Chapter #3: Diodes

from **Microelectronic Circuits** Text

by Sedra and Smith

Oxford Publishing

Introduction

- **IN THIS CHAPTER WE WILL LEARN**
  - the characteristics of the ideal diode and how to analyze and design circuits containing multiple ideal diodes together with resistors and dc sources to realize useful and interesting nonlinear function
  - the details of the i-v characteristic of the junction diode (which was derived in Chapter 1) and how to use it to analyze diode circuits operating in the various bias regions: forward, reverse, and breakdown
  - a simple but effective model of the diode i-v characteristic in the forward direction: the constant-voltage-drop model

Introduction

- a powerful technique for the application and modeling of the diode (and in later chapters, transistors): dc-biasing the diode and modeling its operation for small signals around the dc-operating point by means of the small-signal model
- the use of a string of forward-biased diodes and of diodes operating in the breakdown region (zener diodes), to provide constant dc voltages (voltage regulators)
- application of the diode in the design of rectifier circuits, which convert ac voltages to dc as needed for powering electronic equipment
- a number of other practical and important applications

3.1.1. **Current-Voltage Characteristic** of the Ideal Diode

- ideal diode – most fundament nonlinear circuit element
  - two terminal device
  - circuit symbol shown to right
  - operates in two modes
    - on and off

