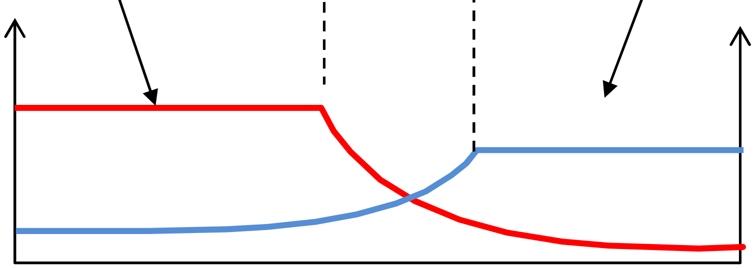
Electron/Hole Concentrations at Junction

$$E_i(x) = E_{iL} - qV(x)$$



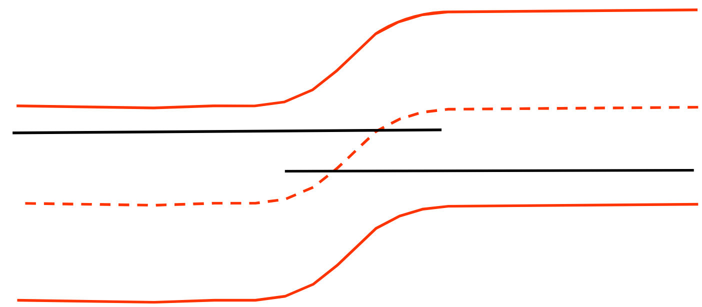
$$n(x) = n_i e^{(F_N - E_i(x))/kT}$$
$$= n_i e^{[F_N - E_{iL} + qV(x)]/kT}$$

$$p(x) = \frac{n_i^{\,2} e^{qV_A/kT}}{n_i e^{[F_N - E_{iL} + qV(x)]/kT}}$$
$$= n_i e^{-[F_N - E_{iL} + qV(x)]/kT + qV_A/kT}$$



Junction Recombination

$$U_{FN} = \frac{F_N - E_{iL}}{kT} \qquad U_A = \frac{V_A}{kT/q}$$



$$\frac{\partial n}{\partial t} = -\frac{n_i (e^{U_A} - 1)}{\tau [e^{U_{FN}+U} + e^{-U_{FN}-U+U_A}]}$$

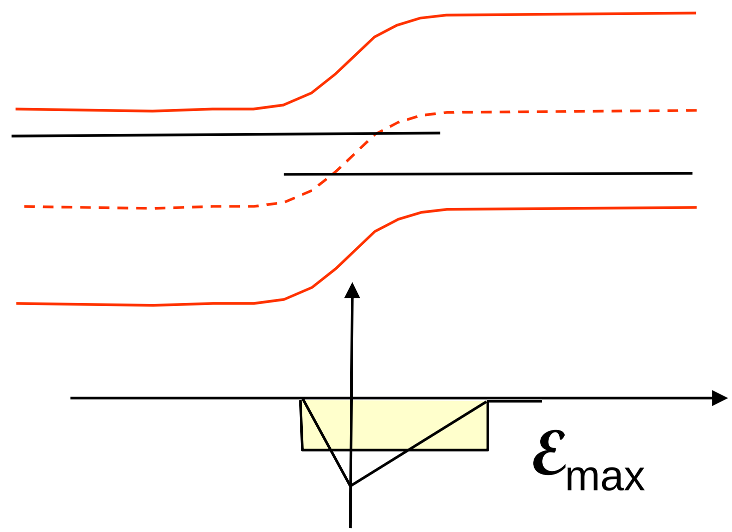
$$I_R = -qA\left(\frac{n_i}{\tau}\right) \times sinh\left(\frac{U_A}{2}\right) \times \int_0^W \frac{dx}{cosh[U_{FN} + U - U_A/2]}$$

$$\Rightarrow \frac{\partial n}{\partial t} = -\frac{n_i}{\tau} \frac{e^{U_A/2}(e^{U_A/2} - e^{-U_A/2})}{e^{U_A/2}[e^{U_{FN}+U-U_A/2} + e^{-U_{FN}-U+U_A/2}]}$$

$$\Rightarrow \frac{\partial n}{\partial t} = -\frac{n_i}{\tau} \frac{sinh(U_A/2)}{cosh[U_{FN} + U - U_A/2]}$$

Junction Recombination in Forward Bias

$$\Rightarrow \frac{\partial n}{\partial t} = -\frac{n_i}{\tau} \frac{\sinh(U_A/2)}{\cosh[U_{FN} + U - U_A/2]}$$



