EE112 - Fall 2016
Analog Integrated Circuits I

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5210 Research Bldg.

pn Junction

- P-type semiconductor in contact with n-type
- Basic building blocks of semiconductor devices
  - » Diodes
  - » Bipolar junction transistors (BJT)
  - » Metal-oxide-semiconductor field effect transistors (MOSFET)

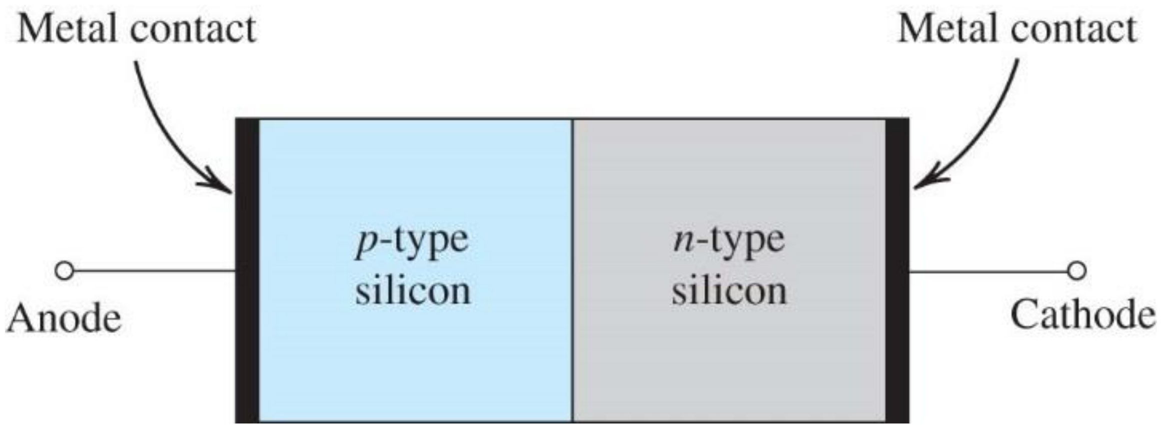

Figure 1.35 Simplified physical structure of the *pn* junction. (Actual geometries are given in Appendix A.) As the *pn* junction implements the junction diode, its terminals are labeled anode and cathode.

Built-in Voltage

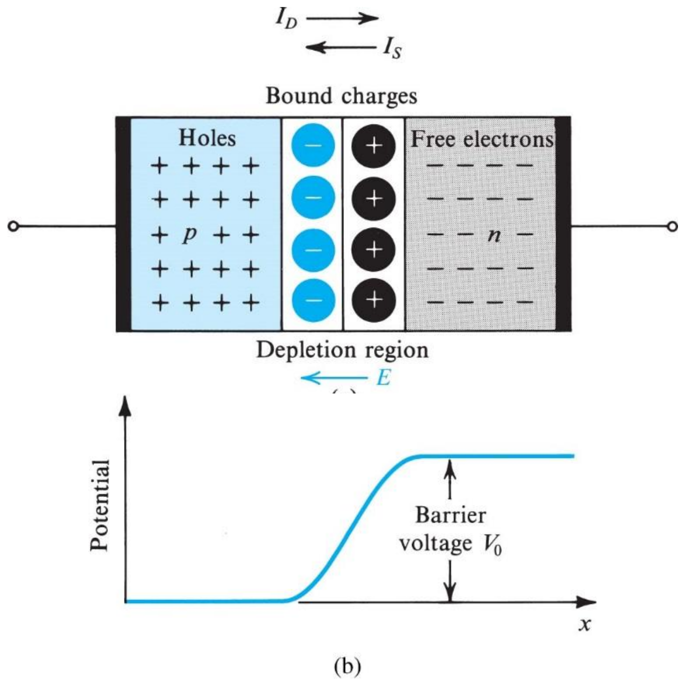

Figure 1.36 (a) The *pn* junction with no applied voltage (open-circuited terminals). **(b)** The potential distribution along an axis perpendicular to the junction.

Example:

- At pn junction, free electrons from n-side "recombine" with free holes from p-side.
- "Depletion region (耗尽区)" has no electrons or holes, but has fixed (immobile) charges from donor and acceptor ions
- The fixed charges establish an electric field, and create a potential difference between p and n-sides.

$$V_o = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

- This potential is called "built-in potential(内建电势)"
  - » V_T: thermal voltage (= 26 mV at room temp)
  - » N_A : acceptor concentration on p-side
  - » N_D : donor concentration on n-side
  - » n_i : intrinsic carrier concentration (=1.5×10^{10} cm^{-3} at room temp)

