

## 8.2 Generation-Recombination Currents and High-Injection Levels

In deriving our ideal  $I$ - $V$  relationship, we have assumed low injection levels and neglected any effects inside the depletion layer (space region). Some causes for changes from the ideal include:

- generation-recombination
- high-level injection

### 8.2.1 Generation-Recombination Currents

Section 6.5 (skipped) discusses the Shockley-Read-Hall recombination theory. We will not go into this material in depth, but use some key portions.

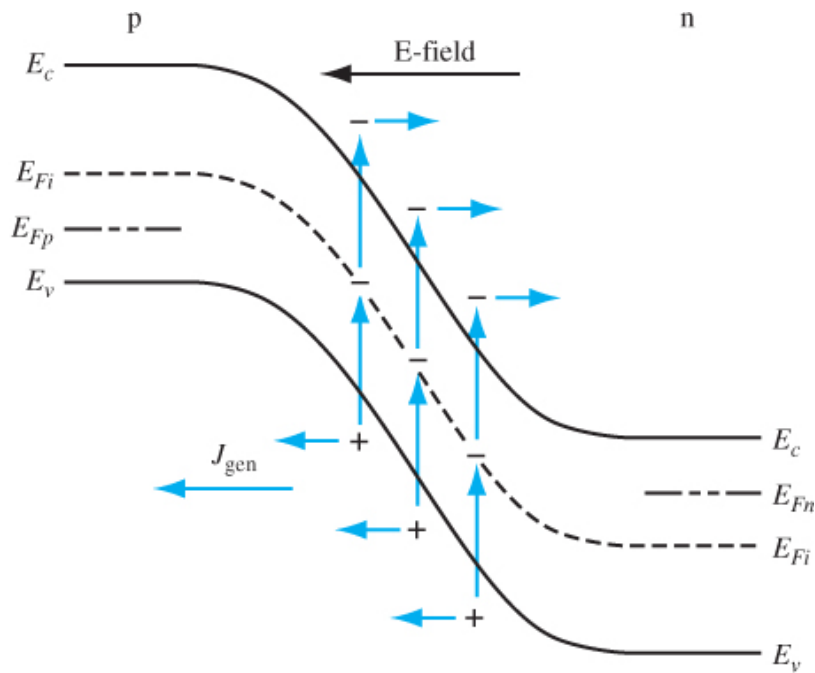
- The recombination rate (see section 6.5) is  $R = \frac{C_n C_p N_t (np - n_i^2)}{C_n (n + n') + C_p (p + p')}$  (8.35).

We won't worry about the parameters  $C_n$ ,  $C_p$ ,  $N_t$ ,  $n'$ , &  $p'$ .

### **Reverse-Biased Generation Current**

- In the reverse-biased depletion layer, there are few free/mobile charge carriers, i.e.,  $n \approx p \approx 0 \Rightarrow R = \frac{-C_n C_p N_t n_i^2}{C_n n' + C_p p'} < 0$  (8.36).
- A **negative** recombination rate  $R$  implies that electron-hole pairs are being **generated** in the depletion layer!
- The semiconductor atoms in the depletion layer, at temperature  $T$ , continue to produce thermal mobile electrons and holes (trying to reestablish thermal equilibrium concentrations).
- As these mobile electrons and holes are generated, the electric field in the depletion layer 'sweeps' them out via Coulomb force (see Figure 8.12 on next page)  $\Rightarrow$  **reverse-biased generation current (density)  $J_{\text{gen}}$ .**

From *Semiconductor Physics and Devices: Basic Principles* (4th Edition), Donald A. Neamen, McGraw Hill, 2012, ISBN 978-0-07-352958-5.



**Figure 8.12** | Generation process in a reverse-biased pn junction.

➤ This can be rewritten as  $R = \frac{-n_i}{\frac{1}{N_t C_p} + \frac{1}{N_t C_n}} = \frac{-n_i}{\tau_{p0} + \tau_{n0}}$  where  $n_i$  is the intrinsic

carrier concentration for the semiconductor and  $\tau_{p0}$  &  $\tau_{n0}$  are the excess minority carrier hole & electron lifetimes.

➤ Defining an average excess carrier lifetime as  $\tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2}$  (8.39), we get

$$R = \frac{-n_i}{2\tau_0} = -G \quad (8.4). \text{ So, the generation rate in the depletion layer is } G = \frac{n_i}{2\tau_0}.$$

➤ Now, we can find the reverse-biased generation current (density) as

$$J_{\text{gen}} = \int_{x=0}^W eG dx = \int_{x=0}^W e \frac{n_i}{2\tau_0} dx \Rightarrow \boxed{J_{\text{gen}} = \frac{e n_i W}{2\tau_0}} \quad (8.42).$$

➤ Now, the total reverse-biased current density is  $\underline{J_R = J_s + J_{\text{gen}}}$  (8.43).

