Chapter 6-3. Deviations from the ideal

Mostly qualitative understanding of non-ideal behavior of the diodes:

Reverse-bias breakdown

- Avalanching
- Zener process

The R-G current

If $V_A \rightarrow V_{bi}$, then high-current phenomena result

- Series current
- High-level injection

I-*V* Characteristic of commercial Si diode at 300K

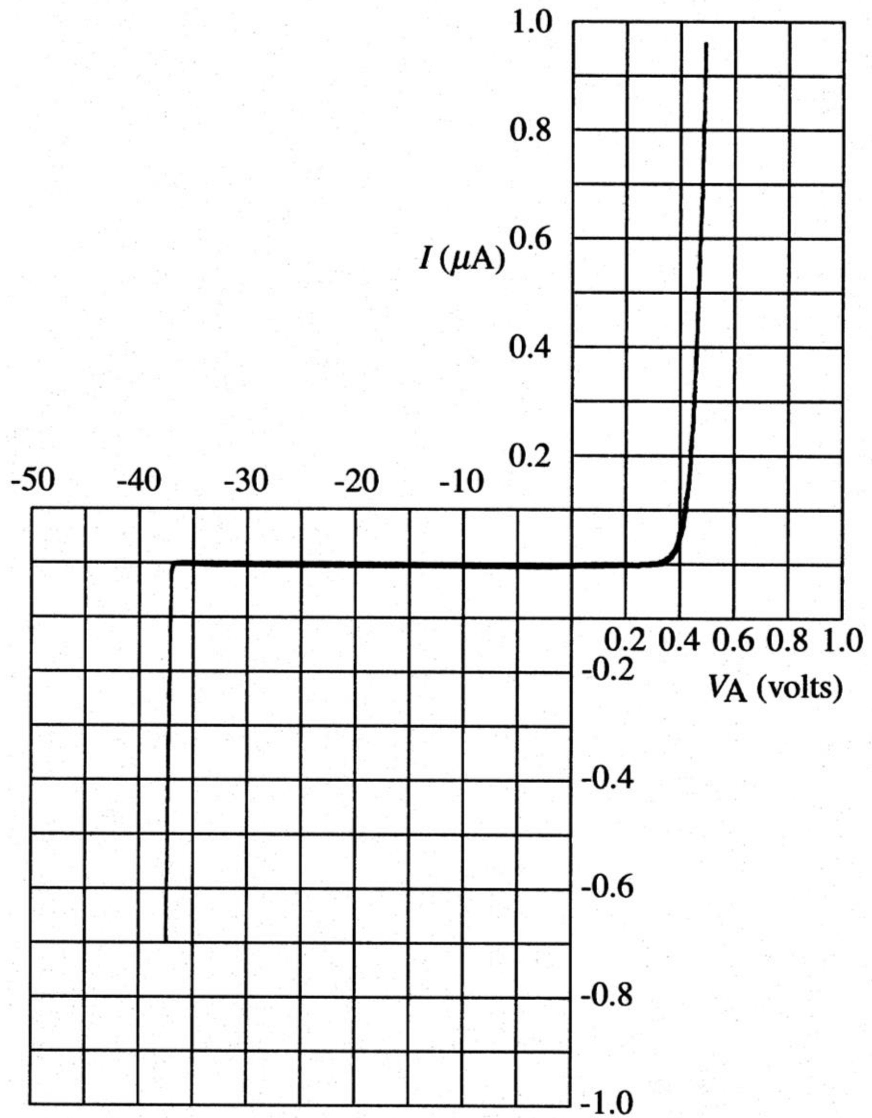
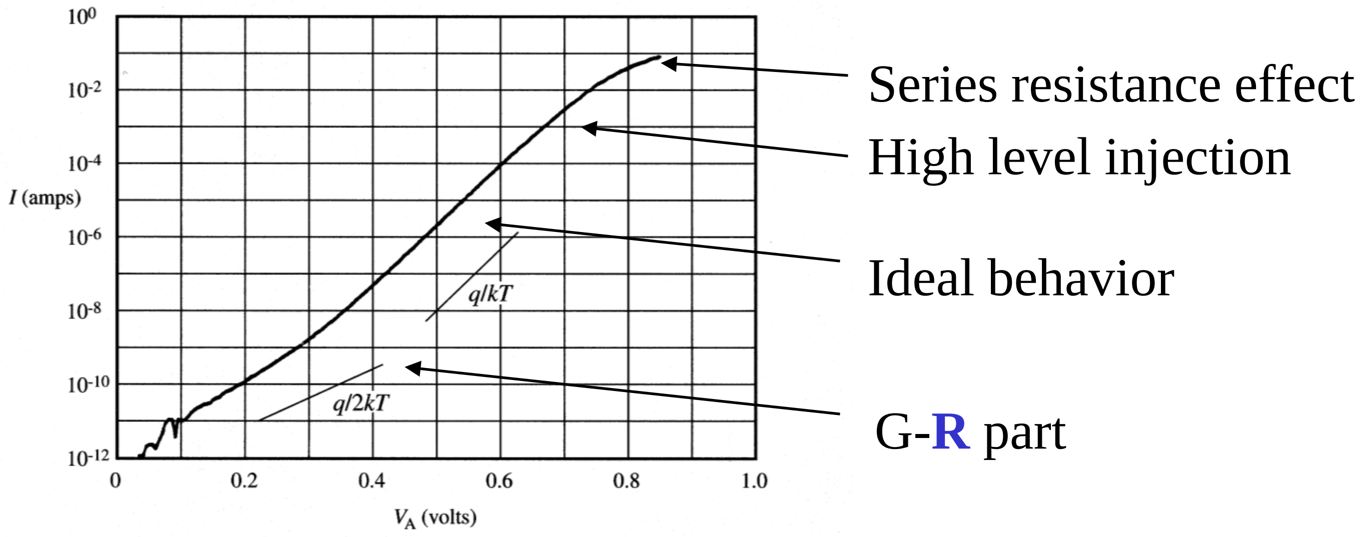