Electrostatic Analysis of pn Junction

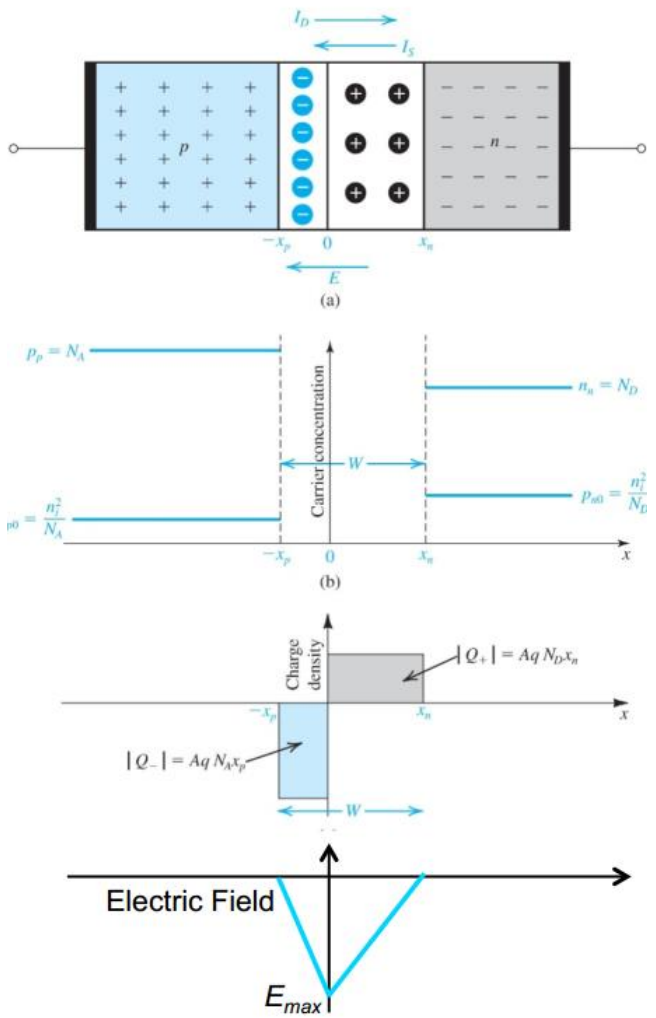

Figure 1.37 (a) A *pn* junction with the terminals open-circuited. **(b)** Carrier concentrations; note that $N_A > N_D$. **(c)** The charge stored in both sides of the depletion region; $Q_J = |Q_+| = |Q_-|$. **(d)** The electric field.

Gauss's Law: The net *electric flux* through any closed surface is equal to 1⁄ε times the net electric charge within that closed surface

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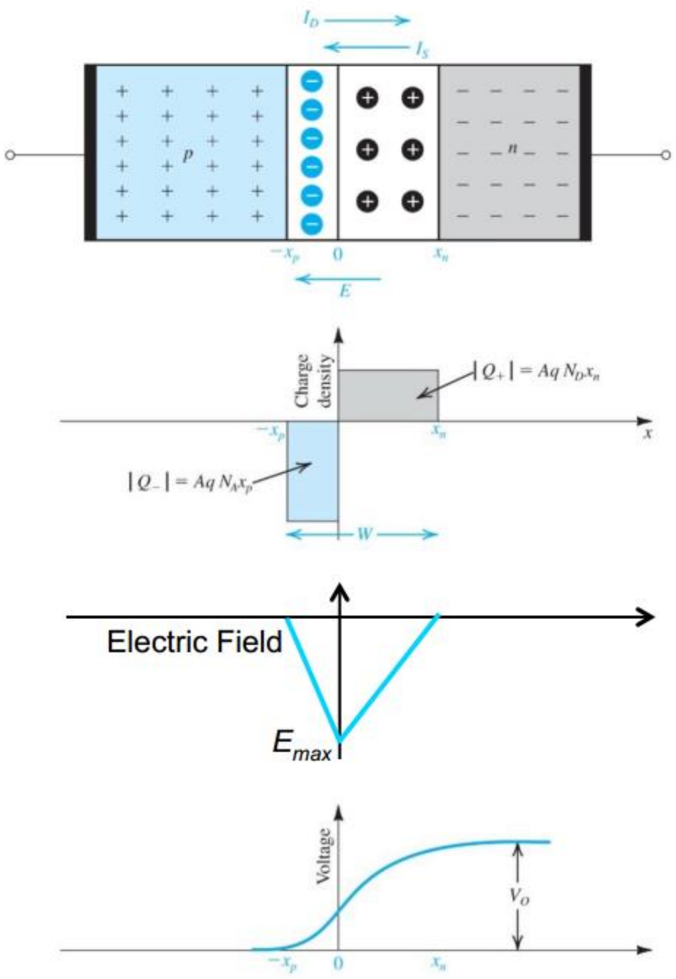
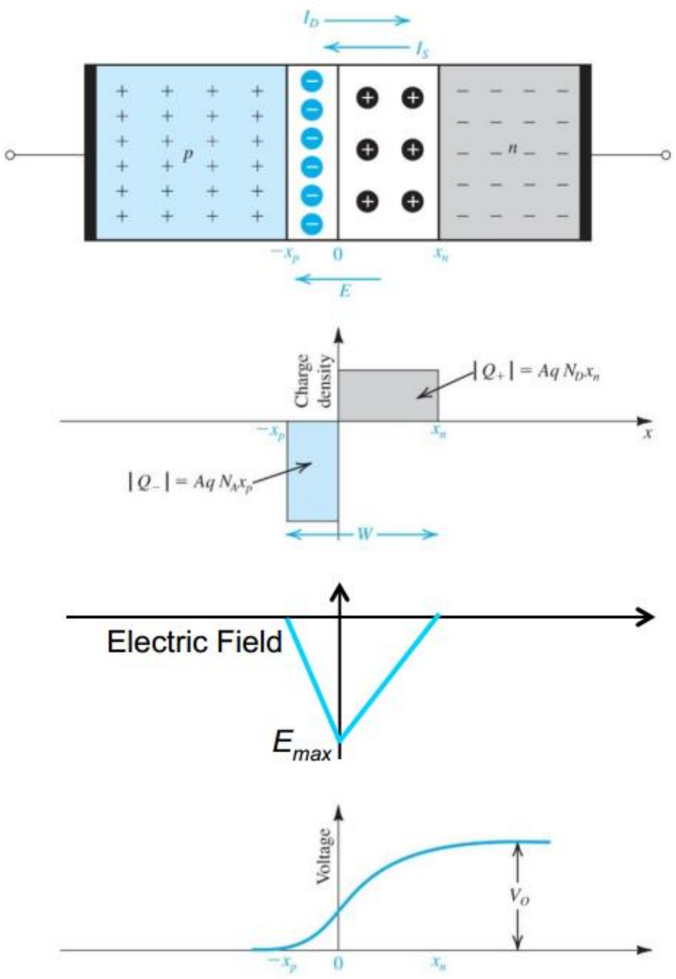