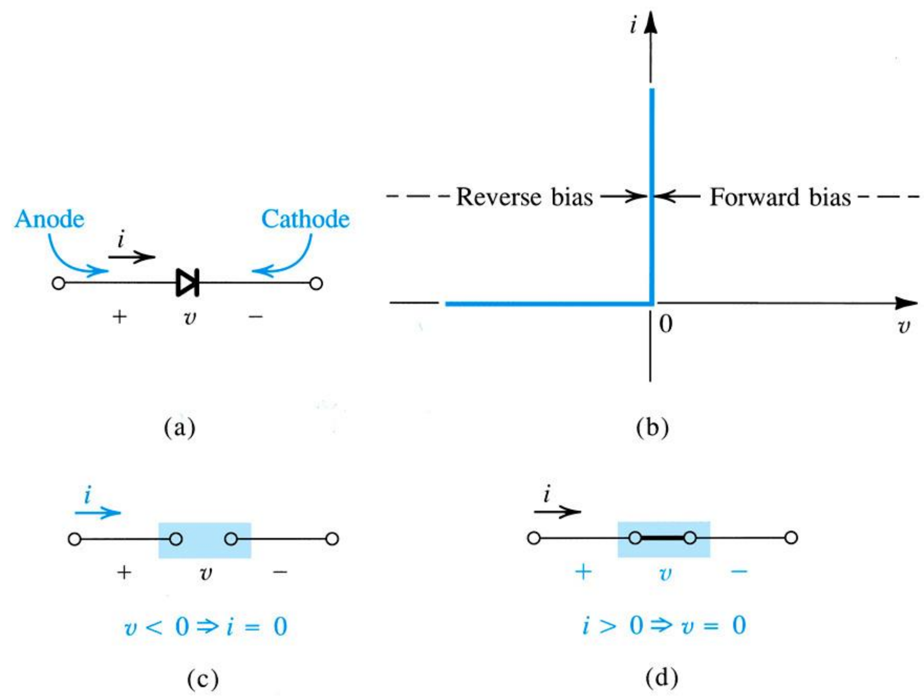

Figure 3.1: Diode characteristics

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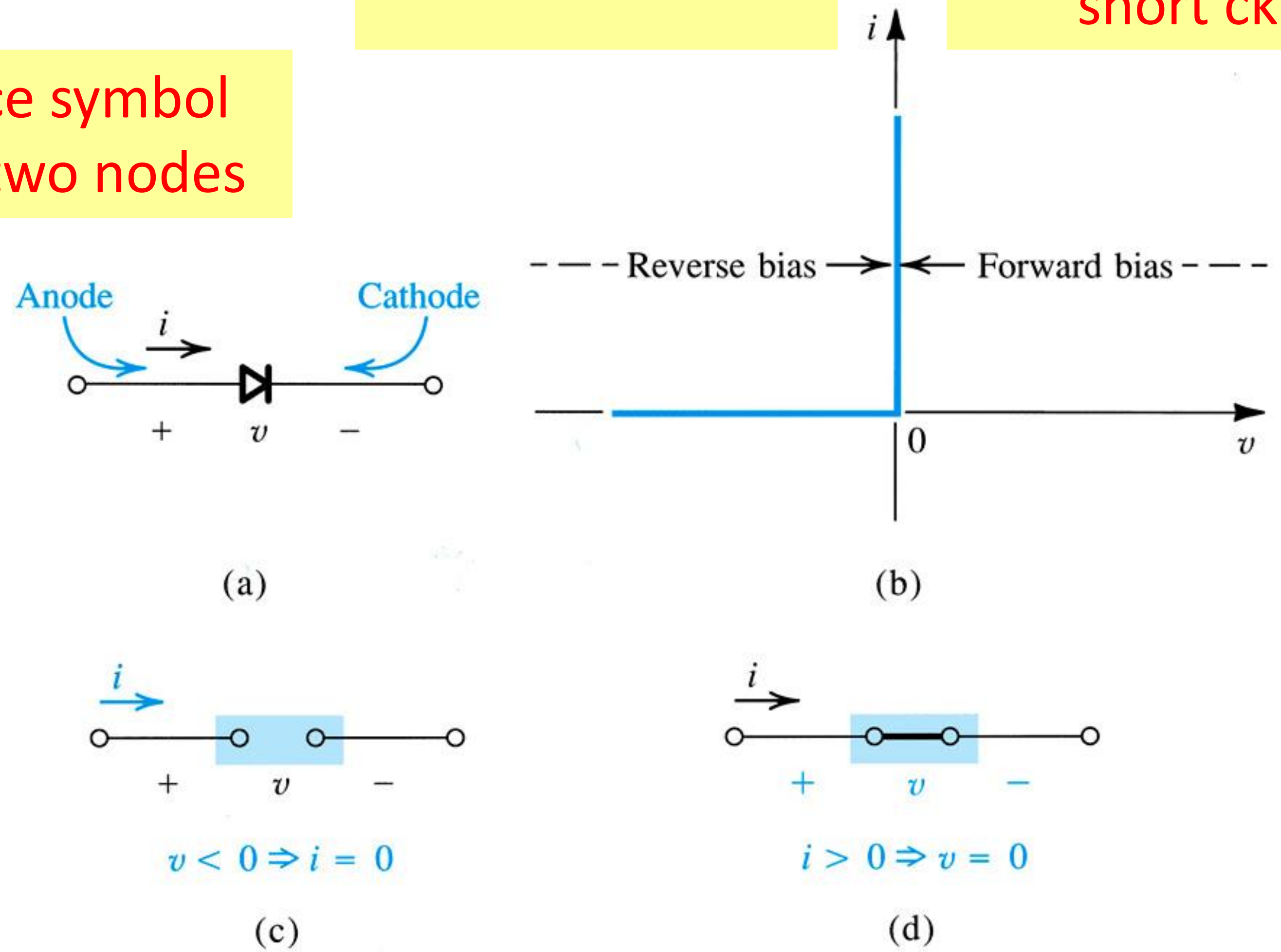
3.1.1. **Current-Voltage Characteristic**

- **cathode** – negative terminal, from which current flows
- **anode** – positive terminal of diode, into which current flows
- voltage-current (*VI*) behavior is:
  - piecewise linear for rated values
  - nonlinear beyond this range

mode #2: reverse bias = open ckt.

mode #1: forward bias = short ckt

device symbol with two nodes



3.1.1. Current-Voltage Characteristic

- External circuit should be designed to limit…
  - current flow across conducting diode
  - voltage across blocking diode
- Examples are shown to right…