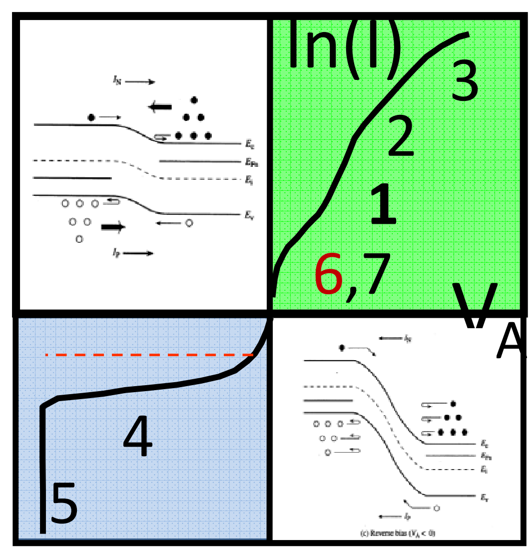
$$\Rightarrow I_R \approx -qA(\frac{n_i}{\tau})\sinh(\frac{U_A}{2})\int_0^W \frac{dx}{e^{(U_{FN}+U-U_A/2)}}$$

$$\Rightarrow I_R \approx -qA(\frac{n_i}{\tau})\times \sinh(\frac{U_A}{2})\int_0^W \frac{dx}{e^{-(\mathcal{E}_{max}x)/(kT/2q)}}$$

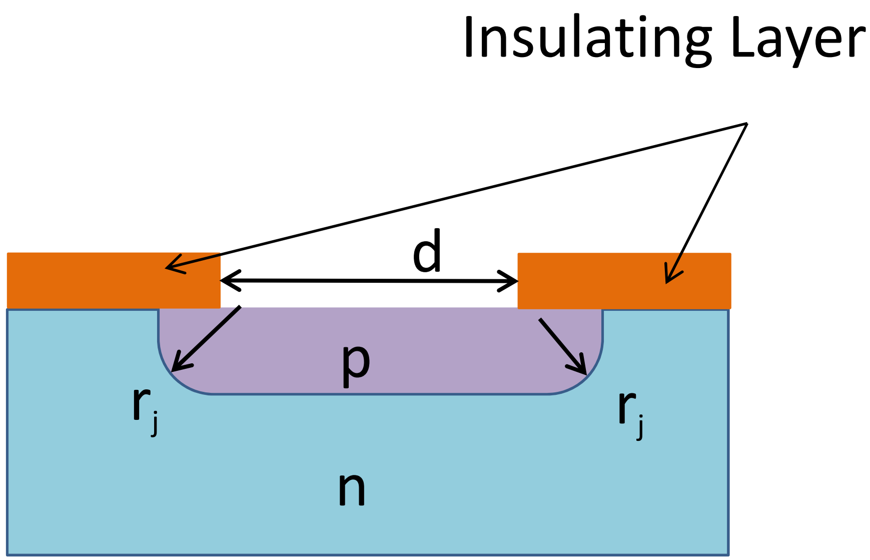
$$\Rightarrow I_{Dep} = -qA\left[\frac{kT}{2q\mathcal{E}_{max}}\right]\left[\frac{n_i}{\tau}e^{qV_A/2kT}\right]$$