Figure 6.9

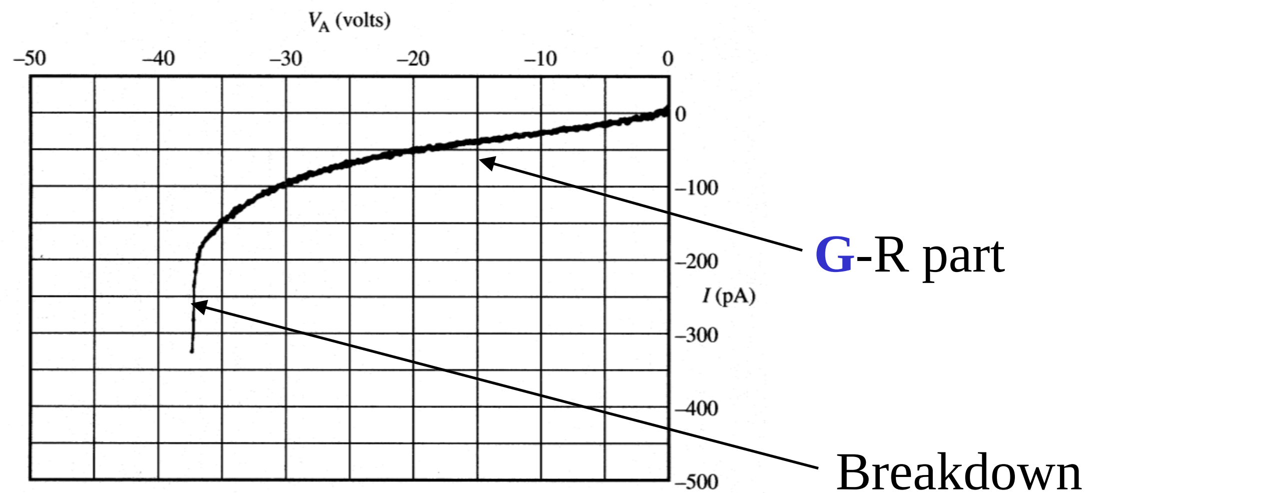
Detailed *I-V* plots of commercial Si diode at 300 K

Forward bias



(a)

Reverse bias



(b)

Figure 6.10

Reverse-bias breakdown

A large reverse current flows when the voltage exceeds certain value. Not destructive unless power dissipation causes excessive heating.