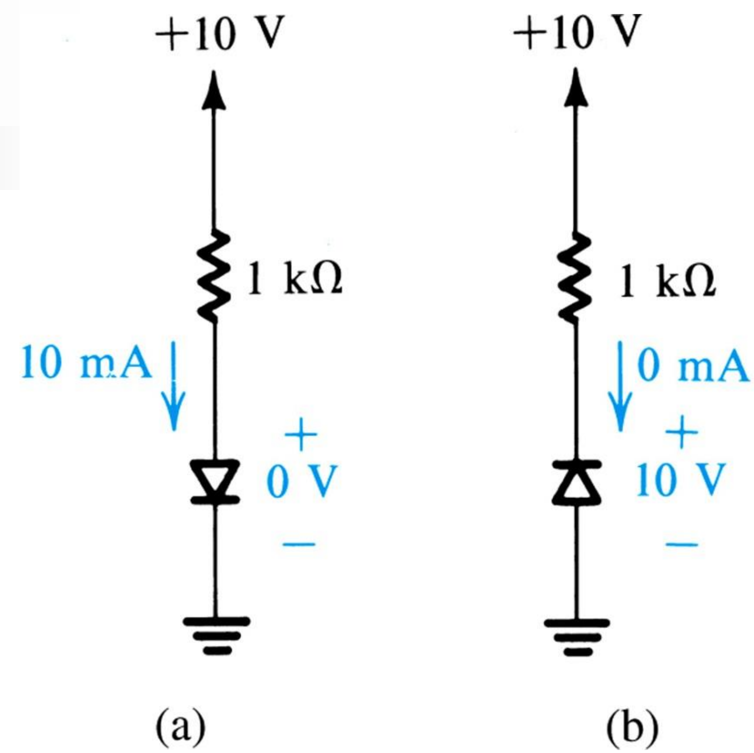


Figure 3.2: The two modes of operation of ideal diodes and the use of an external circuit to limit **(a)** the forward current and **(b)** the reverse voltage.

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3.1.2: **A Simple Application – The Rectifier**

- One fundamental application of this piecewise linear behavior is the rectifier.
- **Q:** What is a **rectifier**?
  - **A:** Circuit which converts AC waves in to DC…ideally with no loss.

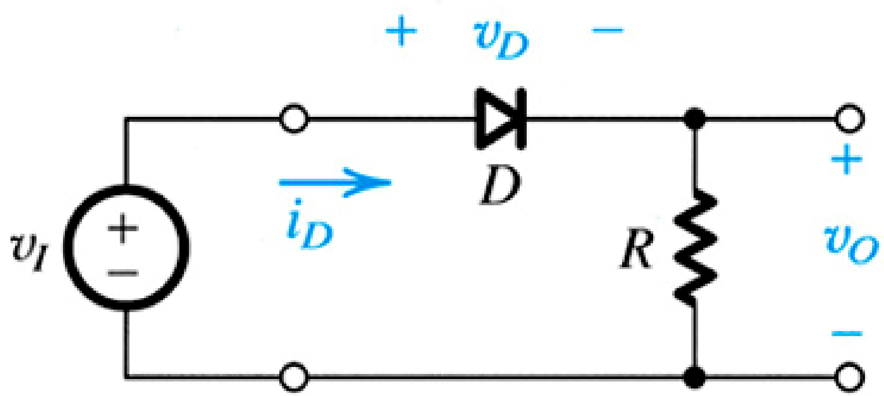


Figure 3.3(a): Rectifier Circuit

3.1.2: **A Simple Application – The Rectifier**

- This circuit is composed of diode and series resistor.
- **Q:** How does this circuit operate?
  - **A:** The diode blocks reverse current flow, preventing negative voltage across *R*.

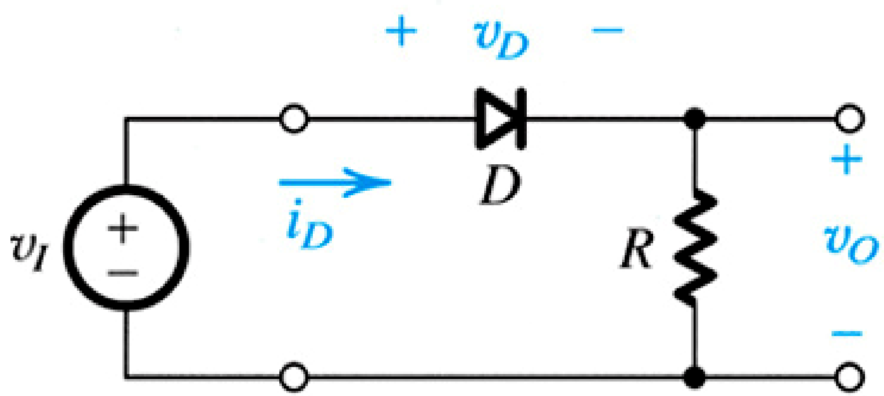


Figure 3.3(a): Rectifier Circuit

3.1.3. **Another Application, Diode Logic Gates**

- **Q:** How may diodes be used to create logic gates?
  - **A:** Examples of AND / OR gates are shown right.
    - Refer to next slide.