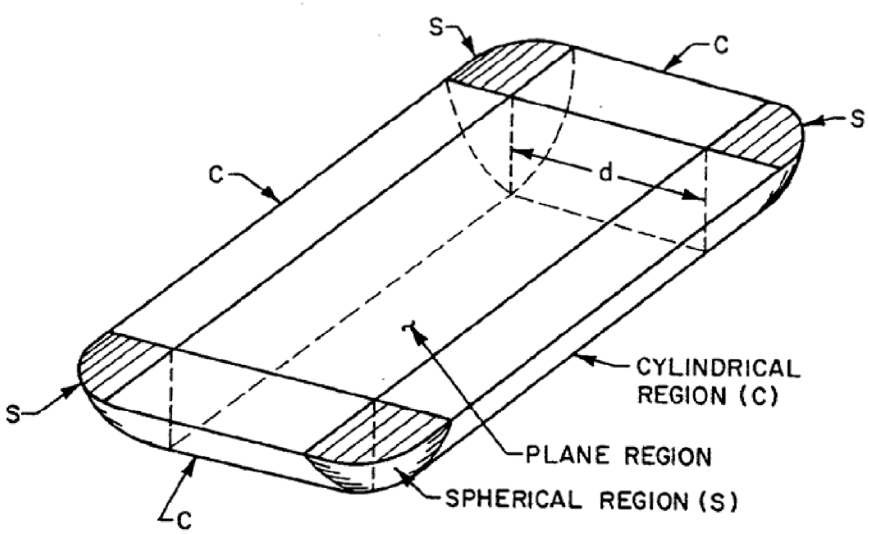
Effective width

Excess Carrier at mid-junction



Junction Leakage in Practice

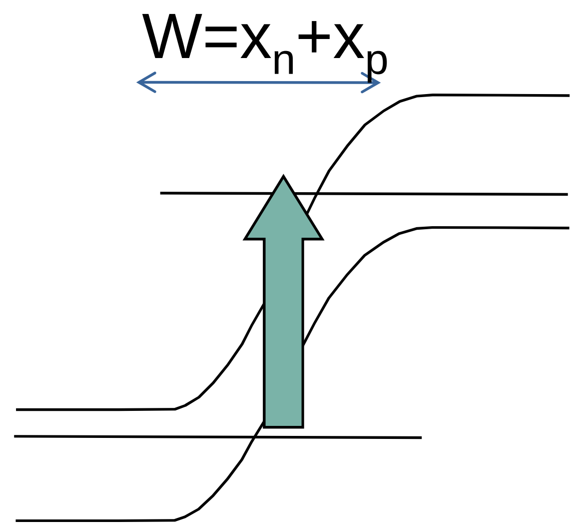




Junction Recombination in Reverse Bias

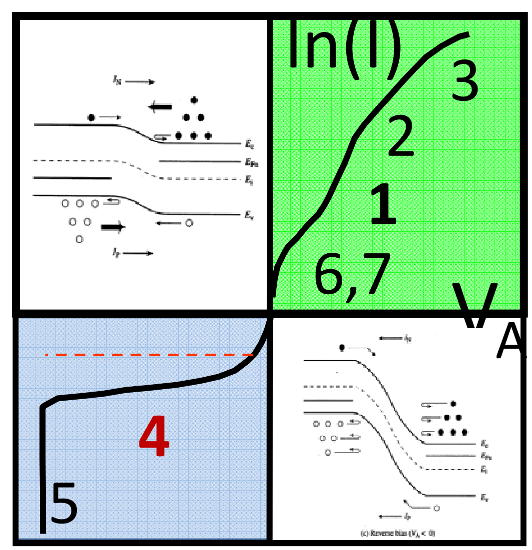
$$\frac{\partial n}{\partial t} = -\frac{n_i}{2\tau}$$

(Recombination in depletion region)



$$I_R \approx -qA\int_0^{W}\left(\frac{n_i}{2\tau}\right)dx$$

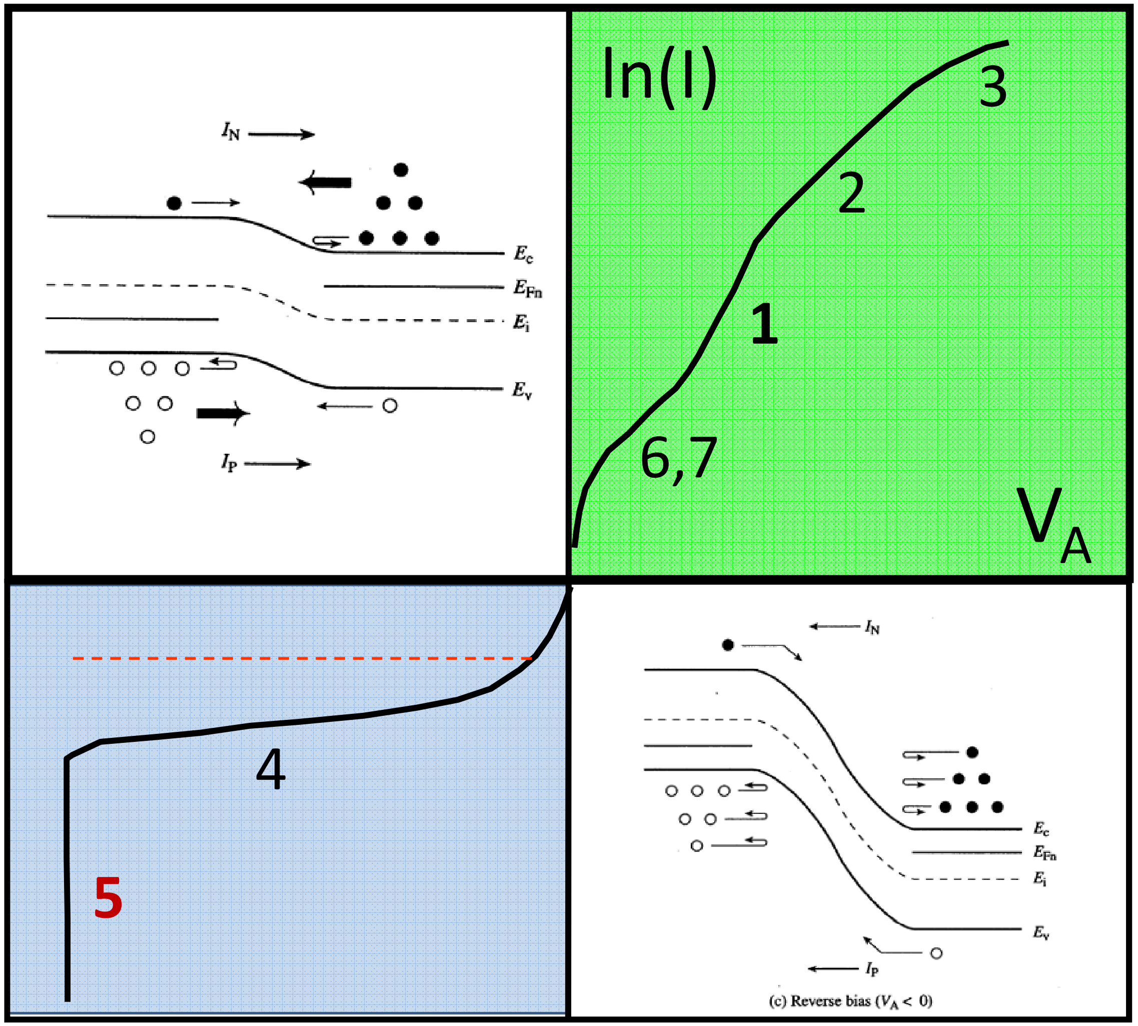
$$= -qA\frac{n_i W}{2\tau} \propto \sqrt{V_{bi} - V_A}$$