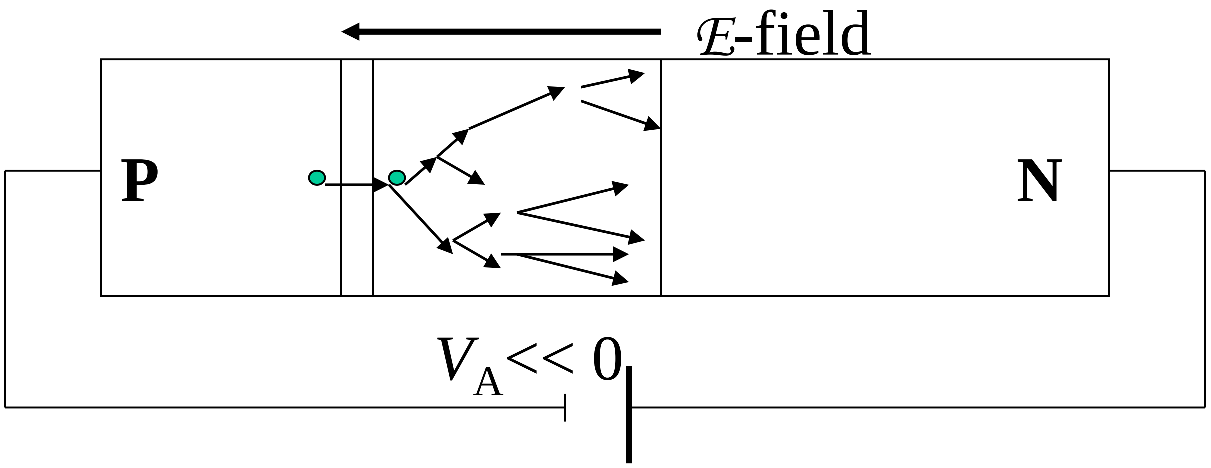
For a p^+n or pn^+ diode: $V_{BR} \propto N_B^{-1}$

where V_{BR} is the breakdown voltage and N_B is the (bulk) doping on the lightly doped side.

Two processes:
Avalanching: Dominant process in lightly doped diodes
Zener process: More important in heavily doped diodes

Avalanching

Carrier multiplication due to **impact ionization** occurs at high reverse voltage, when the electric field reaches a **critical** value, $\mathcal{E}_{CR}$. These additional carriers are swept across the depletion layer due the high electric field.



The increase in current associated with the carrier multiplication is modeled by introducing a multiplication factor, M $(= I / I_0)$ and the multiplication factor can be empirically fit to an equation

$$M = \frac{1}{1 - \left[\frac{|V_A|}{V_{BR}}\right]^m}$$

where m is between 3 and 6.