Note:  $J_s$  does not depend on  $V_R$ , however,  $J_{\text{gen}}$  depends on  $W$  which does  $\Rightarrow J_R$  **changes with  $V_R$ !**

How big of an effect is the reverse-biased generation current density  $J_{gen}$  compared to the ideal reverse saturation current density  $J_s$ ?

**Example-**

Let's revisit our germanium pn junction at 300 K where  $N_a = 6 \times 10^{15} \text{ cm}^{-3}$  (p region) &  $N_d = 3 \times 10^{15} \text{ cm}^{-3}$  (n region). The carrier lifetimes are  $\tau_{p0} = 2 \times 10^{-8} \text{ s}$  &  $\tau_{n0} = 2 \times 10^{-8} \text{ s}$ . Find  $J_s$  and then calculate  $J_{gen}$  when  $V_R = 0, 1, \& 2 \text{ V}$ .

From earlier examples-

**Figure 5.3**       $\mu_p := 1600 \text{ cm}^2/\text{V}\cdot\text{s}$        $\mu_n := 3400 \text{ cm}^2/\text{V}\cdot\text{s}$

**Table B.4**       $\epsilon_{r\_Ge} := 16$        $n_{i\_Ge} := 2.4 \cdot 10^{19} \text{ m}^{-3}$

(5.47) Einstein relation       $D_p := \mu_p \cdot \frac{kB \cdot T}{qe}$        $D_n := \mu_n \cdot \frac{kB \cdot T}{qe}$

$D_p = 41.363 \text{ cm}^2/\text{s}$        $D_n = 87.897 \text{ cm}^2/\text{s}$

**Calculate diffusion lengths in meters**

$L_n := \frac{\sqrt{D_n \cdot \tau_{n0}}}{100}$        $L_n = 2.651744 \times 10^{-5}$       m

$L_p := \frac{\sqrt{D_p \cdot \tau_{p0}}}{100}$        $L_p = 9.095405 \times 10^{-6}$       m

**p region**       $pp0 := N_a$        $pp0 = 6 \times 10^{21} \text{ m}^{-3}$       **majority**

$np0 := \frac{n_{i\_Ge}^2}{pp0}$        $np0 = 9.6 \times 10^{16}$        $\text{m}^{-3}$       **minority**

**n region**       $nn0 := N_d$        $nn0 = 3 \times 10^{21} \text{ m}^{-3}$       **majority**

$pn0 := \frac{n_{i\_Ge}^2}{nn0}$        $pn0 = 1.92 \times 10^{17}$        $\text{m}^{-3}$       **minority**

(8.26)       $J_s := \frac{qe \cdot D_p \cdot 10^{-4} \cdot pn0}{L_p} + \frac{qe \cdot D_n \cdot 10^{-4} \cdot np0}{L_n}$        $J_s = 19.0878$        $\text{A}/\text{m}^2$

Find thermal and built-in voltages as well as average lifetime-

$$(7.10) \quad V_t := \frac{k_B \cdot T}{q_e} \quad V_t = 0.025852 \quad \text{V}$$

$$V_{bi} := V_t \cdot \ln\left(\frac{N_a \cdot N_d}{n_i \cdot \text{Ge}^2}\right) \quad V_{bi} = 0.267562 \quad \text{V}$$

$$(8.39) \quad \tau_0 := 0.5 \cdot (\tau_{p0} + \tau_{n0}) \quad \tau_0 = 5 \times 10^{-8} \quad \text{s}$$

$$\boxed{V_R = 0}$$

$$\boxed{V_{R0} := 0}$$

$$(7.34) \quad W_0 := \sqrt{\frac{2 \cdot \epsilon_r \cdot \text{Ge} \cdot \epsilon_0 \cdot (V_{bi} + V_{R0})}{q_e} \cdot \left(\frac{N_a + N_d}{N_a \cdot N_d}\right)} \quad W_0 = 4.86398 \times 10^{-7} \quad \text{m}$$

$$(8.42) \quad J_{gen0} := \frac{q_e \cdot n_i \cdot \text{Ge} \cdot W_0}{2 \cdot \tau_0} \quad \boxed{J_{gen0} = 18.7031} \quad \text{A/m}^2$$

$$(8.43) \text{ total reverse-biased current density} \quad J_{R0} := J_s + J_{gen0} \quad \boxed{J_{R0} = 37.7909} \quad \text{A/m}^2$$

$$\frac{J_s}{J_{gen0}} = 1.021 \quad J_R \text{ percentage due to } J_s \quad \frac{J_s}{J_{R0}} \cdot 100 = 50.509 \quad \%$$

$$J_R \text{ percentage due to } J_{gen} \quad \frac{J_{gen0}}{J_{R0}} \cdot 100 = 49.491 \quad \%$$

