## 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 $R = \dfrac{C_n C_p N_t (np - n_i^2)}{C_n (n + n') + C_p (p + p')}$ (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., $n \approx p \approx 0$ $\Rightarrow$ $R = \dfrac{-C_n C_p N_t n_i^2}{C_n n' + C_p p'} < 0$ (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) $J_{gen}$**.

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

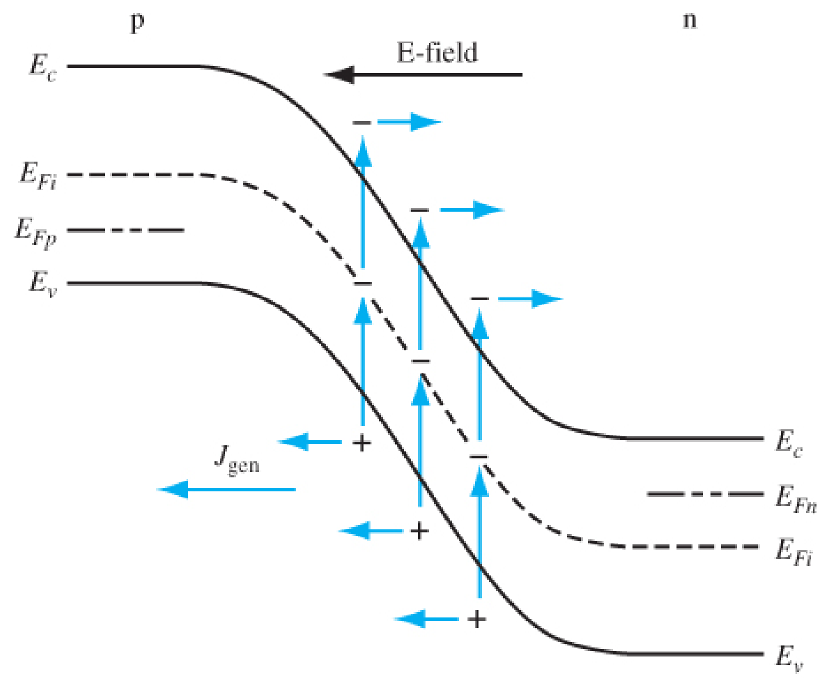


**Figure 8.12** | Generation process in a reverse-biased pn junction.

- This can be rewritten as $R = \dfrac{-n_i}{\dfrac{1}{N_t C_p} + \dfrac{1}{N_t C_n}} = \dfrac{-n_i}{\tau_{p0} + \tau_{n0}}$ 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 $\tau_0 = \dfrac{\tau_{p0} + \tau_{n0}}{2}$ (8.39), we get $R = \dfrac{-n_i}{2\tau_0} = -G$ (8.4). So, the generation rate in the depletion layer is $G = \dfrac{n_i}{2\tau_0}$.

- Now, we can find the reverse-biased generation current (density) as $J_{\text{gen}} = \int_{x=0}^{W} eG\,dx = \int_{x=0}^{W} e\dfrac{n_i}{2\tau_0}dx \Rightarrow \boxed{J_{\text{gen}} = \dfrac{e\,n_i W}{2\tau_0} \quad (8.42)}$.

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

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

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 $N_a = 6 \times 10^{15}$ cm$^{-3}$ (p region) & $N_d = 3 \times 10^{15}$ cm$^{-3}$ (n region). The carrier lifetimes are $\tau_{p0} = 2\times10^{-8}$ s & $\tau_{n0} = 2\times10^{-8}$ s. Find $J_s$ and then calculate $J_{gen}$ when $V_R = 0$, 1, & 2 V.

From earlier examples-

**Figure 5.3** $\mu p := 1600$ cm$^2$/V-s $\mu n := 3400$ cm$^2$/V-s

**Table B.4** $\varepsilon r\_Ge := 16$ $ni\_Ge := 2.4 \cdot 10^{19}$ m$^{-3}$

(5.47) Einstein relation $Dp := \mu p \cdot \dfrac{kB \cdot T}{qe}$ $Dn := \mu n \cdot \dfrac{kB \cdot T}{qe}$

$Dp = 41.363$ cm$^2$/s $Dn = 87.897$ cm$^2$/s

**Calculate diffusion lengths in meters**

$$Ln := \frac{\sqrt{Dn \cdot \tau n0}}{100} \qquad \boxed{Ln = 2.651744 \times 10^{-5}} \text{ m}$$

$$Lp := \frac{\sqrt{Dp \cdot \tau p0}}{100} \qquad \boxed{Lp = 9.095405 \times 10^{-6}} \text{ m}$$