Outline

1) Non-ideal effects: Junction recombination
2) **Non-ideal effects: Impact ionization**
3) Conclusion

Avalanche Breakdown



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Slide 14

MAA2 Asad: We should redraw the figure ...

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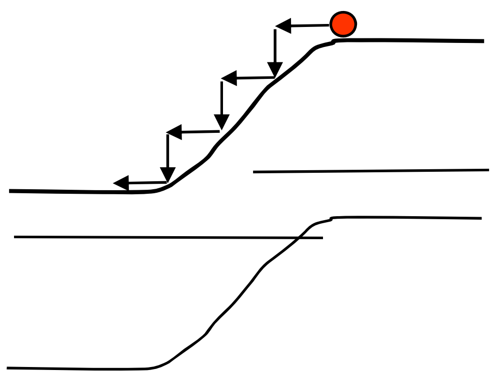
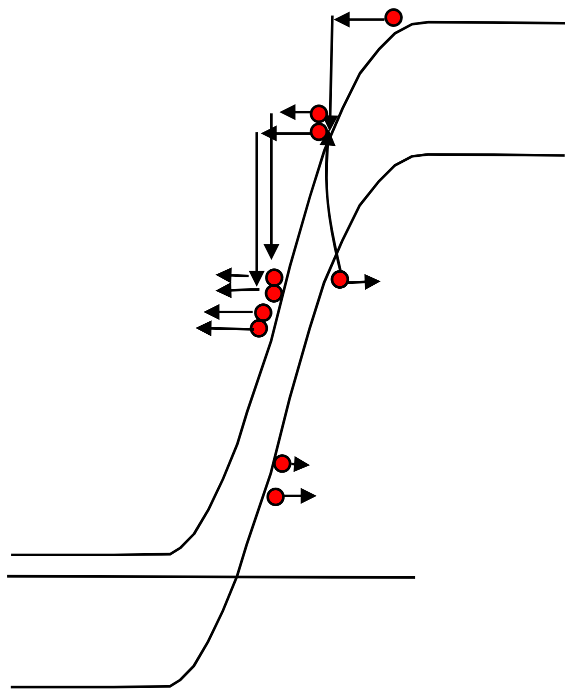
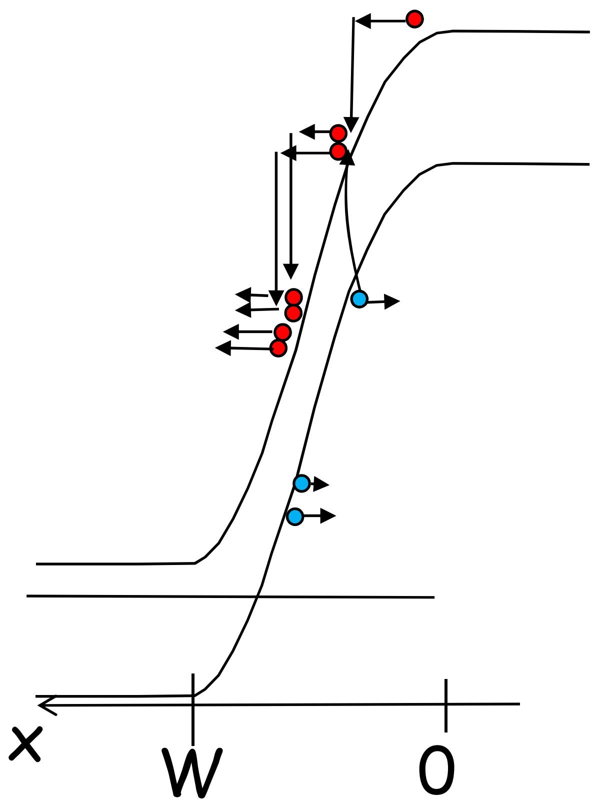
Nonlinearity due to Impact-Ionization