I_D
I_S
p
n
$-x_p$
0
x_n
E
Charge density
$|Q_+| = Aq N_D x_n$
$|Q_-| = Aq N_A x_p$
x
W
Electric Field
E_{max}
Voltage
V_O

Continued 2

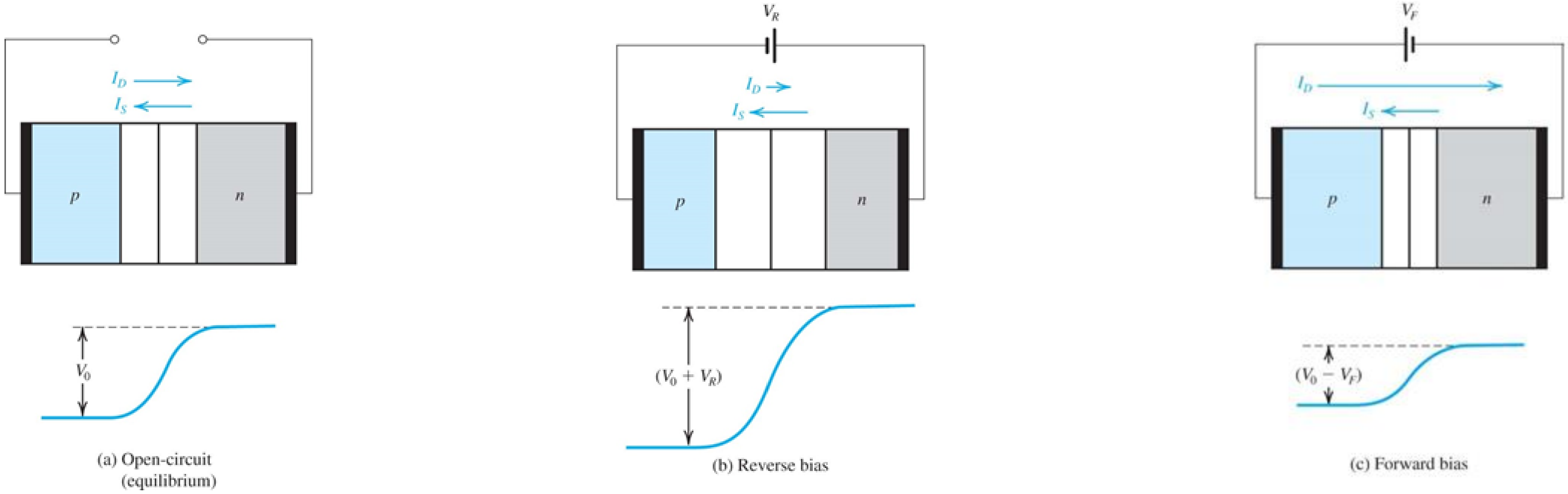


I_D
I_S
p
n
$-x_p$
0
x_n
E
Charge density
$|Q_+| = Aq N_D x_n$
$|Q_-| = Aq N_A x_p$
x
W
Electric Field
E_{max}
Voltage
V_o