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

$np0 := \dfrac{ni\_Ge^2}{pp0}$ $\boxed{np0 = 9.6 \times 10^{16}}$ m$^{-3}$ **minority**

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

$pn0 := \dfrac{ni\_Ge^2}{nn0}$ $\boxed{pn0 = 1.92 \times 10^{17}}$ m$^{-3}$ **minority**

**(8.26)** $$Js := \frac{qe \cdot Dp \cdot 10^{-4} \cdot pn0}{Lp} + \frac{qe \cdot Dn \cdot 10^{-4} \cdot np0}{Ln} \qquad \boxed{Js = 19.0878} \text{ A/m}^2$$

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

(7.10) $Vt := \frac{kB \cdot T}{qe}$ $Vt = 0.025852$ V

$Vbi := Vt \cdot \ln\left(\frac{Na \cdot Nd}{ni\_Ge^2}\right)$ $Vbi = 0.267562$ V

(8.39) $\tau 0 := 0.5 \cdot (\tau p0 + \tau n0)$ $\tau 0 = 5 \times 10^{-8}$ s

$\boxed{V_R = 0}$

$\boxed{VR0 := 0}$

(7.34) $W0 := \sqrt{\frac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi + VR0)}{qe} \cdot \left(\frac{Na + Nd}{Na \cdot Nd}\right)}$ $W0 = 4.86398 \times 10^{-7}$ m

(8.42) $Jgen0 := \frac{qe \cdot ni\_Ge \cdot W0}{2 \cdot \tau 0}$ $\boxed{Jgen0 = 18.7031}$ $A/m^2$

(8.43) total reverse-biased current density $JR0 := Js + Jgen0$ $\boxed{JR0 = 37.7909}$ $A/m^2$

$\frac{Js}{Jgen0} = 1.021$

$J_R$ percentage due to Js $\frac{Js}{JR0} \cdot 100 = 50.509$ %

$J_R$ percentage due to Jgen $\frac{Jgen0}{JR0} \cdot 100 = 49.491$ %

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

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

$\boxed{VR1 := 1}$ V

(7.34) $W1 := \sqrt{\dfrac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi + VR1)}{qe} \cdot \left(\dfrac{Na + Nd}{Na \cdot Nd}\right)}$ $W1 = 1.05868 \times 10^{-6}$ m

(8.42) $Jgen1 := \dfrac{qe \cdot ni\_Ge \cdot W1}{2 \cdot \tau 0}$ $\boxed{Jgen1 = 40.7085}$ A/m$^2$

(8.43) $JR1 := Js + Jgen1$ $\boxed{JR1 = 59.7964}$ A/m$^2$

$\dfrac{Js}{Jgen1} = 0.469$ $J_R$ percentage due to Js $\dfrac{Js}{JR1} \cdot 100 = 31.921$ %

$J_R$ percentage due to Jgen $\dfrac{Jgen1}{JR1} \cdot 100 = 68.079$ %

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

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

$\boxed{VR2 := 2}$ V

(7.34) $W2 := \sqrt{\dfrac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi + VR2)}{qe} \cdot \left(\dfrac{Na + Nd}{Na \cdot Nd}\right)}$ $W2 = 1.41599 \times 10^{-6}$ m

(8.42) $Jgen2 := \dfrac{qe \cdot ni\_Ge \cdot W2}{2 \cdot \tau 0}$ $\boxed{Jgen2 = 54.4478}$ A/m$^2$

(8.43) $JR2 := Js + Jgen2$ $\boxed{JR2 = 73.5356}$ A/m$^2$

$\dfrac{Js}{Jgen2} = 0.351$ $J_R$ percentage due to Js $\dfrac{Js}{JR2} \cdot 100 = 25.957$ %

$J_R$ percentage due to Jgen $\dfrac{Jgen2}{JR2} \cdot 100 = 74.043$ %

➢ **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 deletion layer, i.e., $n \neq 0$ & $p \neq 0$.