Impact-ionization and Flux Conservation



$$I_n(x+dx) = I_n(x) + \alpha_n I_n(x)dx + \alpha_p I_p(x)dx$$

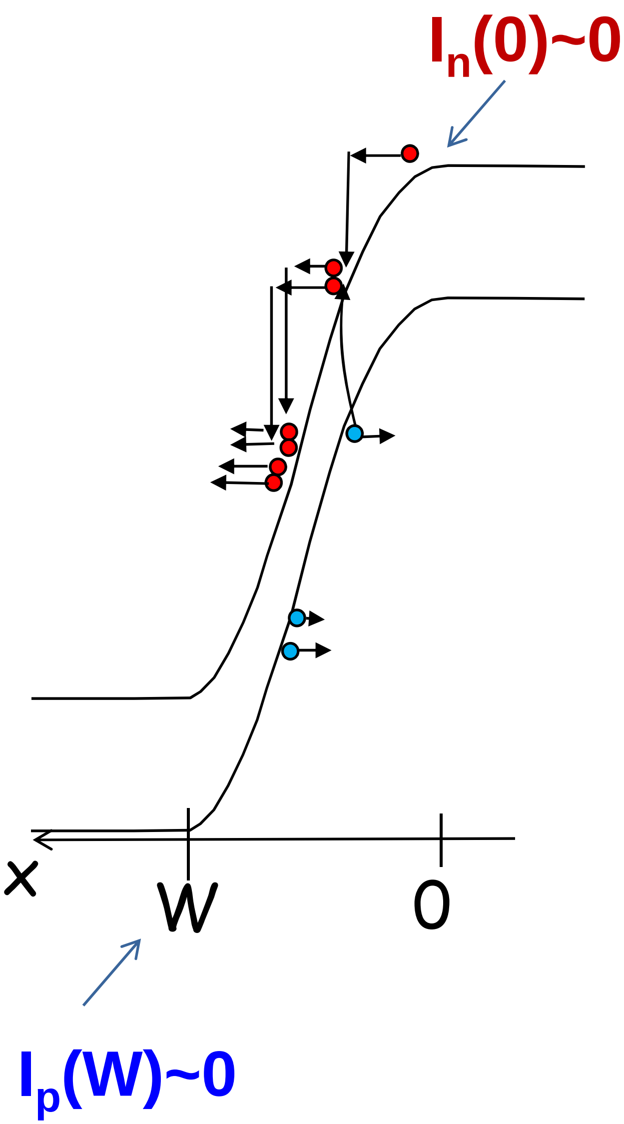
$$\frac{I_n(x+dx) - I_n(x)}{dx} = \alpha_n I_n(x) + \alpha_p I_p(x)$$

$$\Rightarrow \frac{dI_n(x)}{dx} = \alpha_n I_n(x) + \alpha_p I_p(x)$$

$$\frac{dI_n(x)}{dx} = \alpha_p \left[I_T - I_n(x) \right] + \alpha_n I_n(x)$$

$$\frac{dI_n(x)}{dx} - \left(\alpha_n - \alpha_p\right) I_n(x) = \alpha_p I_T$$

Impact-ionization



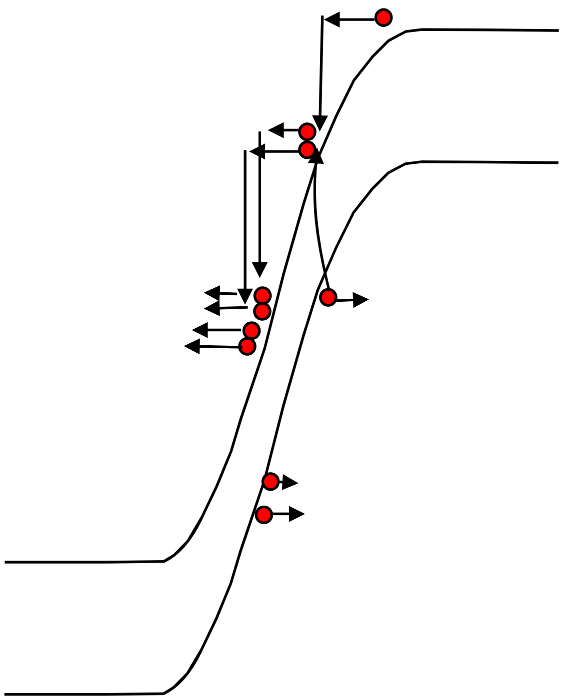
$$\frac{I_n(W)}{I_T} = \frac{\int_0^W \alpha_p e^{-\int_0^x (\alpha_n - \alpha_p) dx'} dx + \frac{I_n(0)}{I_T}}{1 + \int_0^W (\alpha_p - \alpha_n) e^{-\int_0^x (\alpha_n - \alpha_p) dx'} dx}$$

$$\cancel{I_p(W)} + I_n(W) = I_T \Rightarrow I_n(W) \approx I_T$$

$$\frac{I_n(0)}{I_T} \equiv \frac{1}{M_p}$$

$$\left(1 - \frac{1}{M_p}\right) \approx 1 = \int_0^W \alpha_p e^{-\int_0^x (\alpha_p - \alpha_n) dx'} dx$$