Carrier activity within a reversed-biased diode

Carrier multiplication due to impact ionization

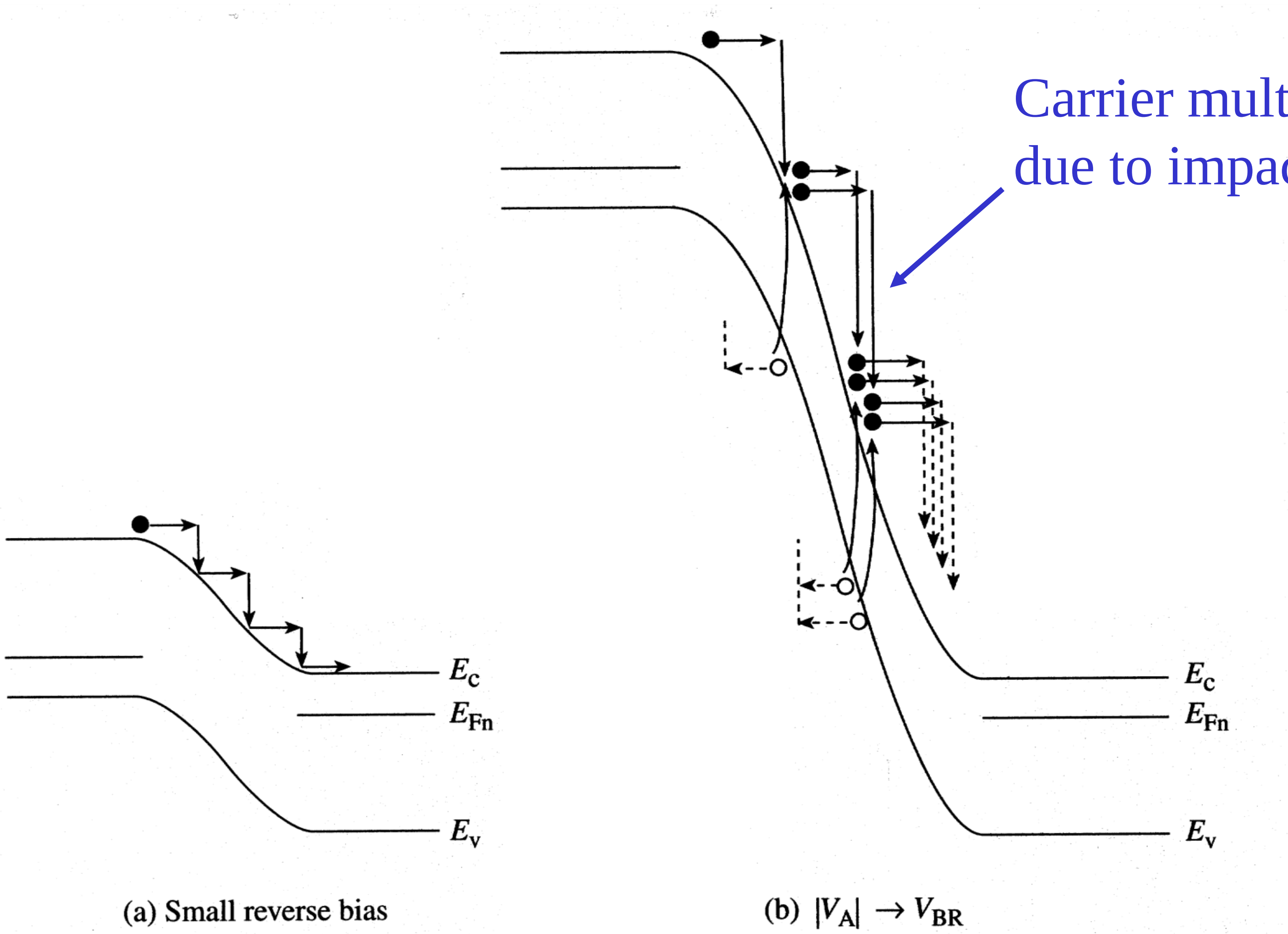
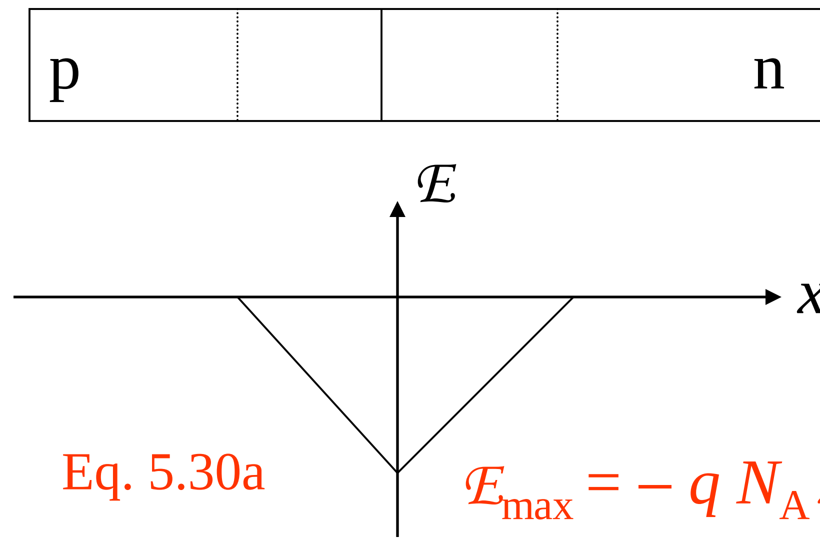


Figure 6.12

Avalanching

$$\mathcal{E}(x=0) = -\frac{qN_D}{\varepsilon_{Si}} x_n$$

$$= -\left[\frac{2q}{\varepsilon_{Si}}\left(\frac{N_A N_D}{N_A + N_D}\right)(V_{bi} - V_A)\right]^{\frac{1}{2}}$$



Eq. 5.30a

$\mathcal{E}_{max} = -\,q\,N_A\,x_p/\varepsilon$
$= -\,q\,N_D\,x_n/\varepsilon$

Breakdown occurs when $\mathcal{E}(0) = \mathcal{E}_{CR}$; and when $(V_{bi} - V_A) \rightarrow (V_{bi} - V_{BR}) \approx V_{BR}$

$$\mathcal{E}_{CR} = \left[\frac{2q}{\varepsilon_{Si}}\left(\frac{N_A N_D}{N_A + N_D}\right)V_{BR}\right]^{1/2} \quad \text{or} \quad V_{BR} \propto \frac{N_A + N_D}{N_A N_D}$$

For asymmetrically doped junctions:

(where N_B is the (bulk) doping on lightly doped side)

$$\boxed{V_{BR} \propto \frac{1}{N_B}}$$

Zener process

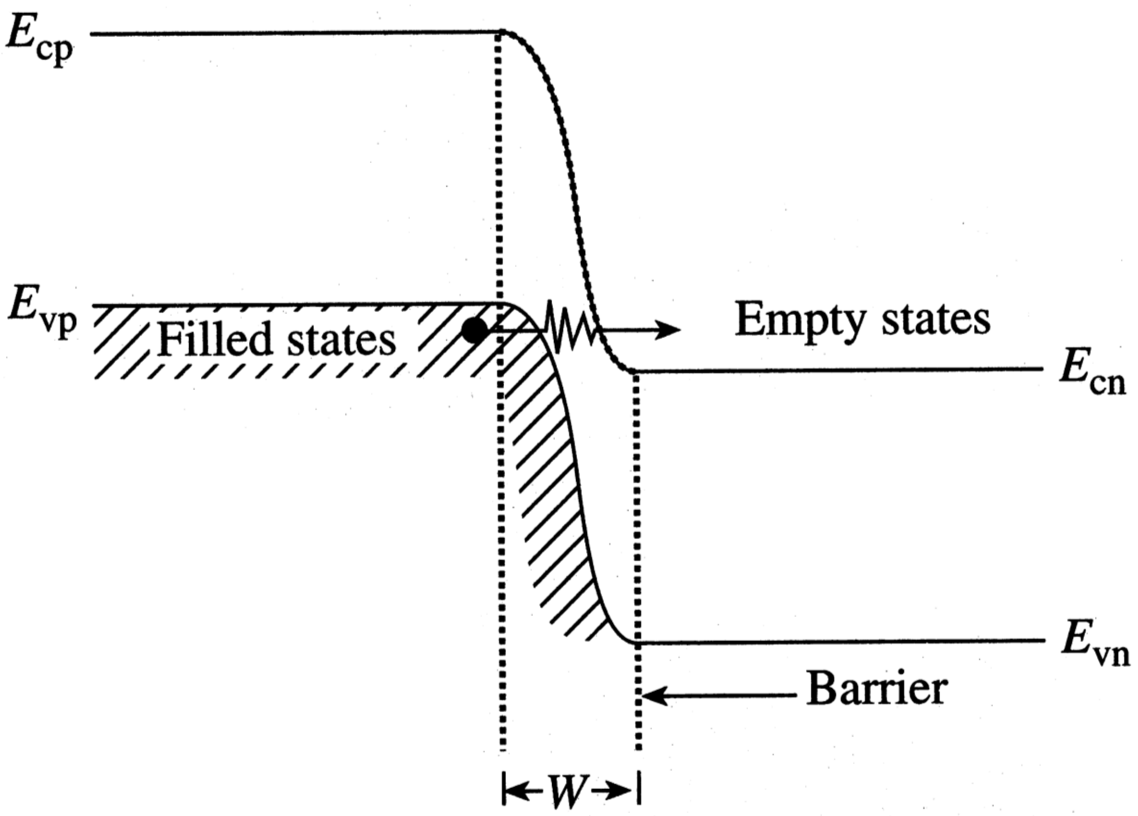


Figure 6.14

Tunneling in a reverse biased diode - occurs in heavily doped diodes

The R-G current: reverse-bias case

In an ideal diode, the reverse current is $I_0 = qA\,[D_p\, p_n/L_p + D_n\, n_p/L_n]$ and this current is a constant. The ideal diode equation was derived assuming no generation of carriers in the depletion layer. In an actual device, the thermal generation of carriers in the depletion layer should be taken into consideration.

The current due to thermal generation ($I_{R\text{-}G}$) increases with the volume of the depletion layer (or W).

Volume (or W) increases with the applied reverse bias. So, $I_{R\text{-}G}$ increases as reverse voltage is increased.

Detailed analysis shows that $I_{R\text{-}G}$ for reverse bias can be written as:

$$I_{R\text{-}G} = -\frac{qAn_i}{2\tau_0}W \qquad \text{where } \tau_0 = f(\tau_p + \tau_n) \approx (\tau_p + \tau_n)/2$$

The R-G current: forward-bias case

Under forward bias, some of the injected carriers may recombine while crossing the depletion layer. This was neglected in the analysis of "ideal" diode. Detailed analysis shows that:

$$I_{\text{R-G}} = I_0{}' \left(e^{\frac{qV_A}{2kT}} - 1 \right)$$

... in the forward bias case.