➤ **With no reverse bias voltage, the ideal reverse-saturation current density and the generation current density are roughly the same size.**

$$\boxed{V_R = 1 \text{ V}}$$

$$\boxed{VR1 := 1} \quad \text{V}$$

$$(7.34) \quad W1 := \sqrt{\frac{2 \cdot \epsilon_r_{\text{Ge}} \cdot \epsilon_0 \cdot (V_{bi} + VR1)}{q_e} \cdot \left( \frac{Na + Nd}{Na \cdot Nd} \right)} \quad W1 = 1.05868 \times 10^{-6} \quad \text{m}$$

$$(8.42) \quad J_{gen1} := \frac{q_e \cdot n_{i_{\text{Ge}}} \cdot W1}{2 \cdot \tau_0} \quad \boxed{J_{gen1} = 40.7085} \quad \text{A/m}^2$$

$$(8.43) \quad J_{R1} := J_s + J_{gen1} \quad \boxed{J_{R1} = 59.7964} \quad \text{A/m}^2$$

$$\frac{J_s}{J_{gen1}} = 0.469 \quad J_R \text{ percentage due to } J_s \quad \frac{J_s}{J_{R1}} \cdot 100 = 31.921 \%$$

$$J_R \text{ percentage due to } J_{gen1} \quad \frac{J_{gen1}}{J_{R1}} \cdot 100 = 68.079 \%$$

- With a reverse bias voltage of 1 V, the ideal reverse-saturation current density is roughly half the size of the generation current density.

$$\boxed{V_R = 2 \text{ V}}$$

$$\boxed{VR2 := 2} \quad \text{V}$$

$$(7.34) \quad W2 := \sqrt{\frac{2 \cdot \epsilon_r_{\text{Ge}} \cdot \epsilon_0 \cdot (V_{bi} + VR2)}{q_e} \cdot \left( \frac{Na + Nd}{Na \cdot Nd} \right)} \quad W2 = 1.41599 \times 10^{-6} \quad \text{m}$$

$$(8.42) \quad J_{gen2} := \frac{q_e \cdot n_{i_{\text{Ge}}} \cdot W2}{2 \cdot \tau_0} \quad \boxed{J_{gen2} = 54.4478} \quad \text{A/m}^2$$

$$(8.43) \quad J_{R2} := J_s + J_{gen2} \quad \boxed{J_{R2} = 73.5356} \quad \text{A/m}^2$$

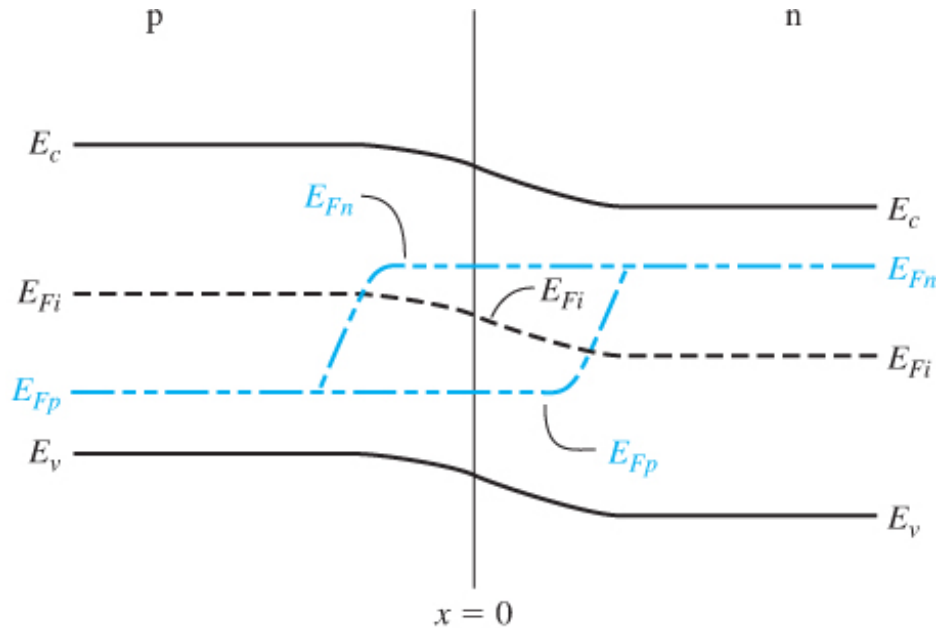
$$\frac{J_s}{J_{gen2}} = 0.351 \quad J_R \text{ percentage due to } J_s \quad \frac{J_s}{J_{R2}} \cdot 100 = 25.957 \%$$

$$J_R \text{ percentage due to } J_{gen2} \quad \frac{J_{gen2}}{J_{R2}} \cdot 100 = 74.043 \%$$

- With a reverse bias voltage of 2 V, the ideal reverse-saturation current density is roughly a third the size of the generation current density.