Impact-ionization

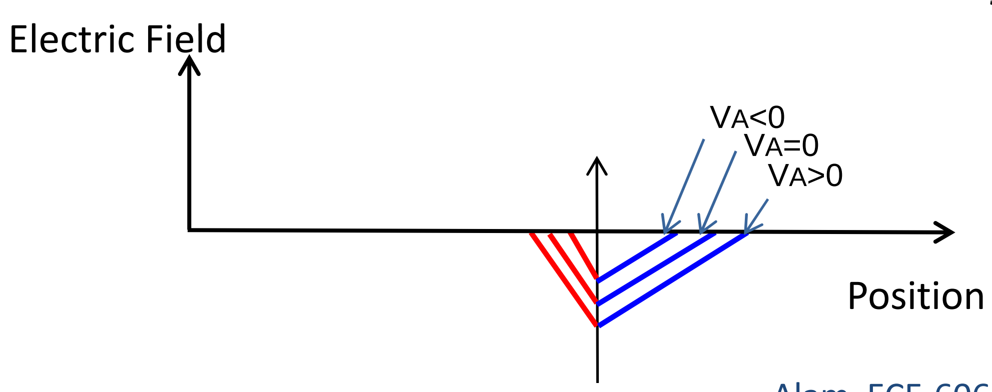


$$\int_0^W \alpha_p e^{-\int_0^x (\alpha_p - \alpha_n) dx'} dx \approx 1$$

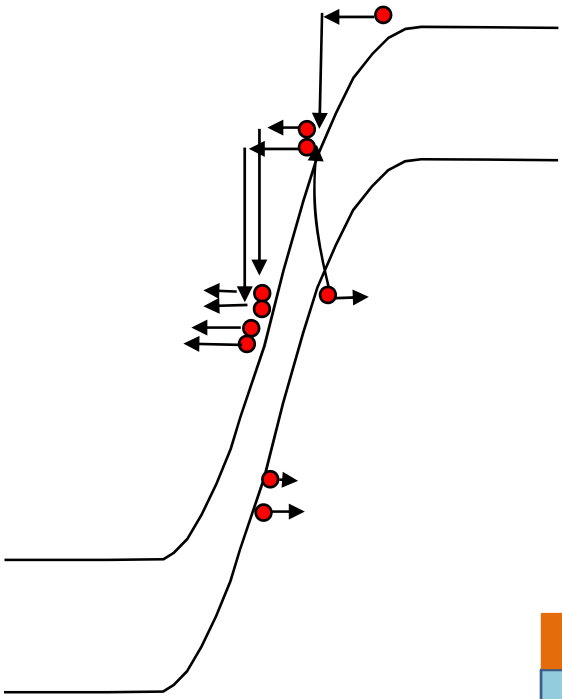
$$\alpha_p = \alpha_n \Rightarrow \alpha_p W = 1$$

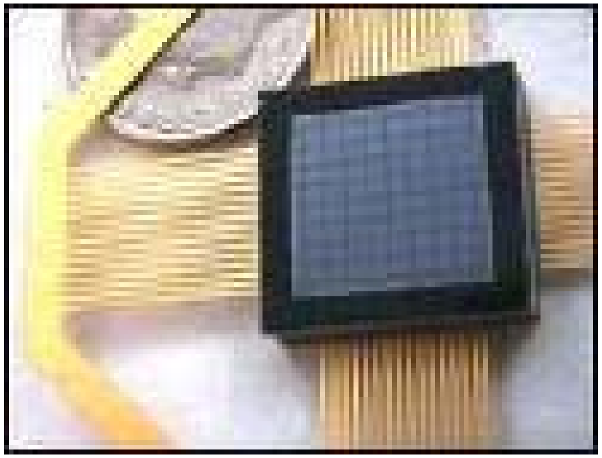
$$\alpha_p = A_0 e^{-B/\mathcal{E}}$$

$$\mathcal{E}(0^-) = \frac{qN_D x_n}{k_s \varepsilon_0} = \left[\frac{2q}{k_s \varepsilon_0} \frac{N_D N_A}{N_D + N_A} (V_{bi} - V_A) \right]^{1/2}$$