Total forward current: $I = I_{\text{diff}} + I_{\text{R-G}}$ where I_{diff} is the current (called diffusion current) described by the "ideal" diode equation.

$$I_{\text{diff}} = I_0 \left(e^{\frac{qV_A}{kT}} - 1 \right) \quad \text{where} \quad I_0 = qA \left(\frac{D_n}{L_n} \frac{n_i^2}{N_A} + \frac{D_p}{L_p} \frac{n_i^2}{N_D} \right)$$

I_{diff} increases more more rapidly with bias compared to $I_{\text{R-G}}$. So, I_{diff} dominates at higher forward voltage.

Relative values of $I_{R\text{-}G}$ and I_{diff}

In Si, $q A n_i W / 2\tau >> I_0$ and $I_{R\text{-}G}$ current dominates at reverse bias and at small forward bias. Since $I_{R\text{-}G} \propto W$, the reverse current never saturates, but continually increases with reverse bias.

Since $I_{diff} \propto n_i^2$ and $I_{R\text{-}G} \propto n_i$, the relative values of I_{diff} and $I_{R\text{-}G}$ varies from semiconductor to semiconductor. In Si and GaAs at 300 K, $q A n_i W / (2\tau) >> I_0$ whereas in Ge, $I_0 >> q A n_i W / (2\tau)$. So, Ge more closely follows ideal diode equation,
$I = I_0 [\exp (qV_A/kT) - 1]$ at 300K.

Since $I_{diff} \propto n_i^2$ and $I_{R\text{-}G} \propto n_i$, I_{diff} increases at a faster rate with increasing temperature. So, even Si follows the ideal diode equation, $I = I_0 [\exp (q V_A /kT) - 1]$ at higher temperature.

$V_A \to V_{bi}$ high-current phenomena

As V_A approaches V_{bi}, a large current flows. Two phenomena become important: series resistance effect and high-level injection.

Series resistance effect:

Some voltage drops in the "quasi-neutral" and ohmic-contact region reducing the actual voltage drop across the junction.

$$I = I_0 \left(e^{\frac{qV_j}{kT}} - 1 \right) \approx I_0\, e^{\frac{qV_j}{kT}} = I_0\, e^{\frac{q(V_A - IR_s)}{kT}} \quad \text{when} \quad V_A \to V_{bi}$$

Here, V_j is the actual voltage across the junction, and V_A is the applied voltage. Some of the applied voltage is wasted, so that larger applied voltage is necessary to achieve the same level of current compared to the ideal.