### Forward-Bias Generation Current

- Here, electrons and holes are continually injected across the depletion layer, i.e.,  $n \neq 0$  &  $p \neq 0$ .

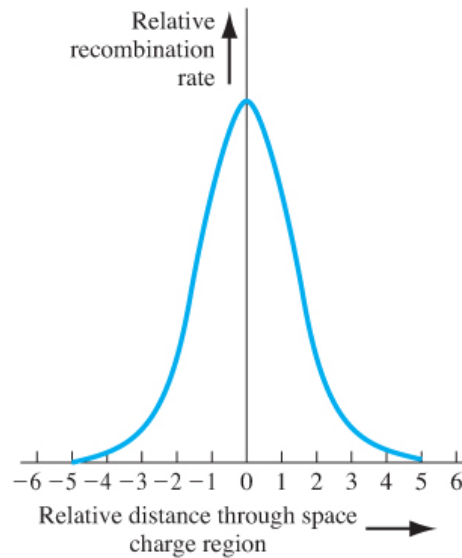


**Figure 8.13** | Energy-band diagram of a forward-biased pn junction including quasi-Fermi levels.

- Using Chapter 6 results, we can get  $n = n_i e^{(E_{Fn} - E_{Fi})/k_B T}$  and  $p = n_i e^{(E_{Fi} - E_{Fp})/k_B T}$ .
- In Figures 8.3 & 8.13, we showed  $eV_a = E_{Fn} - E_{Fp} = (E_{Fn} - E_{Fi}) + (E_{Fi} - E_{Fp})$  where  $V_a$  is the applied forward-bias voltage.
- Per section 6.5, let  $n' = p' = n_i$  and rewrite the recombination rate  $R$  as

$$R = \frac{np - n_i^2}{\tau_{p0}(n + n') + \tau_{p0}(p + p')} \quad (8.44).$$

- As shown in Figure 8.14 below,  $R$  peaks at the center of the depletion layer.



**Figure 8.14** | Relative magnitude of the recombination rate through the space charge region of a forward-biased pn junction.

- The maximum recombination rate  $R_{\max}$  can be found by noting that at the center of the depletion layer  $E_{Fn} - E_{Fi} = E_{Fi} - E_{Fp} = eV_a / 2$  which gives  $n = p = n_i e^{eV_a/2k_B T}$ . Then, letting  $\tau_{p0} = \tau_{n0} = \tau_0$  at the center of the depletion layer, we find

$$R_{\max} = \frac{n_i}{2\tau_0} \frac{e^{eV_a/k_B T} - 1}{e^{eV_a/2k_B T} + 1} \quad (8.51).$$

- This can be further simplified by assuming  $V_a \gg V_t = k_B T / e$  which makes the exponential terms in (8.51) much bigger than 1, i.e., we can neglect the -1 & +1 terms. This leads to  $R_{\max} \approx \frac{n_i}{2\tau_0} e^{eV_a/2k_B T}$  (8.52).

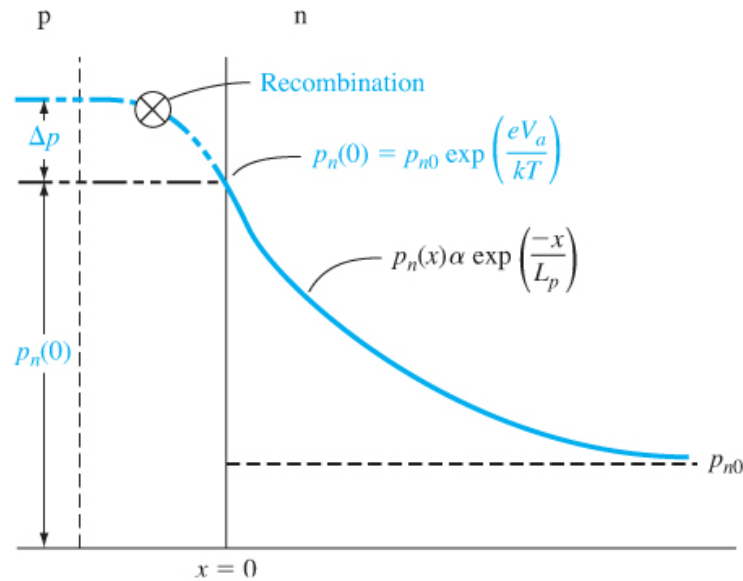
- We can find the recombination current density as  $J_{\text{rec}} = \int_{x=0}^W e R dx$ .

