Non-idealities of PN Junctions

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Outline

- pn junction non-idealities
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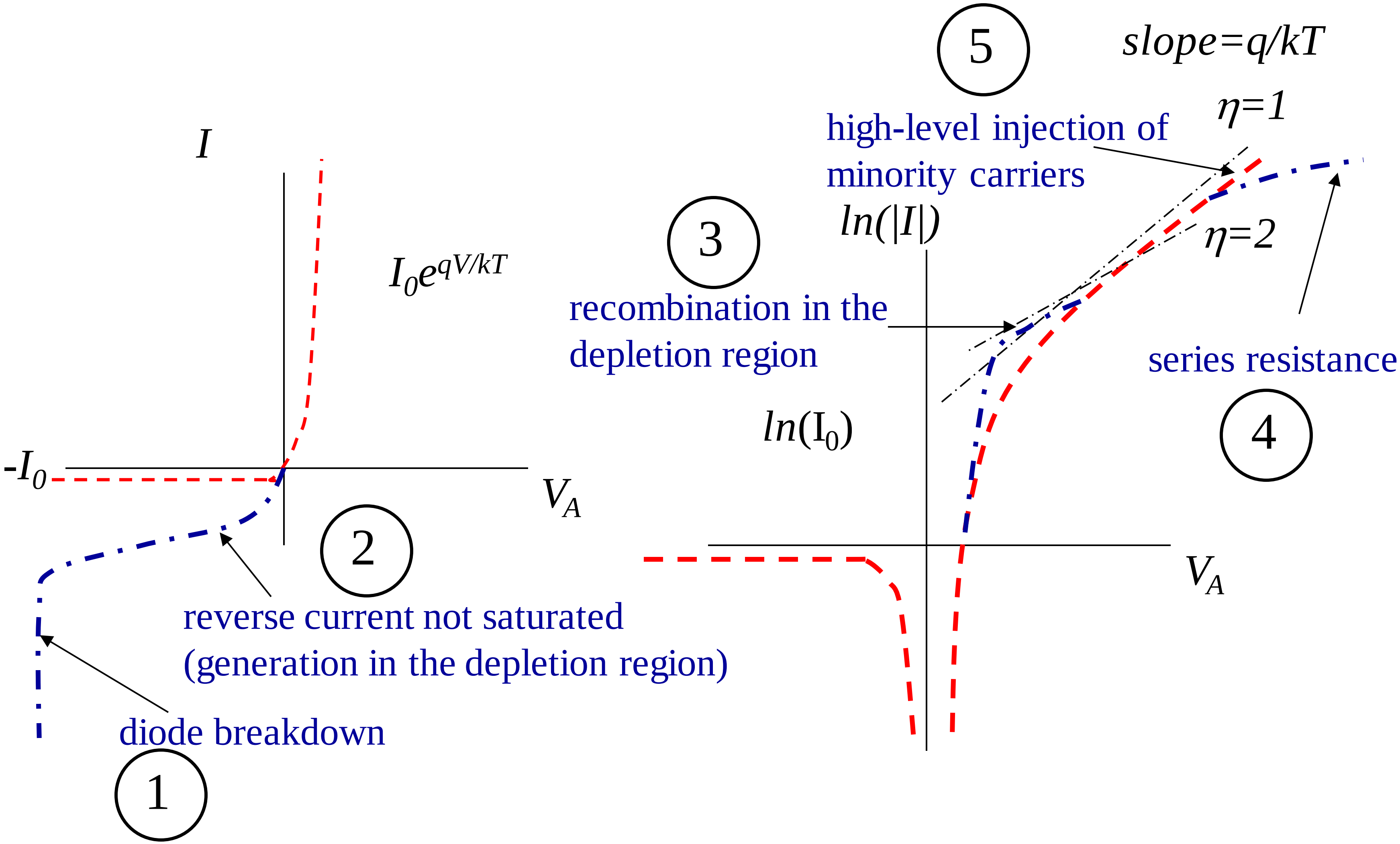
Diode DC Non-ideal Characteristics



Generation / Recombination

- Think: Where is the excess carrier density forward bias compared to equilibrium
  - Draw band diagram in f.b. and equilibrium next to each other
  - Draw the carrier profile on same graph;
- Pair: What is the recombination rate?
  - If locally
  - Then integrate

$$R-G\Big|_{thermalSRH} = -\frac{np-n_i^2}{\tau_p\left(n+n_1\right)+\tau_n\left(p+p_1\right)}$$