Depletion Width Under Bias

$$W = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_o - V)}$$

V is the applied voltage to the pn junction,
it is positive for forward bias and negative for reverse bias.
Depletion width is widened in reverse bias



(a) equilibrium; **(b)** reverse bias; **(c)** forward bias

Figure 1.38 The *pn* junction in:

Current-Voltage (I-V) Characteristics

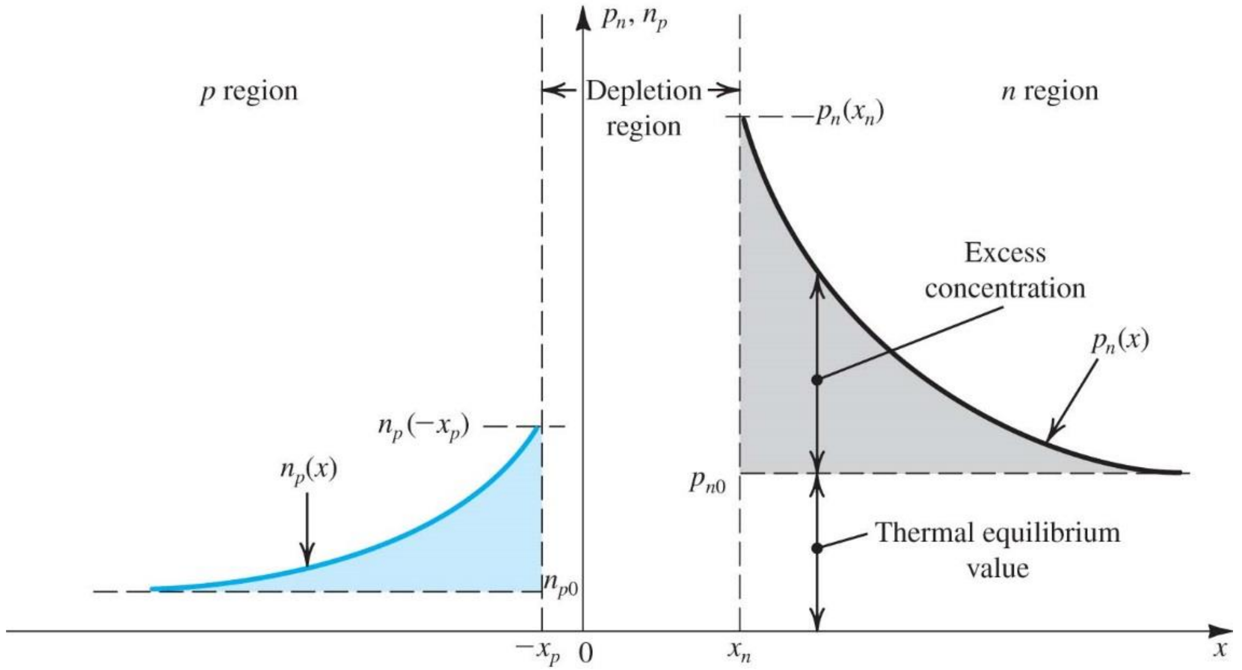


Figure 1.39 Minority-carrier distribution in a forward-biased pn junction. It is assumed that the p region is more heavily doped than the n region; $N_A >> N_D$

- Under forward bias, minority carriers at the edge of the depletion region is boosted up by

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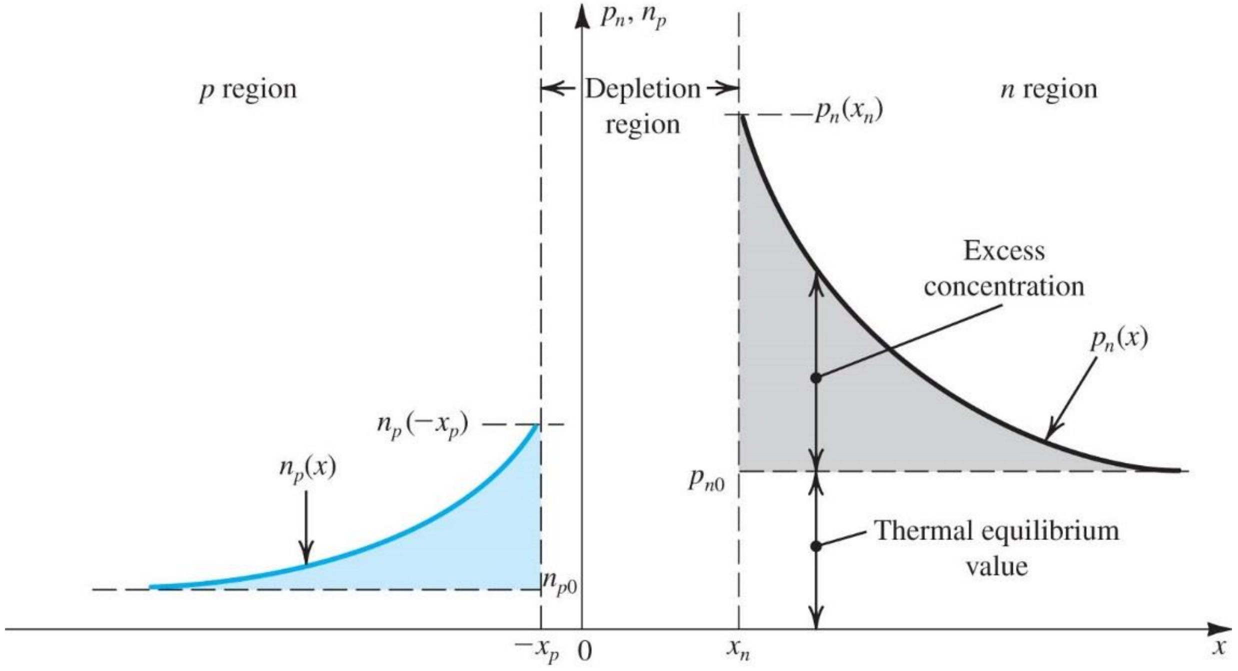