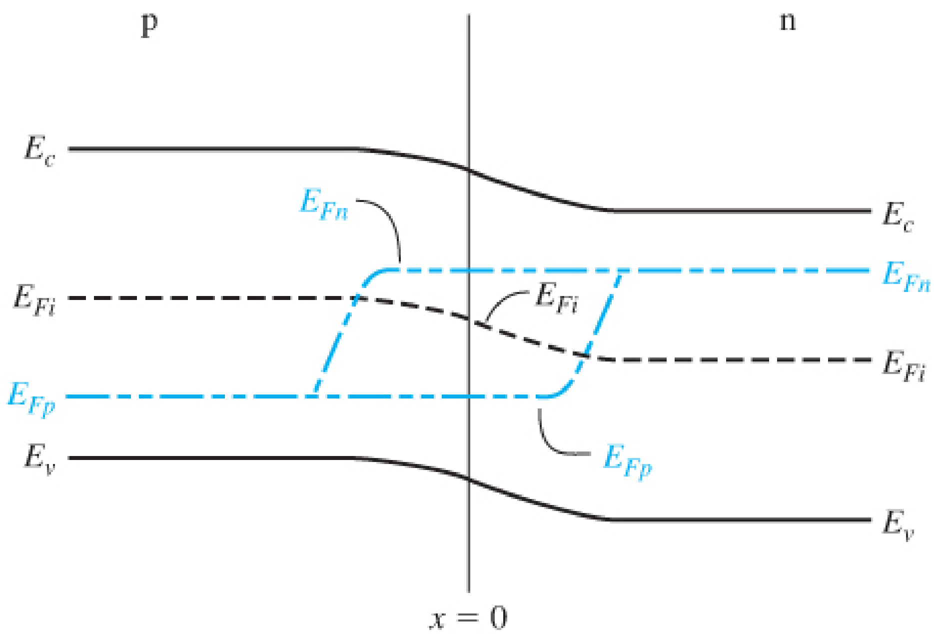


**Figure 8.13** | Energy-band diagram of a forward-biased pn junction including quasi-Fermi levels.

- Using Chapter 6 results, we can get $n = n_i\, e^{(E_{Fn}-E_{Fi})/k_BT}$ and $p = n_i\, e^{(E_{Fi}-E_{Fp})/k_BT}$.

- 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.

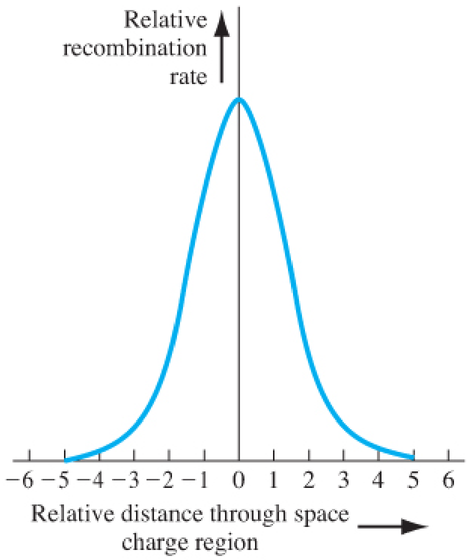


**Figure 8.14** | Relative magnitude of the recombination rate through the space charge region of a forward-biased pn junction.

➢ The maximum recombination rate $R_{\text{max}}$ 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 $n = p = n_i \, e^{eV_a/2k_BT}$. Then, letting $\tau_{p0} = \tau_{n0} = \tau_0$ at the center of the depletion layer, we find

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

➢ This can be further simplified by assuming $V_a >> V_t = k_BT/e$ which makes the exponential terms in (8.51) much bigger than 1, i.e., we can neglect the -1 & +1 terms. This leads to $R_{\text{max}} \simeq \frac{n_i}{2\tau_0} e^{eV_a/2k_BT}$ ( 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 $R = R_{\text{max}}$, yielding

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

## 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 $p_n = p_{n0}e^{eV_a/k_BT}$ 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 $J_{\text{rec}}$.