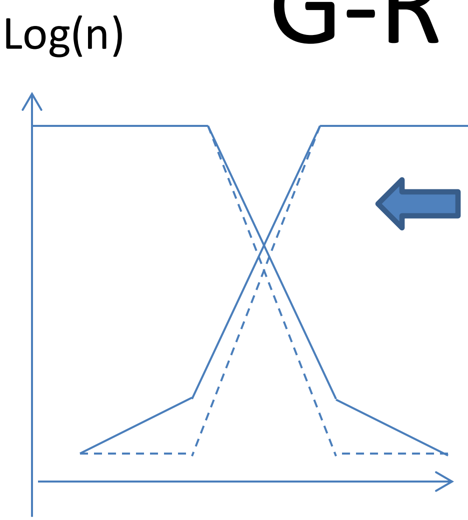
$$I_{R-G} \cong qA\int_{-x_p}^{x_n} \left(G-R\right)\Big|_{thermalSRH} dx$$

http://ecee.colorado.edu/~bart/book/book/chapter2/ch2_8.htm

$$n_1 = N_c \exp\left(-\frac{E_c - E_t}{k_B T_L}\right)$$

n_1: trap based carrier density; this term dominates compared to n during generation

G-R approximate calculation

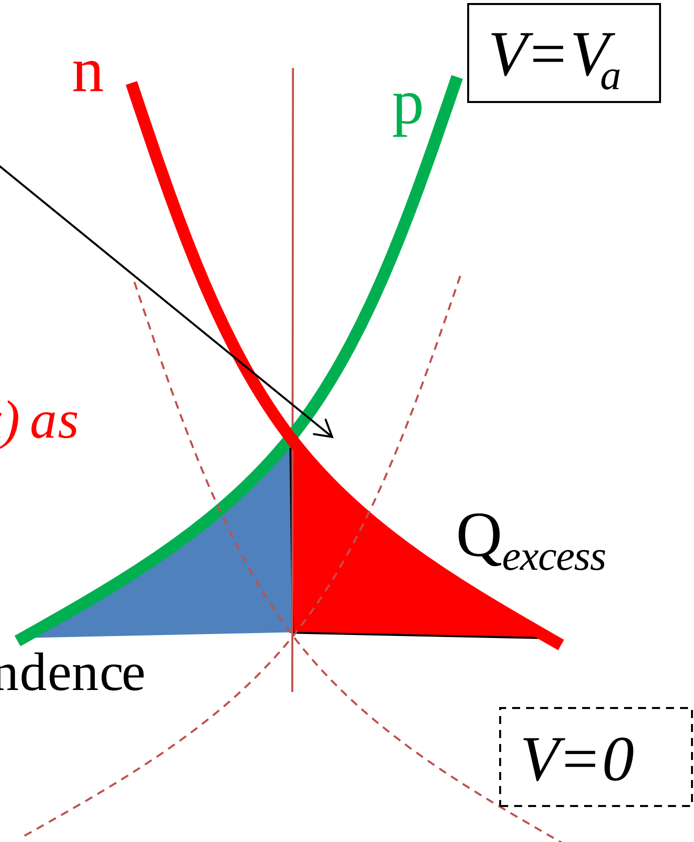


Assuming E_{Fn}, E_{Fp} are flat in depletion region, we get carrier profile; $R(x)=n_p(x)/\tau_n = p_n(x)/\tau_p$ (minority carrier dependent). At center,

$$n_c=p_c=n_i\, exp\, (qV_a/2kT)$$

Total recombination is sum of all local recombination = $\int_{-Wp}^{Wn} R dx$

Let us model $p(x)=p_c\, exp\, (-x/x_c)$; what is x_c?
where $x = f(E_{fp}-E_c(x))$ Can we approximate $E_c(x)$ as linearly dependent upon x to simplify math?