Identification and determination of diode series resistance

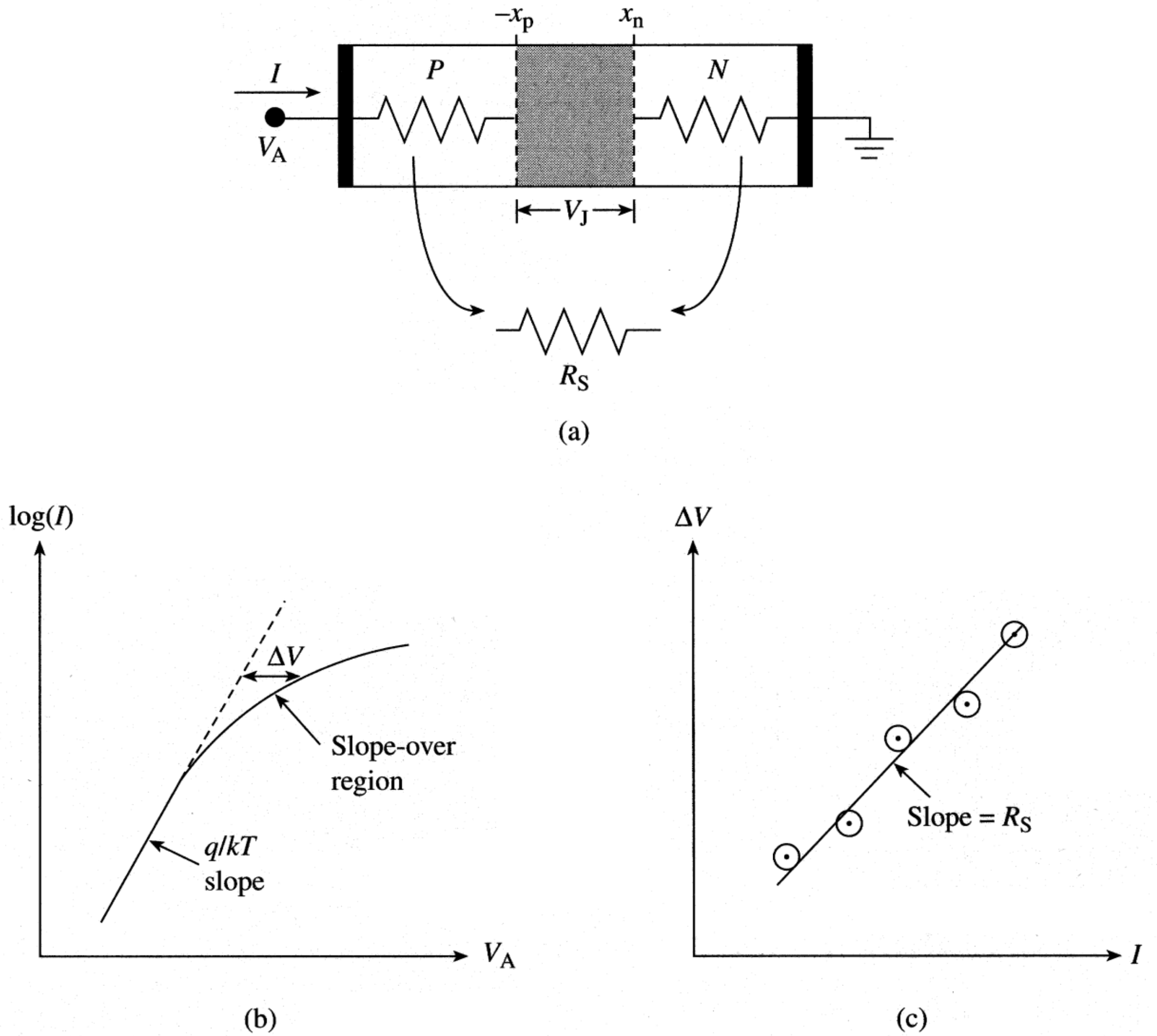


Figure 6.16

High level injection

When the forward voltage is within a few tenths of a volt below V_{bi} , high current flows, and the low-level injection assumption begins to fail. High level injection phenomena should be considered in deriving *I*-*V* characteristics. More detailed analysis shows that the current increases roughly as exp $[q V_A / (2kT)]$ when $V_A \rightarrow V_{bi}$