- However,  $R$  changes across the depletion layer as shown in Figure 8.14. So, considering that  $\tau_0$  may not be known to great precision,  $J_{\text{rec}}$  is approximated by letting  $R = R_{\max}$ , yielding

$$J_{\text{rec}} = \frac{e n_i W}{2\tau_0} e^{eV_a/2k_B T} = J_{r0} e^{eV_a/2k_B T} \quad (8.55).$$

### Total Forward-Bias Current

- Figure 8.15 gives an overview of what is happening. (Note: The horizontal axis is shifted by  $-x_n$  so the right edge of the depletion layer is at  $x = 0$ .) In order to have  $p_n = p_{n0} e^{eV_a/k_B T}$  at the right edge of the depletion layer, we start with  $p_n + \Delta p$  at the left edge of the depletion layer to allow for recombination. These extra holes account for the recombination current density  $J_{rec}$ .



**Figure 8.15** | Because of recombination, additional holes from the p region must be injected into the space charge region to establish the minority carrier hole concentration in the n region.

- The total forward-biased current density is the sum of the recombination current density  $J_{rec}$  and the ideal diffusion current density  $J_D$ , i.e.,

$$J = J_{rec} + J_D = \frac{e n_i W}{2 \tau_0} e^{eV_a/2k_B T} + J_s [e^{eV_a/k_B T} - 1] \approx J_{r0} e^{eV_a/2k_B T} + J_s e^{eV_a/k_B T} \quad (8.56)$$

or

$$J \approx J_{r0} e^{V_a/2V_t} + J_s e^{V_a/V_t}$$

where  $J_{r0} = \frac{e n_i W}{2 \tau_0}$  and  $J_s = \frac{e D_p p_{n0}}{L_p} + \frac{e D_n n_{p0}}{L_n} = \frac{e D_p p_{n0}}{\sqrt{D_p \tau_{p0}}} + \frac{e D_n n_{p0}}{\sqrt{D_n \tau_{n0}}}$ .

- The total current is then  $I = J(A) \approx (J_{r0} e^{V_a/2V_t} + J_s e^{V_a/V_t}) A$ .

- From the prior example, we can expect that  $J_{r,0} > J_s$ .
- Taking the natural log of each current density component gives

$$\ln(J_{\text{rec}}) = \ln(J_{r0}) + \frac{eV_a}{2k_B T} = \frac{1}{2} V_a + \ln(J_{r0}) \quad \text{and}$$

$$\ln(J_D) \approx \ln(J_s) + \frac{eV_a}{k_B T} = \frac{1}{1} V_a + \ln(J_s).$$

These are linear equations!

- Figure 8.15 shows that for small values of the forward bias voltage  $V_a \ll V_{bi}$ , i.e., when it is near  $V_t$ , the recombination current dominates.
- For larger values of the forward bias voltage  $V_t \ll V_a < V_{bi}$ , the ideal diffusion current  $J_D$  dominates. [Note: We can't calculate  $J_{\text{rec}}$  when  $V_a \geq V_{bi}$  as the depletion layer width  $W$  goes to zero (or less), i.e., NOT low-level injection.]

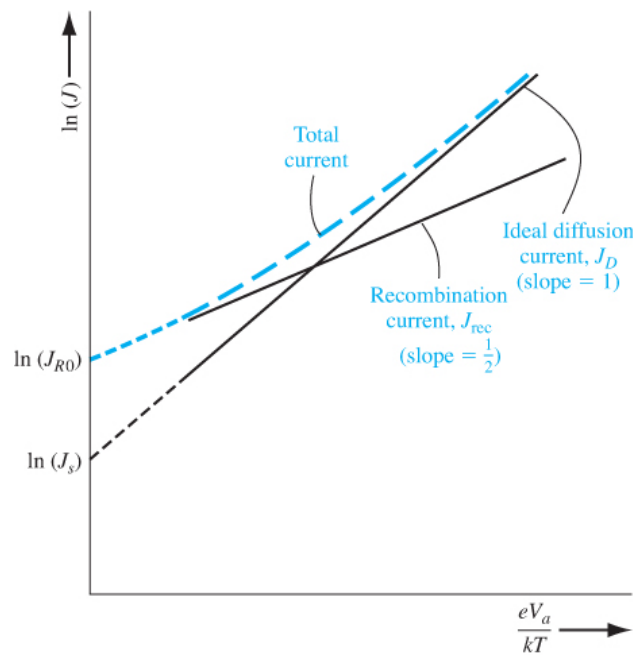


Figure 8.16 | Ideal diffusion, recombination, and total current in a forward-biased pn junction.