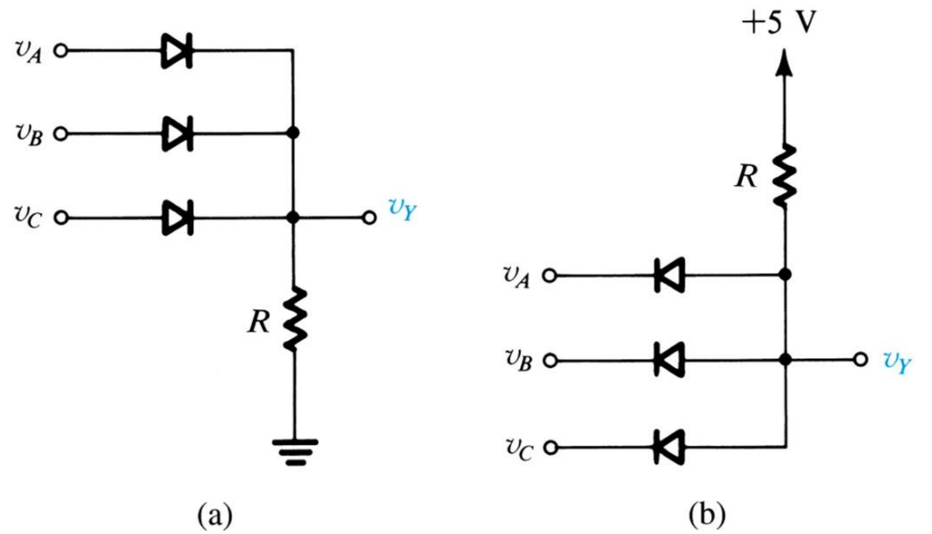
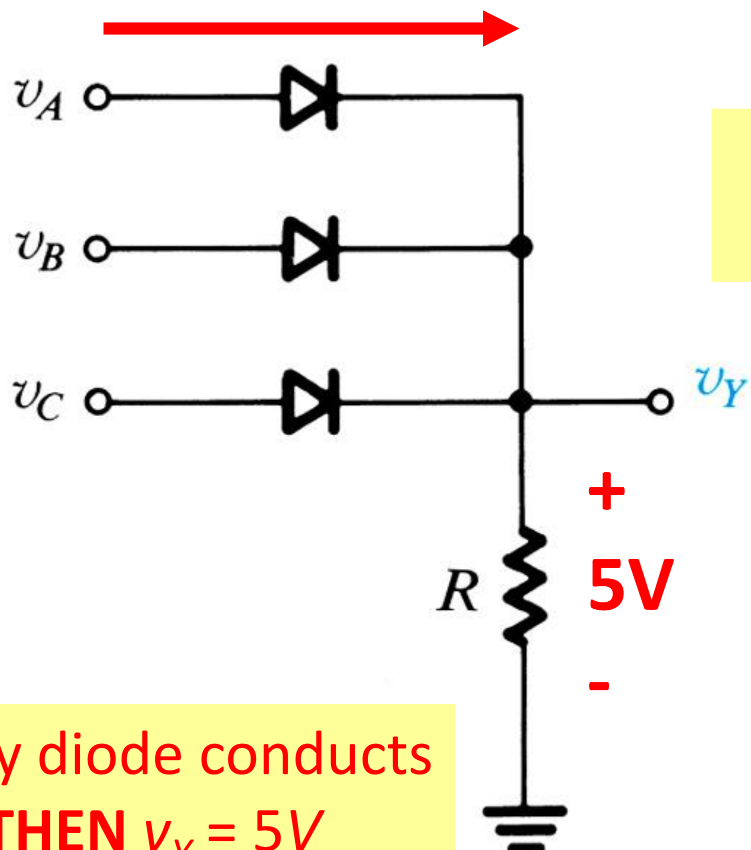


Figure 3.5: Diode logic gates: **(a)** OR gate; **(b)** AND gate (in a positive-logic system).