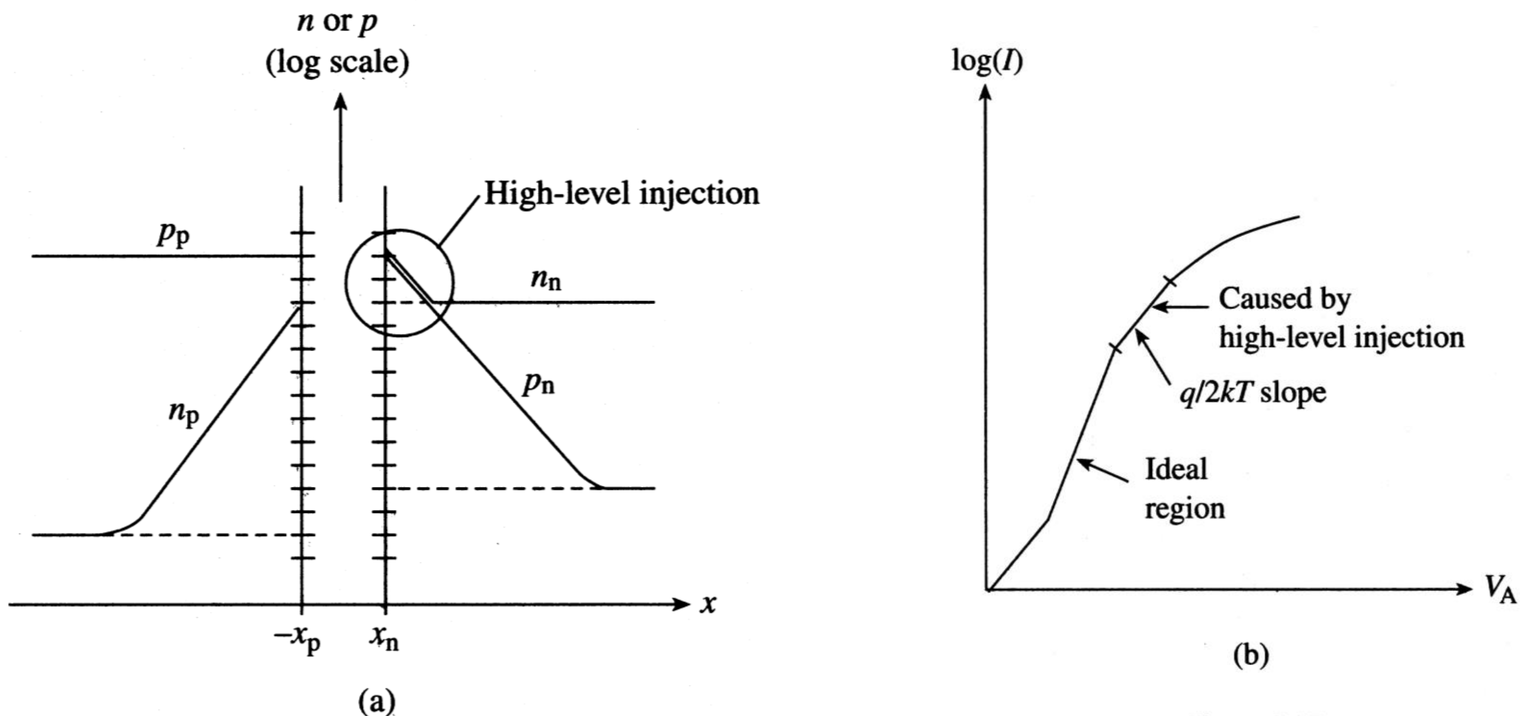
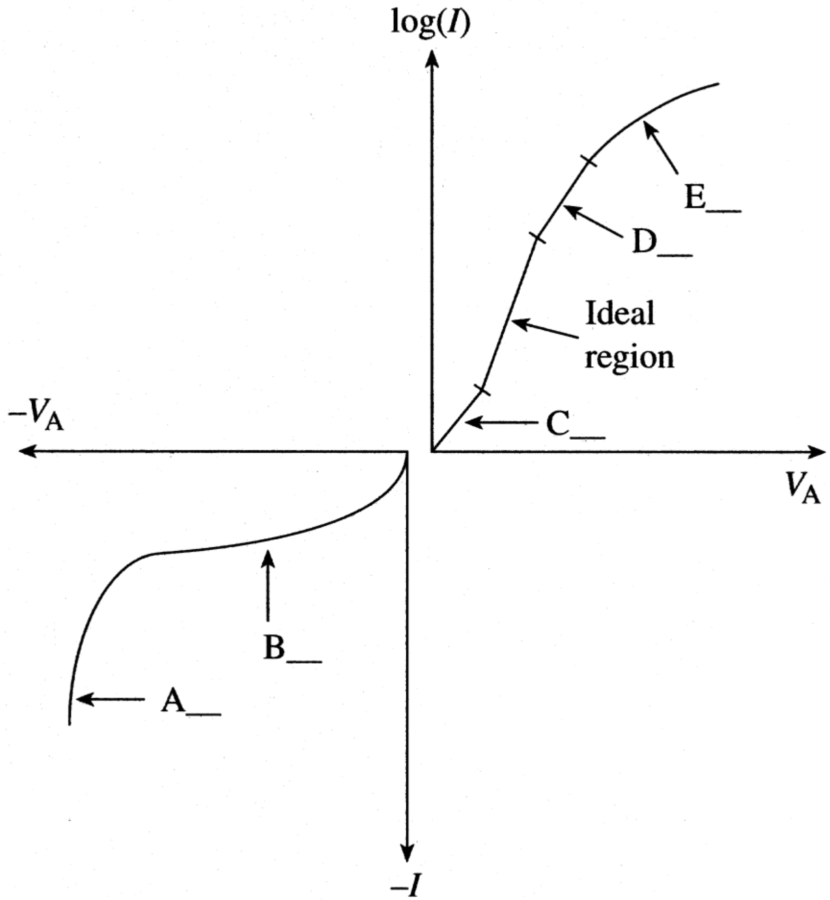


Figure 6.17

Review



1. Photogeneration
2. Thermal recombination in the depletion region
3. Avalanching and/or Zener process
4. Low-level injection
5. Depletion approximation
6. Thermal generation in the depletion region
7. Band bending
8. Series resistance
9. $V_A > V_{bi}$
10. High-level injection

S: A3, B6, C2, D10, E8

Figure E6.9

Plot the *I*-*V* characteristics for an ideal diode in the same graph above