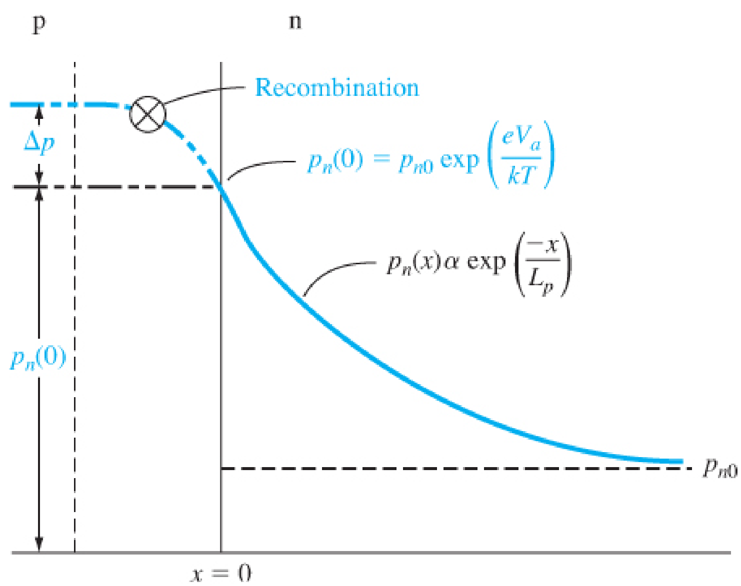


**Figure 8.15** | Because of recombination, additional holes from the p region must be injected into the space charge region to establish the minority carrier hole concentration in the n region.

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

$$\boxed{J = J_{\text{rec}} + J_D = \frac{e\,n_i W}{2\tau_0} e^{eV_a/2k_BT} + J_s\left[e^{eV_a/k_BT} - 1\right] \simeq J_{r0}\,e^{eV_a/2k_BT} + J_s\,e^{eV_a/k_BT}} \quad (8.56)$$

or

$$\boxed{J \simeq J_{r0}\,e^{V_a/2V_t} + J_s\,e^{V_a/V_t}}$$

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

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

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

$$\boxed{\ln(J_{\text{rec}}) = \ln(J_{r0}) + \frac{eV_a}{2k_BT} = \frac{1}{2V_t}V_a + \ln(J_{r0})} \text{ and}$$

$$\boxed{\ln(J_D) \simeq \ln(J_s) + \frac{eV_a}{k_BT} = \frac{1}{V_t}V_a + \ln(J_s)}.$$

These are linear equations!

- Figure 8.15 shows that for small values of the forward bias voltage $V_a << V_{bi}$, i.e., when it is near $V_t$, the recombination current dominates.
- For larger values of the forward bias voltage $V_t << V_a < V_{bi}$, 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.]

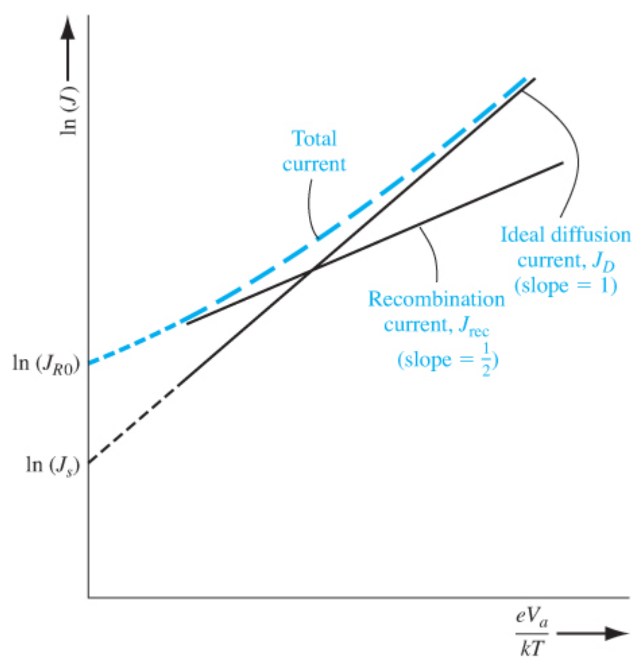


**Figure 8.16** | Ideal diffusion, recombination, and total current in a forward-biased pn junction.

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

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

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 $N_a = 6 \times 10^{15}$ cm$^{-3}$ (p region) & $N_d = 3 \times 10^{15}$ cm$^{-3}$ (n region). The carrier lifetimes are $\tau_{p0} = 2\times10^{-8}$ s & $\tau_{n0} = 2\times10^{-8}$ s. Find $J_s$ and $J_{r,0}$. Then, calculate $J_D$, $J_{rec}$, and $J$ as $V_a$ varies.