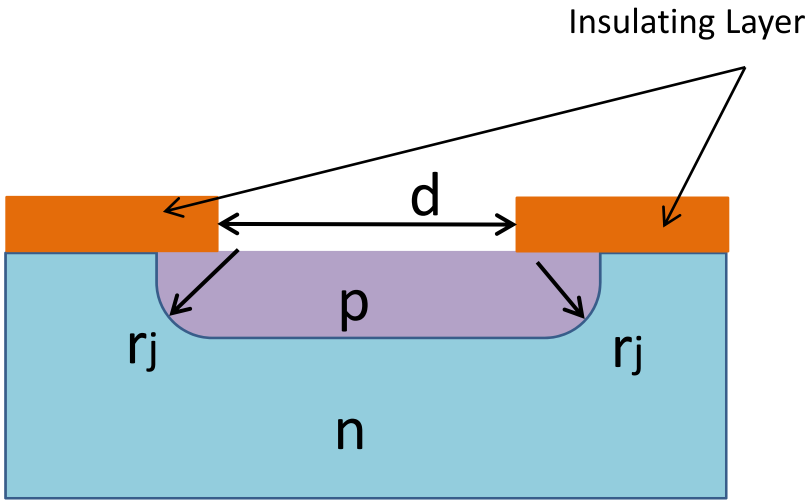


Impact-ionization: In Practice



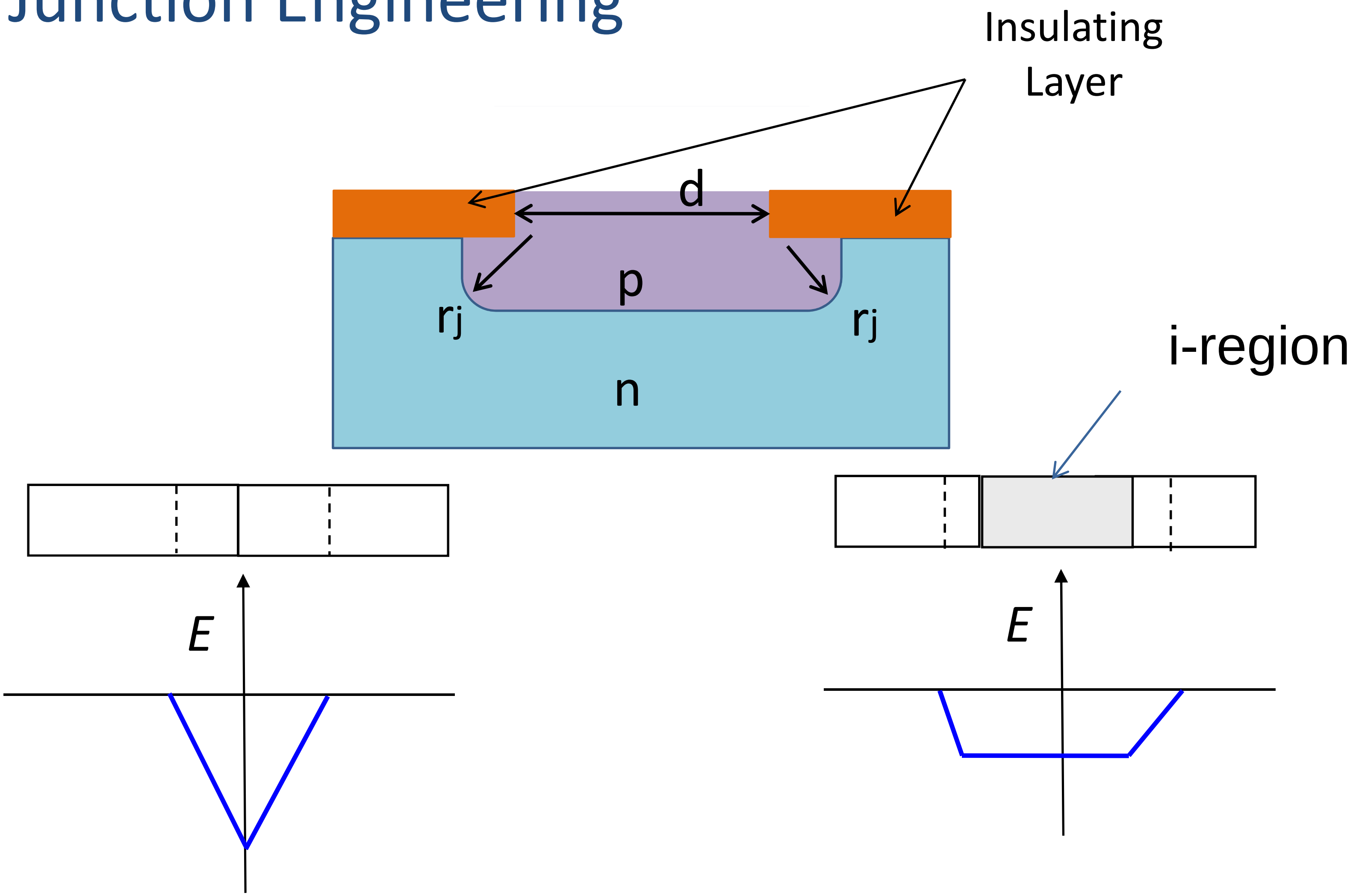


Good ….