p_n, n_p
p region
Depletion region
n region
$p_n(x_n)$
Excess concentration
$p_n(x)$
$n_p(-x_p)$
$n_p(x)$
p_{n0}
Thermal equilibrium value
n_{p0}
$-x_p$
0
x_n
x

I-V Curve

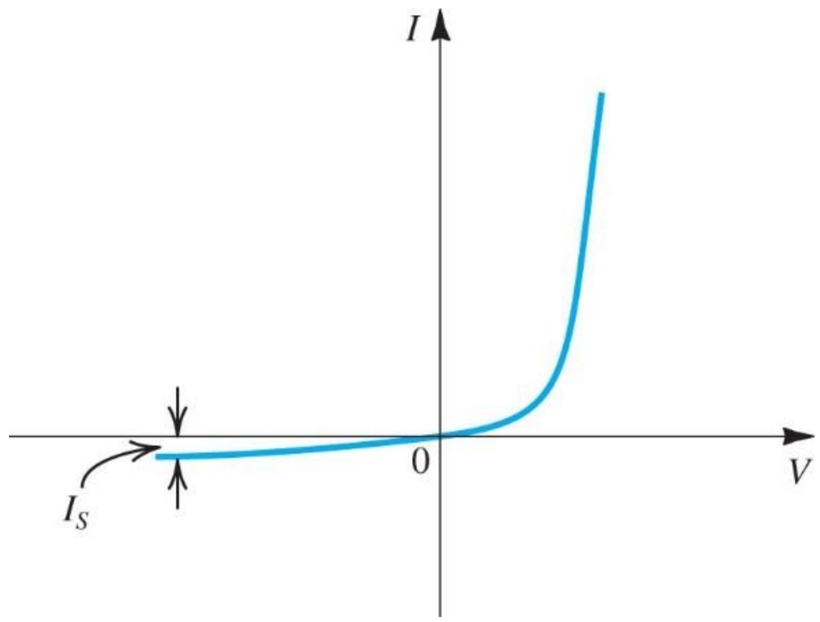

Figure 1.40 The *pn* junction *I–V* characteristic.