From earlier examples-

**Figure 5.3** $\mu p := 1600$ cm$^2$/V-s $\mu n := 3400$ cm$^2$/V-s

**Table B.4** $\varepsilon r\_Ge := 16$ $ni\_Ge := 2.4 \cdot 10^{19}$ m$^{-3}$

(5.47) Einstein relation $Dp := \mu p \cdot \frac{kB \cdot T}{qe}$ $Dn := \mu n \cdot \frac{kB \cdot T}{qe}$

$Dp = 41.363$ cm$^2$/s $Dn = 87.897$ cm$^2$/s

**Calculate diffusion lengths in meters**

$Ln := \frac{\sqrt{Dn \cdot \tau n0}}{100}$ $\boxed{Ln = 2.651744 \times 10^{-5}}$ m

$Lp := \frac{\sqrt{Dp \cdot \tau p0}}{100}$ $\boxed{Lp = 9.095405 \times 10^{-6}}$ m

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

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

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

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

**(8.26)** $Js := \frac{qe \cdot Dp \cdot 10^{-4} \cdot pn0}{Lp} + \frac{qe \cdot Dn \cdot 10^{-4} \cdot np0}{Ln}$ $\boxed{Js = 19.0878}$ A/m$^2$

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

(7.10) $Vt := \dfrac{kB \cdot T}{qe}$ $Vt = 0.025852$ V

$Vbi := Vt \cdot \ln\left(\dfrac{Na \cdot Nd}{ni\_Ge^2}\right)$ $Vbi = 0.267562$ V

(8.39) $\tau 0 := 0.5 \cdot (\tau p0 + \tau n0)$ $\tau 0 = 5 \times 10^{-8}$ s

$\boxed{V_a = 0}$

$\boxed{Va0 := 0}$

(7.34) $W0 := \sqrt{\dfrac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi - Va0)}{qe} \cdot \left(\dfrac{Na + Nd}{Na \cdot Nd}\right)}$ $W0 = 4.86398 \times 10^{-7}$ m

(8.55) $Jr0\_0 := \dfrac{qe \cdot W0 \cdot ni\_Ge}{2 \cdot \tau 0}$ $\boxed{Jr0\_0 = 18.7031}$ A/m$^2$

Roughly same size as $J_s$=19.07 A/m$^2$.

$Jrec\_0 := Jr0\_0 \cdot e^{\frac{Va0}{2 \cdot Vt}}$ $\boxed{Jrec\_0 = 18.703}$ A/m$^2$

$JD\_0 := Js \cdot \left(e^{\frac{Va0}{Vt}} - 1\right)$ $\boxed{JD\_0 = 0}$

(8.56) total forward-biased current density $J\_0 := JD\_0 + Jrec\_0$ $\boxed{J\_0 = 18.703}$ A/m$^2$

$\dfrac{Jrec\_0}{J\_0} = 1$ 100% due to $J_{rec}$

## $\boxed{V_a = V_t}$

$\boxed{VaVt := Vt}$ $VaVt = 0.02585$ V

$$WVt := \sqrt{\frac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi - VaVt)}{qe} \cdot \left(\frac{Na + Nd}{Na \cdot Nd}\right)}$$ $WVt = 4.62303 \times 10^{-7}$ m

$$Jr0\_Vt := \frac{qe \cdot WVt \cdot ni\_Ge}{2 \cdot \tau 0}$$ $\boxed{Jr0\_Vt = 17.7766}$ A/m$^2$

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

$$Jrec\_Vt := Jr0\_Vt \cdot e^{\frac{VaVt}{2 \cdot Vt}}$$ $\boxed{Jrec\_Vt = 29.309}$ A/m$^2$

$$JD\_Vt := Js \cdot \left(e^{\frac{VaVt}{Vt}} - 1\right)$$ $\boxed{JD\_Vt = 32.798}$ A/m$^2$

$J\_Vt := JD\_Vt + Jrec\_Vt$ $\boxed{J\_Vt = 62.1069}$ A/m$^2$

$$\frac{Jrec\_Vt}{J\_Vt} = 0.472$$ ~47.2% due to $J_{rec}$

## $\boxed{V_a = 4V_t}$

$\boxed{Va4Vt := 4Vt}$ $Va4Vt = 0.10341$ V

$$W4Vt := \sqrt{\frac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi - Va4Vt)}{qe} \cdot \left(\frac{Na + Nd}{Na \cdot Nd}\right)}$$ $W4Vt = 3.80983 \times 10^{-7}$ m

$$Jr0\_4Vt := \frac{qe \cdot W4Vt \cdot ni\_Ge}{2 \cdot \tau 0}$$ $\boxed{Jr0\_4Vt = 14.6496}$ A/m$^2$

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

$$Jrec\_4Vt := Jr0\_4Vt \cdot e^{\frac{Va4Vt}{2 \cdot Vt}}$$ $\boxed{Jrec\_4Vt = 108.247}$ A/m$^2$

$$JD\_4Vt := Js \cdot \left(e^{\frac{Va4Vt}{Vt}} - 1\right)$$ $\boxed{JD\_4Vt = 1023.072}$ A/m$^2$