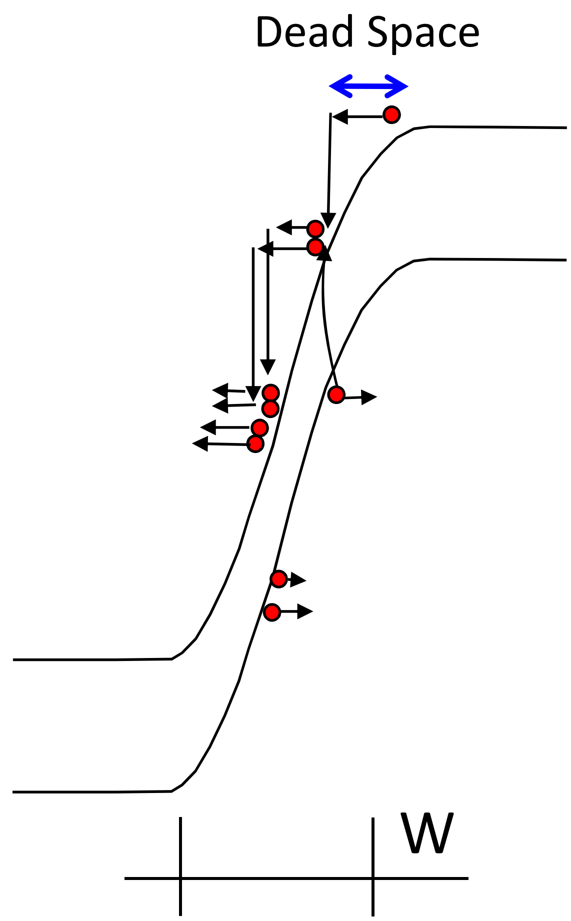
Bad….

Junction Engineering



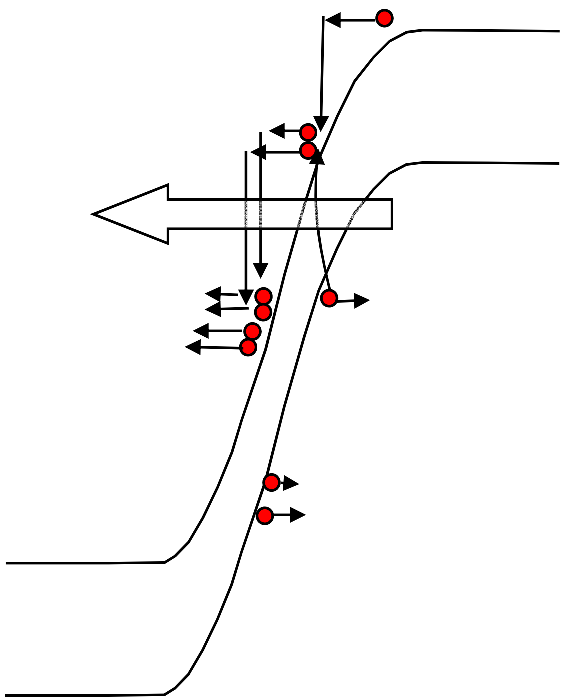
Reduced field for p-i-n junction, because V_{bi} (area under the curve) must be the same.

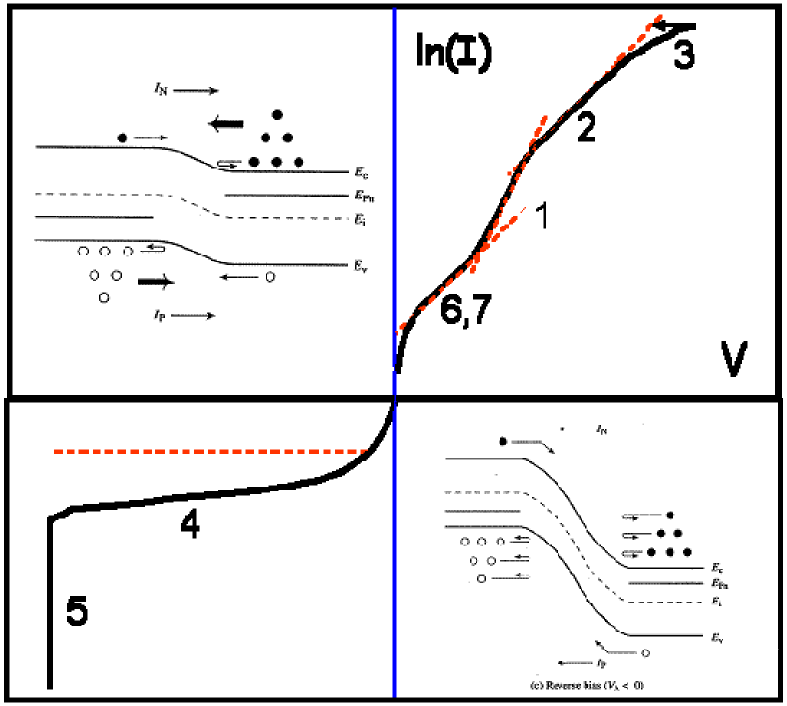
Modern Considerations: Dead Space



What happens if W is less than the mean-free path ?

Zener Breakdown vs. Impact Ionization





How do you differentiate between Zener tunneling and impact-ionization?

Conclusion

1) Junction recombination is often used as a diagnostic tool for process maturity. Defects in junction arises from misplaced donor impurities, not necessary from deep-trap impurities.
2) Impact ionization plays an important role in wide variety of devices (e.g. avalanche photo-diodes).
3) In the next class, we will discuss AC response of p-n junction diodes.