- A combined approximate  $I$ - $V$  equation can be written as

$$I = J(A) \approx I_s \left[ e^{V_a/nV_t} - 1 \right] \quad (8.59)$$

where  $n$  is called the ideality factor;  $n = 2$  when  $V_a$  is small (recombination dominates) and  $n = 1$  when  $V_a$  is larger (diffusion dominates).

**Example-**

Let's revisit our germanium pn junction at 300 K where  $N_a = 6 \times 10^{15} \text{ cm}^{-3}$  (p region) &  $N_d = 3 \times 10^{15} \text{ cm}^{-3}$  (n region). The carrier lifetimes are  $\tau_{p0} = 2 \times 10^{-8} \text{ s}$  &  $\tau_{n0} = 2 \times 10^{-8} \text{ s}$ . Find  $J_s$  and  $J_{r,0}$ . Then, calculate  $J_D$ ,  $J_{\text{rec}}$ , and  $J$  as  $V_a$  varies.

From earlier examples-

**Figure 5.3**       $\mu_p := 1600 \text{ cm}^2/\text{V}\cdot\text{s}$        $\mu_n := 3400 \text{ cm}^2/\text{V}\cdot\text{s}$

**Table B.4**       $\epsilon_{r\_Ge} := 16$        $n_{i\_Ge} := 2.4 \cdot 10^{19} \text{ m}^{-3}$

(5.47) Einstein relation       $D_p := \mu_p \cdot \frac{k_B \cdot T}{q_e}$        $D_n := \mu_n \cdot \frac{k_B \cdot T}{q_e}$

$D_p = 41.363 \text{ cm}^2/\text{s}$        $D_n = 87.897 \text{ cm}^2/\text{s}$

**Calculate diffusion lengths in meters**

$L_n := \frac{\sqrt{D_n \cdot \tau_{n0}}}{100}$        $L_n = 2.651744 \times 10^{-5}$       m

$L_p := \frac{\sqrt{D_p \cdot \tau_{p0}}}{100}$        $L_p = 9.095405 \times 10^{-6}$       m

**p region**       $pp0 := N_a$        $pp0 = 6 \times 10^{21} \text{ m}^{-3}$       **majority**

$np0 := \frac{n_{i\_Ge}^2}{pp0}$        $np0 = 9.6 \times 10^{16}$        $\text{m}^{-3}$       **minority**

**n region**       $nn0 := N_d$        $nn0 = 3 \times 10^{21} \text{ m}^{-3}$       **majority**

$pn0 := \frac{n_{i\_Ge}^2}{nn0}$        $pn0 = 1.92 \times 10^{17}$        $\text{m}^{-3}$       **minority**

(8.26)       $J_s := \frac{q_e \cdot D_p \cdot 10^{-4} \cdot pn0}{L_p} + \frac{q_e \cdot D_n \cdot 10^{-4} \cdot np0}{L_n}$        $J_s = 19.0878$        $\text{A}/\text{m}^2$

Find thermal and built-in voltages as well as average lifetime-

$$(7.10) \quad V_t := \frac{k_B \cdot T}{q_e} \quad V_t = 0.025852 \quad \text{V}$$

$$V_{bi} := V_t \cdot \ln\left(\frac{N_a \cdot N_d}{n_{i\_Ge}^2}\right) \quad V_{bi} = 0.267562 \quad \text{V}$$

$$(8.39) \quad \tau_0 := 0.5 \cdot (\tau_{p0} + \tau_{n0}) \quad \tau_0 = 5 \times 10^{-8} \quad \text{s}$$

$$V_a = 0$$

$$V_{a0} := 0$$

$$(7.34) \quad W_0 := \sqrt{\frac{2 \cdot \epsilon_r \cdot \epsilon_0 \cdot (V_{bi} - V_{a0})}{q_e} \cdot \left(\frac{N_a + N_d}{N_a \cdot N_d}\right)} \quad W_0 = 4.86398 \times 10^{-7} \quad \text{m}$$

$$(8.55) \quad J_{r0\_0} := \frac{q_e \cdot W_0 \cdot n_{i\_Ge}}{2 \cdot \tau_0} \quad J_{r0\_0} = 18.7031 \quad \text{A/m}^2$$