$J\_4Vt := JD\_4Vt + Jrec\_4Vt$ $\boxed{J\_4Vt = 1131.319}$ A/m$^2$

$$\frac{Jrec\_4Vt}{J\_4Vt} = 0.096$$ ~9.6% due to $J_{rec}$

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

$\boxed{Va8Vt := 8Vt}$ $\quad Va8Vt = 0.20682 \quad$ V

$$W8Vt := \sqrt{\frac{2 \cdot \varepsilon r\_Ge \cdot \varepsilon 0 \cdot (Vbi - Va8Vt)}{qe} \cdot \left(\frac{Na + Nd}{Na \cdot Nd}\right)} \qquad W8Vt = 2.3176 \times 10^{-7} \text{ m}$$

$$Jr0\_8Vt := \frac{qe \cdot W8Vt \cdot ni\_Ge}{2 \cdot \tau 0} \qquad \boxed{Jr0\_8Vt = 8.9117} \text{ A/m}^2$$

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

$$Jrec\_8Vt := Jr0\_8Vt \cdot e^{\frac{Va8Vt}{2 \cdot Vt}} \qquad \boxed{Jrec\_8Vt = 486.563} \text{ A/m}^2$$

$$JD\_8Vt := Js \cdot \left(e^{\frac{Va8Vt}{Vt}} - 1\right) \qquad \boxed{JD\_8Vt = 56880.908} \text{ A/m}^2$$

$$J\_8Vt := JD\_8Vt + Jrec\_8Vt \qquad \boxed{J\_8Vt = 57367.471} \text{ A/m}^2$$

$$\frac{Jrec\_8Vt}{J\_8Vt} = 0.00848$$

~0.85% 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 $\delta n\,\delta p \simeq n_i^2 e^{V_a/V_t}$.
- Since $\delta n = \delta p$, this leads to $\delta n = \delta p \simeq n_i e^{V_a/2V_t}$ (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 $V_a$.

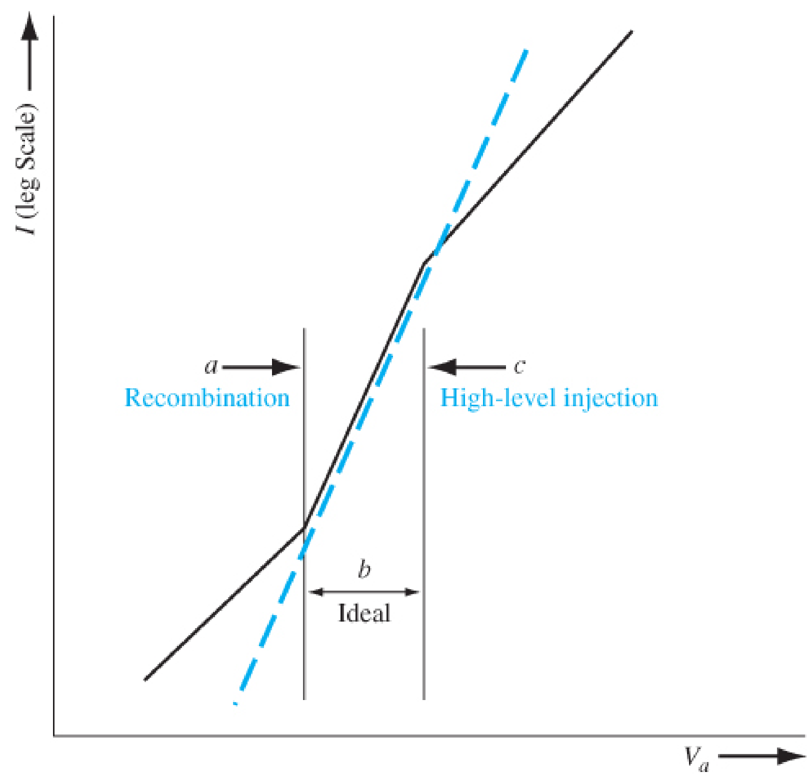


**Figure 8.17** | Forward-bias current versus voltage from low forward bias to high forward bias.

- Per (8.59) and (8.63), $I \propto e^{V_a/2V_t} \Rightarrow \ln(I) \propto \dfrac{1}{2V_t} V_a$ 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 $I \propto e^{V_a/V_t} \Rightarrow \ln(I) \propto \dfrac{1}{V_t} V_a$.