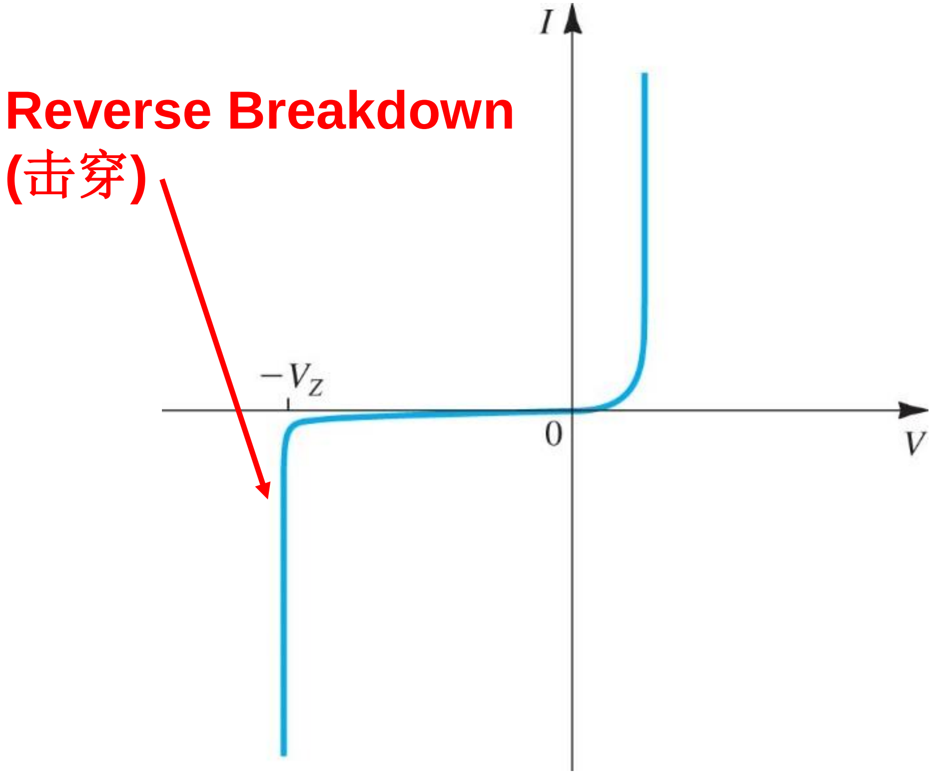

Figure 1.41 The *I–V* characteristic of the *pn* junction showing the rapid increase in reverse current in the breakdown region.

Depletion Capacitance (mainly reverse bias)

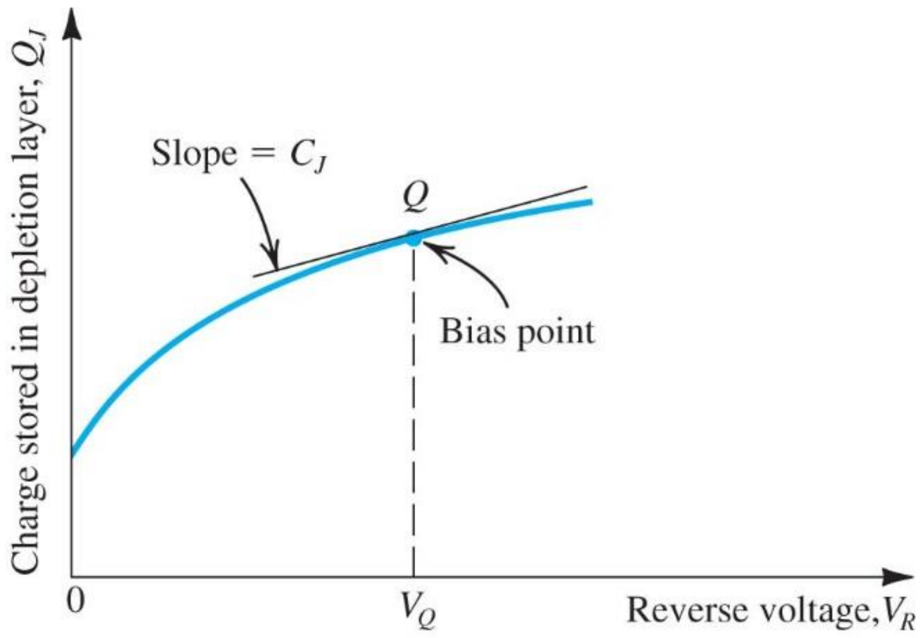

Figure 1.42 The charge stored on either side of the depletion layer as a function of the reverse voltage V_R.