OR GATE

IF $v_A = 5V$ **THEN** diode$_A$ will conduct **AND** $v_Y = v_A = 5V$



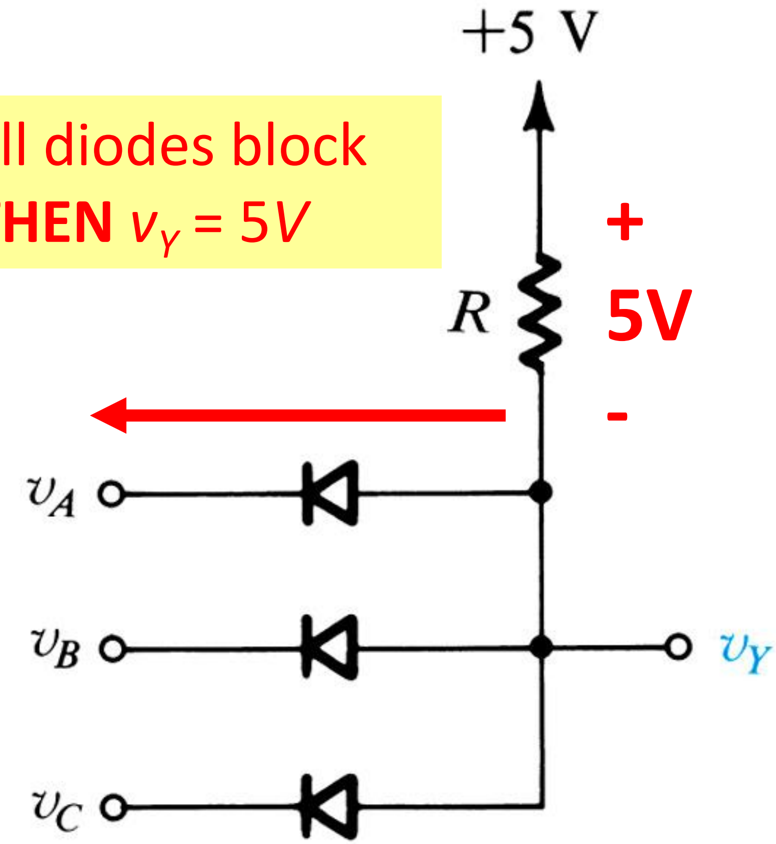
IF any diode conducts **THEN** $v_Y = 5V$

(a)

AND GATE

IF $v_A = 0V$ **THEN** diode$_A$ will conduct **AND** $v_Y = v_A = 0V$

IF all diodes block **THEN** $v_Y = 5V$

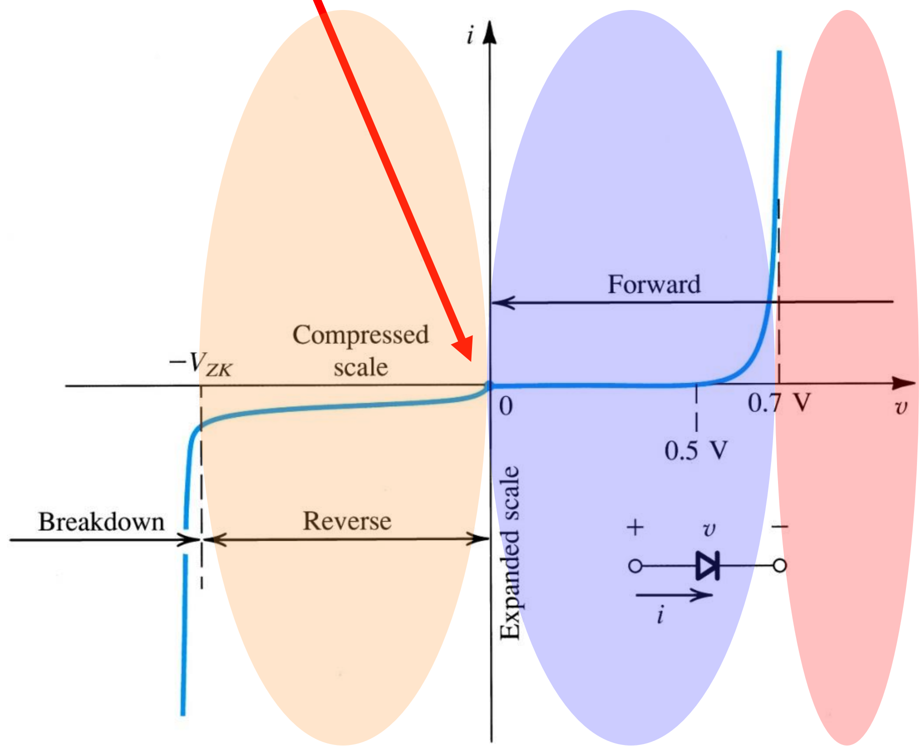


(b)

3.2. **Terminal Characteristics of Junction Diodes**

discontinuity caused by differences in scale

- Most common implementation of a diode utilizes pn junction.
- *I-V* curve consists of three characteristic regions
  - forward bias: $v > 0$
  - reverse bias: $v < 0$
  - breakdown: $v << 0$



3.2.1. The Forward-Bias Region

- The forward-bias region of operation is entered when $v > 0$.
- *I-V* relationship is closely approximated by equations to right.