$$Q_{excess} = q\int_0^{x_n} n(x)dx = q\int_0^{\infty} n(x)dx = qn_c x_c$$

➔ f.b. has V_a dependence

$$R-G\big|_{thermalSRH} = -\frac{Q_{excess}}{\tau_p}$$

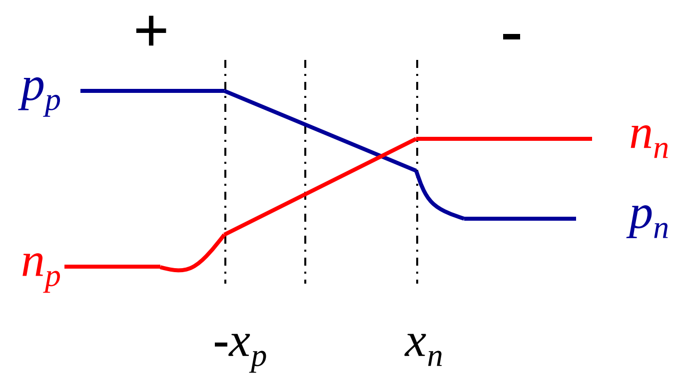
$$R-G\big|_{thermalSRH} = -\frac{Q_{eqm}}{\tau_p} = -\frac{qn_i^2}{\tau_p(n_1)}$$

➔ r.b. has no V_a dependence

Assume $n < n_1$

High Injection Region

- Think: When $p_n < n_{no}$ then why are bands flat- despite excess charge?
- Pair – if $p_n > n_{no}$ draw the band diagram
  - if $p_n > n_{no}$ the should the n_n respond?
  - How will it affect band diagram ➔ p_n ➔ J_p



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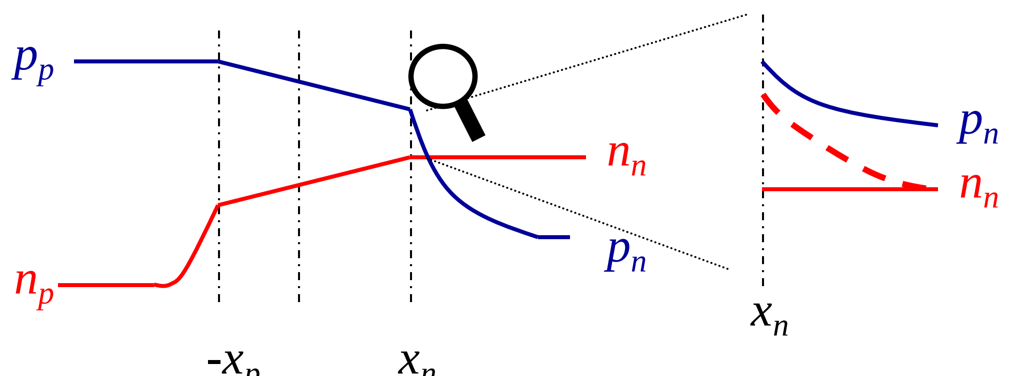


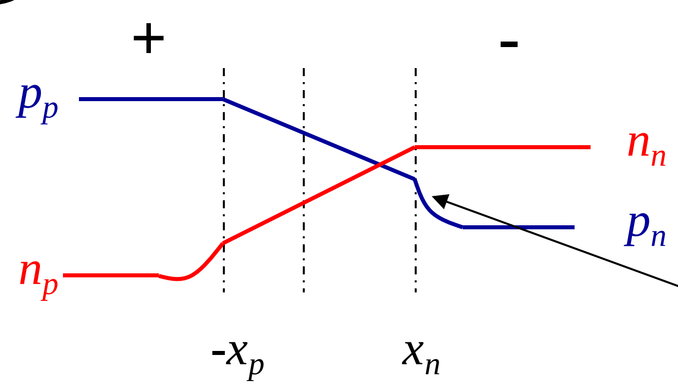
$np \neq n_i^2$ Inside the Depletion Region with $V_A \neq 0$

① $$I_G \approx -\frac{qAn_i}{2\tau_0}W \qquad \tau_0 = \frac{1}{2}\left(\tau_p \frac{n_1}{n_i} + \tau_n \frac{p_1}{n_i}\right)$$

Traps increase generation rate

This generation current results in a reverse-bias current that never really saturates since it is typically larger than I_0. When other generation mechanism exists (such as photo-generation), it deviates further from I_0.