Roughly same size as  $J_s = 19.07 \text{ A/m}^2$ .

$$J_{rec\_0} := J_{r0\_0} \cdot e^{\frac{V_{a0}}{2 \cdot V_t}} \quad J_{rec\_0} = 18.703 \quad \text{A/m}^2$$

$$J_{D\_0} := J_s \cdot \left( e^{\frac{V_{a0}}{V_t}} - 1 \right) \quad J_{D\_0} = 0$$

$$(8.56) \text{ total forward-biased current density} \quad J\_0 := J_{D\_0} + J_{rec\_0} \quad J\_0 = 18.703 \quad \text{A/m}^2$$

$$\frac{J_{rec\_0}}{J\_0} = 1 \quad \text{100\% due to } J_{rec}$$

$$V_a = V_t$$

$$V_{aVt} := V_t \quad V_{aVt} = 0.02585 \quad V$$

$$W_{Vt} := \sqrt{\frac{2 \cdot \epsilon_r \cdot \epsilon_0 \cdot (V_{bi} - V_{aVt})}{q \cdot e} \cdot \left( \frac{N_a + N_d}{N_a \cdot N_d} \right)} \quad W_{Vt} = 4.62303 \times 10^{-7} \quad m$$

$$J_{r0\_Vt} := \frac{q \cdot e \cdot W_{Vt} \cdot n_{i\_Ge}}{2 \cdot \tau_0} \quad J_{r0\_Vt} = 17.7766 \quad A/m^2$$

Little smaller than  $J_s = 19.07 A/m^2$ .

$$J_{rec\_Vt} := J_{r0\_Vt} \cdot e^{\frac{V_{aVt}}{2 \cdot V_t}} \quad J_{rec\_Vt} = 29.309 \quad A/m^2$$

$$J_{D\_Vt} := J_s \cdot \left( e^{\frac{V_{aVt}}{V_t}} - 1 \right) \quad J_{D\_Vt} = 32.798 \quad A/m^2$$

$$J_{\_Vt} := J_{D\_Vt} + J_{rec\_Vt} \quad J_{\_Vt} = 62.1069 \quad A/m^2$$

$$\frac{J_{rec\_Vt}}{J_{\_Vt}} = 0.472 \quad \sim 47.2\% \text{ due to } J_{rec}$$

$$V_a = 4V_t$$

$$V_{a4Vt} := 4V_t \quad V_{a4Vt} = 0.10341 \quad V$$

$$W_{4Vt} := \sqrt{\frac{2 \cdot \epsilon_r \cdot \epsilon_0 \cdot (V_{bi} - V_{a4Vt})}{q \cdot e} \cdot \left( \frac{N_a + N_d}{N_a \cdot N_d} \right)} \quad W_{4Vt} = 3.80983 \times 10^{-7} \quad m$$

$$J_{r0\_4Vt} := \frac{q \cdot e \cdot W_{4Vt} \cdot n_{i\_Ge}}{2 \cdot \tau_0} \quad J_{r0\_4Vt} = 14.6496 \quad A/m^2$$

Smaller than  $J_s = 19.07 A/m^2$ .

$$J_{rec\_4Vt} := J_{r0\_4Vt} \cdot e^{\frac{V_{a4Vt}}{2 \cdot V_t}} \quad J_{rec\_4Vt} = 108.247 \quad A/m^2$$

$$J_{D\_4Vt} := J_s \cdot \left( e^{\frac{V_{a4Vt}}{V_t}} - 1 \right) \quad J_{D\_4Vt} = 1023.072 \quad A/m^2$$

$$J_{\_4Vt} := J_{D\_4Vt} + J_{rec\_4Vt} \quad J_{\_4Vt} = 1131.319 \quad A/m^2$$

$$\frac{J_{rec\_4Vt}}{J_{\_4Vt}} = 0.096 \quad \sim 9.6\% \text{ due to } J_{rec}$$

$$V_a = 8V_t < V_{bi} = 0.2676 \text{ V}$$

$$V_{a8Vt} := 8V_t \quad V_{a8Vt} = 0.20682 \quad \text{V}$$

$$W_{8Vt} := \sqrt{\frac{2 \cdot \epsilon_r \cdot \epsilon_0 \cdot (V_{bi} - V_{a8Vt}) \cdot \left( \frac{N_a + N_d}{N_a \cdot N_d} \right)}{q \cdot e}} \quad W_{8Vt} = 2.3176 \times 10^{-7} \text{ m}$$

$$J_{r0\_8Vt} := \frac{q \cdot e \cdot W_{8Vt} \cdot n_i \cdot \mu_{Ge}}{2 \cdot \tau_0} \quad J_{r0\_8Vt} = 8.9117 \text{ A/m}^2$$