(3.3) is a simplification suitable for large *v*

I_S = constant for diode at given temperature (aka. saturation current)

$$\text{(Eq3.1)} \quad i = I_S(e^{v/V_T} - 1)$$

V_T = thermal voltage
k = Boltzmann's constant (8.62**E**-5 eV/K)
q = magnitude of electron charge (1.6**E**-19 C)

$$\text{(Eq3.2)} \quad V_T = \frac{kT}{q} = 25.8mV$$

(at room temperature)

I_S = constant for diode at given temperature (aka. saturation current)

$$\text{(Eq3.3)} \quad i = I_S e^{v/V_T}$$

3.2.1. The Forward-Bias Region

- Equation (3.3) may be reversed to yield (3.4).
- This relationship applies over as many as seven decades of current.

I_S = constant for diode at given temperature (aka. saturation current)

(Eq3.4) $$v = V_T \ln\left(\frac{i}{I_S}\right)$$

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3.2.1. The Forward-Bias Region

- **Q:** What is the relative effect of current flow (*i*) on forward biasing voltage (*v*)?
- **A:** Very small.
  - 10x change in *i*, effects 60*mV* change in *v*.

step #1: consider two cases (#1 and #2)

$$I_1 = I_S e^{V_1/V_T} \text{ and } I_2 = I_S e^{V_2/V_T}$$

step #2: divide I_2 by I_1

$$\frac{I_2}{I_1} = \frac{\cancel{I_S} e^{V_2/V_T}}{\cancel{I_S} e^{V_1/V_T}}$$

step #3: combine two exponentials

$$\frac{I_2}{I_1} = e^{(V_2 - V_1)/V_T}$$

step #4: invert this expression

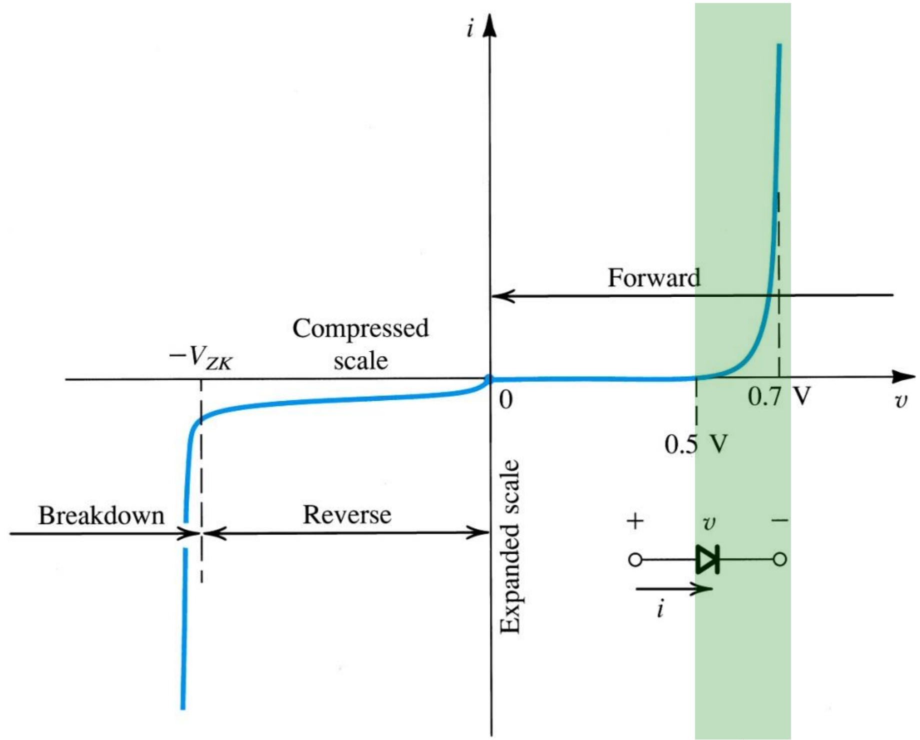
$$V_2 - V_1 = V_T \ln(I_2/I_1)$$

step #5: convert to log base 10

$$V_2 - V_1 = \underbrace{2.3 V_T \log(I_2/I_1)}_{60mV \approx 2.3 V_T \log(10/1)}$$