③ In small forward-bias region: $np >> n_i^2$ for the entire depletion region



Slope has to be negative at the edge of the neutral region, since in the ideal IV relation:

$$I_p \propto -\frac{dp_n}{dx}$$

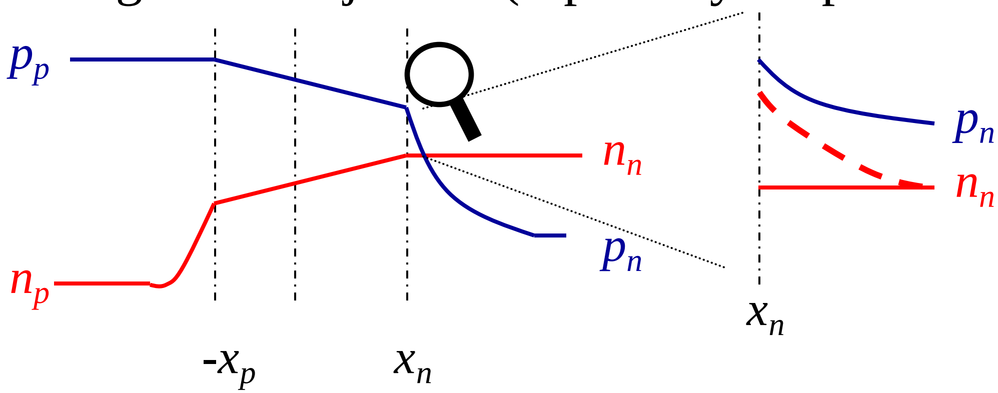
The recombination current in the quasi-neutral region has caused an I-V relationship of $\eta=1$ since all of V_A is reflected on the separation between E_{Fp} and E_{Fn}. In the depletion region, however, as explained in previous slide, the effect is $\eta=2$.

Series Resistance and High-Level Injection

4 Series resistance in the quasi-neutral region: $V_{junction} = V_A - I \cdot R_s$

R_s on the p-type side will be proportional to: $\dfrac{W_p}{Aqp_p\mu_p}$

5 high-level injection (especially for p$^+$-n or n$^+$-p types of doping):

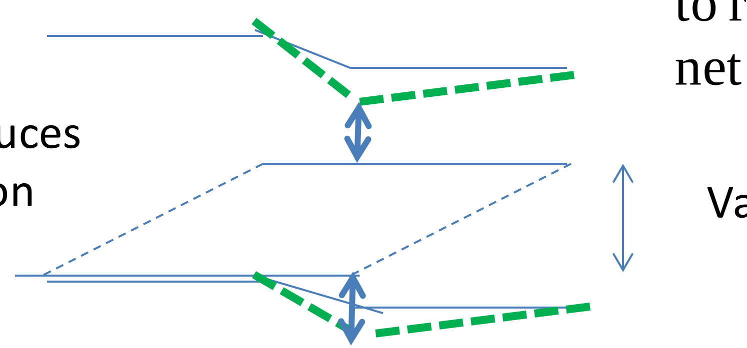


p_n is larger than n_n at the edge of the quasi-neutral region due to high-level injection. The majority carrier has to respond to reduce the net charge.

Before n_n response

$p_n = p_{no}\exp(qV/kT)$; $n_n = n_{no}$

$p_n n_n = n_i^2 \exp(qV/kT)$; but this produces electric field in quasi neutral region



After n_n response $p_n = n_n$ hence

$p_n = n_n = n_i \exp(qV/2kT)$

$\eta=2$

As J_p dependents upon p_n, current has $\eta=2$

High-Level Injection and Ideality Factor Degradation

- When $p_n(x_n)>n_{n0}$, not all V_A can be used in for the separation of E_{Fn} and E_{Fp}, part of V_A is used to support the net extra charge of p_n-n_n in the original quasi-neutral region.
- Recombination is surely serious here (sometime the recombination is so strong that the junction emits lights, exactly what we need for LED and lasers), but we have counted them in the ideal theory except for the extra charge.
- We can also use the point of view that the quasi-neutral region has to remain nearly charge neutral and $n=p=n_i exp(qV_A/2kT)$ since the dopant charge is smaller than $n=p$ at x_n for high injection conditions.

$$I_{R-G} \propto e^{qV_A/\eta kT} \qquad \eta \rightarrow 2$$

Multi-dimensional Junction Diodes

- Realistic junction in CMOS technology is multi-dimensional. To create a good test 1-D junction diode, usually a large circle is necessary.
- Not only that A is harder to define, but W_d will vary with the curvature due to the varying electric field in multi-dimension.
- Usually only numerical solution is possible to obtain accurate solution of the Shockley's equations.
- However, ideality factor for the "ideal part" (E_{Fn} and E_{Fp} separated by the applied bias entirely) will still be one, and an effective I_0 can be extracted from the "ideal part" of the I-V.