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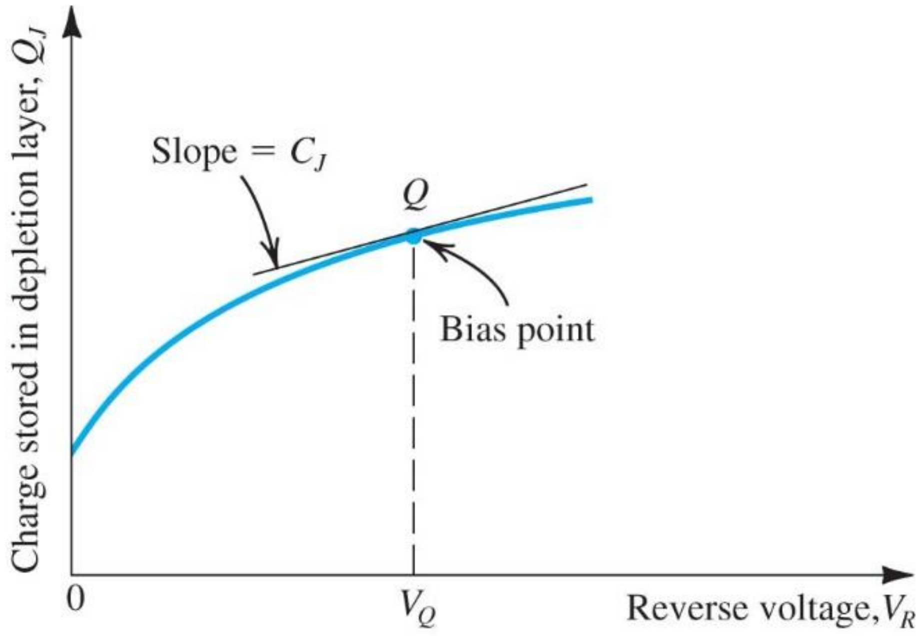
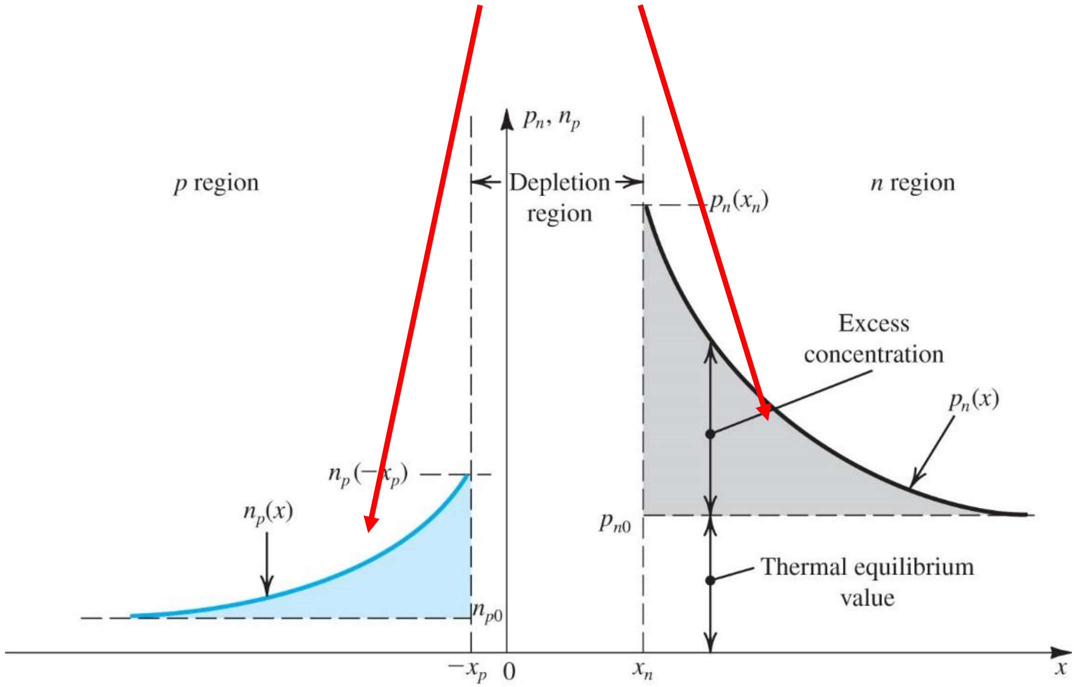


Charge stored in depletion layer, Q_J
Slope = C_J
Q
Bias point
0
V_Q
Reverse voltage, V_R

Diffusion Capacitance (forward bias)

Extra minority carriers stored outside junction under forward bias



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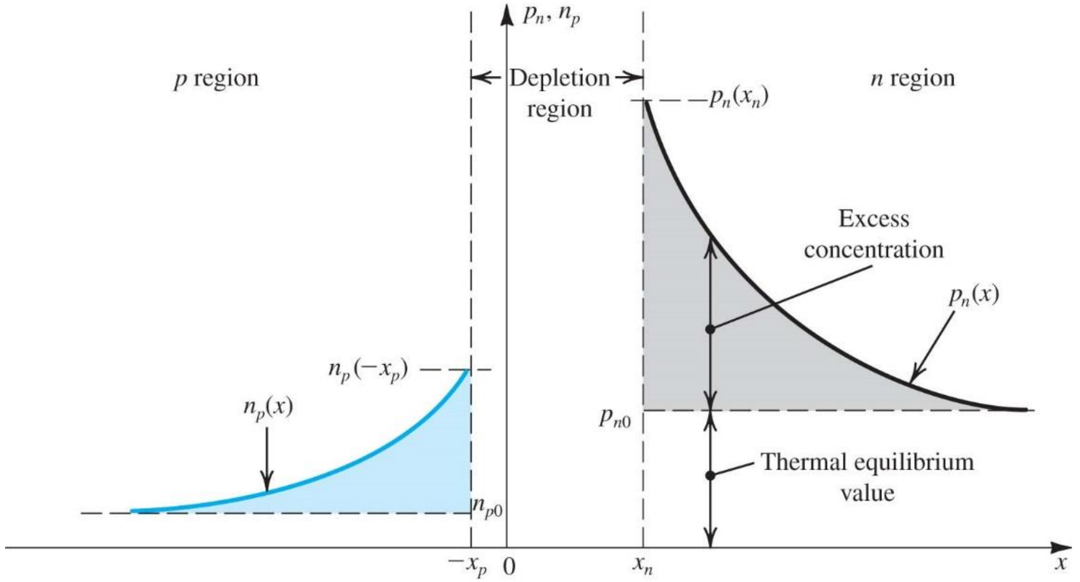
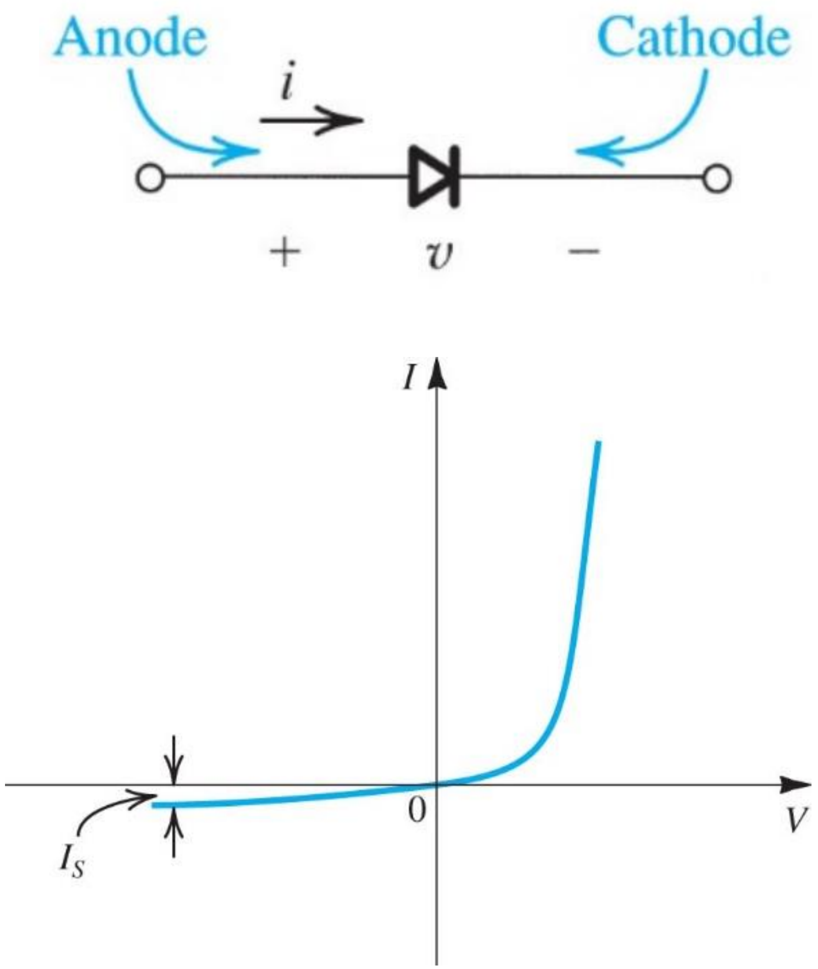