Smaller than  $J_s = 19.07 \text{ A/m}^2$ .

$$J_{rec\_8Vt} := J_{r0\_8Vt} \cdot e^{\frac{V_{a8Vt}}{2 \cdot V_t}} \quad J_{rec\_8Vt} = 486.563 \text{ A/m}^2$$

$$J_{D\_8Vt} := J_s \cdot \left( e^{\frac{V_{a8Vt}}{V_t}} - 1 \right) \quad J_{D\_8Vt} = 56880.908 \text{ A/m}^2$$

$$J_{\_8Vt} := J_{D\_8Vt} + J_{rec\_8Vt} \quad J_{\_8Vt} = 57367.471 \text{ A/m}^2$$

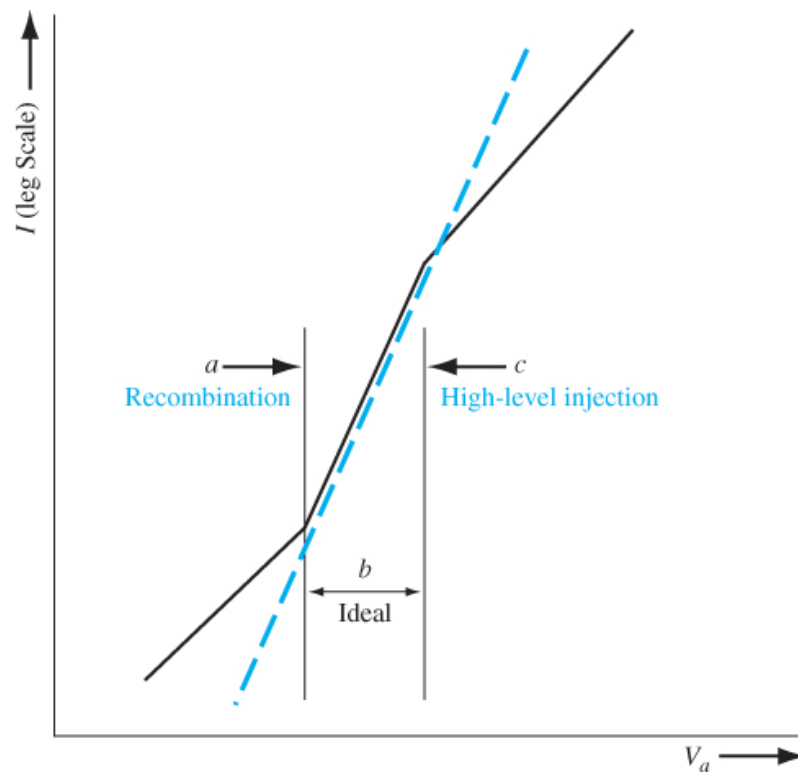
$$\frac{J_{rec\_8Vt}}{J_{\_8Vt}} = 0.00848 \quad \sim 0.85\% \text{ due to } J_{rec}$$

- Note that as  $V_a$  approaches  $V_{bi}$  the recombination current becomes negligible and  $J \approx J_D$ .

## 8.2.2 High-Level Injection

What happens as  $V_a \gtrsim V_{bi}$ ?

- Now, we can no longer assume that  $\delta n$  or  $\delta p$  are smaller than the majority carrier concentrations.
- Per (8.18)  $np = n_i^2 e^{V_a/V_t}$  where  $n = n_0 + \delta n$  and  $p = p_0 + \delta p$ . For high-level injection,  $\delta n > n_0$  &  $\delta p > p_0$  which means  $\delta n \delta p \approx n_i^2 e^{V_a/V_t}$ .
- Since  $\delta n = \delta p$ , this leads to  $\delta n = \delta p \approx n_i e^{V_a/2V_t}$  (8.62) and  $I \propto e^{V_a/2V_t}$  (8.63)
- Figure 8.17 shows a plot of the natural log of the current versus forward bias voltage  $V_a$ .



**Figure 8.17** | Forward-bias current versus voltage from low forward bias to high forward bias.

- Per (8.59) and (8.63),  $I \propto e^{V_a/2V_t} \Rightarrow \ln(I) \propto \frac{1}{2V_t} V_a$  when the recombination current dominates for small values of  $V_a$  (region *a*) **or** for high-level injection where  $V_a \gtrsim V_{bi}$  (region *c*).
- In region *b*, the ideal diffusion current dominates  $I \propto e^{V_a/V_t} \Rightarrow \ln(I) \propto \frac{1}{V_t} V_a$ .