3.2.1: The Forward-Bias Region

- **cut-in voltage** – is voltage, below which, minimal current flows
  - approximately 0.5V
- **fully conducting region** – is region in which R_{diode} is approximately equal 0
  - between 0.6 and 0.8*V*



fully conducting region

3.2.2. **The Reverse-Bias Region**

- The reverse-bias region of operation is entered when $v < 0$.
- *I-V* relationship, for negative voltages with $|v| > V_T$ (25*mV*), is closely approximated by equations to right.

this expression applies for negative voltages

$$i = -I_S e^{-|v|/V_T}$$

action: invert exponential

$$i = -I_S \left(\frac{1}{e^{|v|/V_T}} \right)$$

≈0 for larger voltage magnitudes

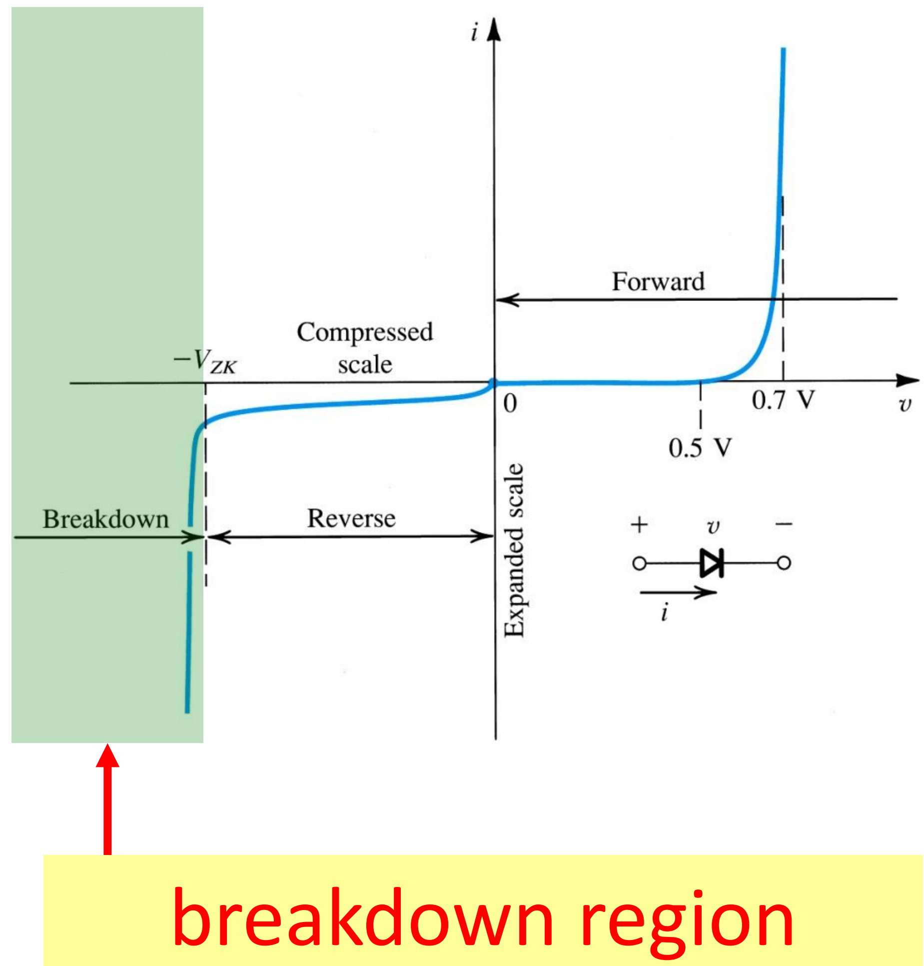
$$i = -I_S$$

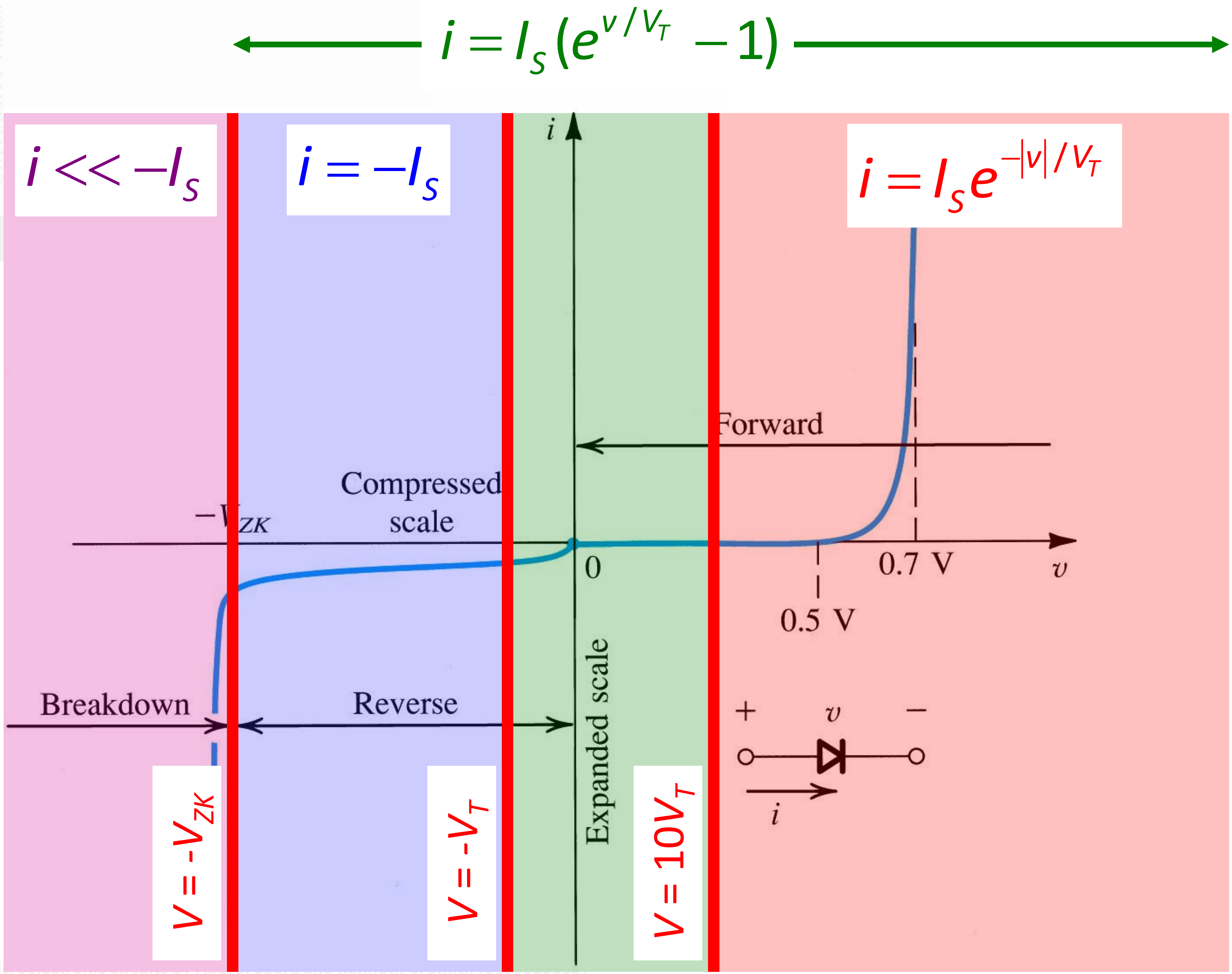
3.2.2. **The Reverse-Bias Region**

- A "real" diode exhibits reverse-bias current, although small, much larger than I_S.
  - 10^{-9} vs. 10^{-14} *Amps*
- A large part of this reverse current is attributed to leakage effects.

3.2.3. The Breakdown Region

- The breakdown region of operation is entered when $v < V_{ZK}$.
  - **Zener-Knee Voltage (V_{ZK})**
- This is normally non-destructive.





$i = I_S(e^{v/V_T} - 1)$
$i << -I_S$
$i = -I_S$
$i = I_S e^{-|v|/V_T}$
i
Forward
Compressed
scale
$-V_{ZK}$
0
0.7 V
v
0.5 V
Breakdown
Reverse
Expanded scale
+
v
−
i
$V = -V_{ZK}$
$V = -V_T$
$V = 10V_T$