p_n, n_p
p region
Depletion region
n region
$p_n(x_n)$
Excess concentration
$p_n(x)$
$n_p(-x_p)$
$n_p(x)$
p_{n0}
Thermal equilibrium value
n_{p0}
$-x_p$
0
x_n
x

Summary of pn Junction



Built-in potential

<u>Forward bias</u>

- I-V curve
- Diffusion capacitance

<u>Reverse Bias</u>

- Negligible current
- Depletion capacitance

Other important parameter

- Depletion Width

Appendix: Derivation of pn Junction Potential

$$E(x)=\begin{cases}\dfrac{-qN_A(x+x_p)}{\varepsilon_S}, & -x_p<x<0\\[2ex] \dfrac{qN_D(x-x_n)}{\varepsilon_S}, & 0<x<x_n\end{cases}$$

$$V(x)=-\int_{-x_p}^{x}E(x')dx'$$

(1) for $-x_p<x<0$: $V(x)=-\int_{-x_p}^{x}E(x')dx'=\int_{-x_p}^{x}\dfrac{qN_A(x'+x_p)}{\varepsilon_S}dx'=\dfrac{qN_A}{2\varepsilon_S}(x'+x_p)^2\Big|_{x'=-x_p}^{x'=x}=\dfrac{qN_A}{2\varepsilon_S}(x+x_p)^2$

(2) for $0<x<x_n$: Because $E(x)$ has different expression for $x<0$ and $x>0$, the integration should be performed in two separate ranges, first from $-x_p$ to 0, and then from 0 to x. We can use $V(x=0)$ from the above equation for the first intgration. Therefore,

$$V(x)=\frac{qN_A}{2\varepsilon_S}x_p^2-\int_0^x\frac{qN_D(x'-x_n)}{\varepsilon_S}dx'=\frac{qN_A}{2\varepsilon_S}x_p^2-\frac{qN_D(x'-x_n)^2}{2\varepsilon_S}\Bigg|_0^x$$

$$=\frac{qN_A}{2\varepsilon_S}x_p^2-\left(\frac{qN_D(x-x_n)^2}{2\varepsilon_S}-\frac{qN_Dx_n^2}{2\varepsilon_S}\right)=\frac{qN_A}{2\varepsilon_S}x_p^2+\frac{qN_Dx_n^2}{2\varepsilon_S}-\frac{qN_D(x-x_n)^2}{2\varepsilon_S}$$

Built-in potential: $V_0=V(x_n)=\dfrac{q}{2\varepsilon_S}\left(N_Ax_p^2+N_Dx_n^2\right)$