BLM1033 - Circuit Theory and Electronics

The Instructors:

Doç. Dr. Hamza Osman İlhan
hoilhan@yildiz.edu.tr
Prof. Dr. Gökhan Bilgin
gbilgin@yildiz.edu.tr

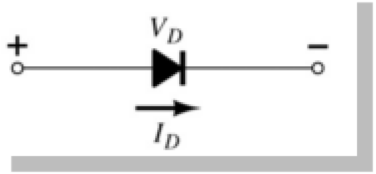
Lab Assistants:

Arş. Gör. Burak Ahmet Özden
Arş. Gör. Emre Parlak
Arş. Gör. Elif Aşıcı
Arş. Gör. Ömer Mutlu Türk Kaya
Arş. Gör. Yunus Karatepe

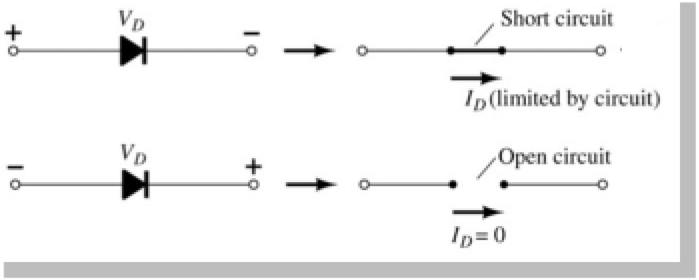
Diodes

Diodes

The diode is a 2-terminal device.

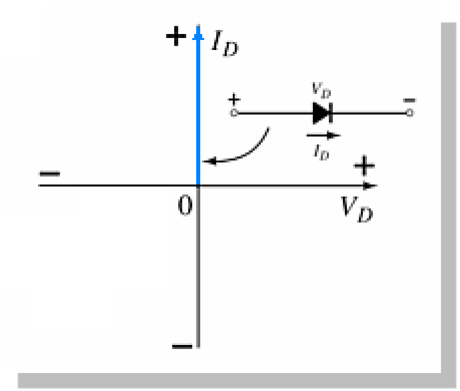


A diode ideally conducts in only one direction.



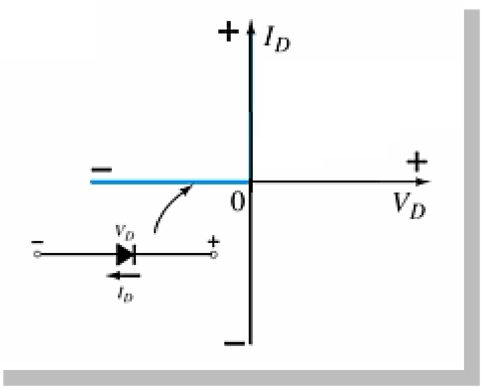
Diode Characteristics

Conduction Region



- The voltage across the diode is 0 V
- The current is infinite
- The forward resistance is defined as $R_F = V_F / I_F$
- The diode acts like a short

Non-Conduction Region



- All of the voltage is across the diode
- The current is 0 A
- The reverse resistance is defined as $R_R = V_R / I_R$
- The diode acts like open

Semiconductor Materials

Materials commonly used in the development of semiconductor devices:

- **Silicon (Si)**
- **Germanium (Ge)**
- **Gallium Arsenide (GaAs)**

Doping

The electrical characteristics of silicon and germanium are improved by adding materials in a process called doping.

There are just two types of doped semiconductor materials:

***n*-type**
***p*-type**

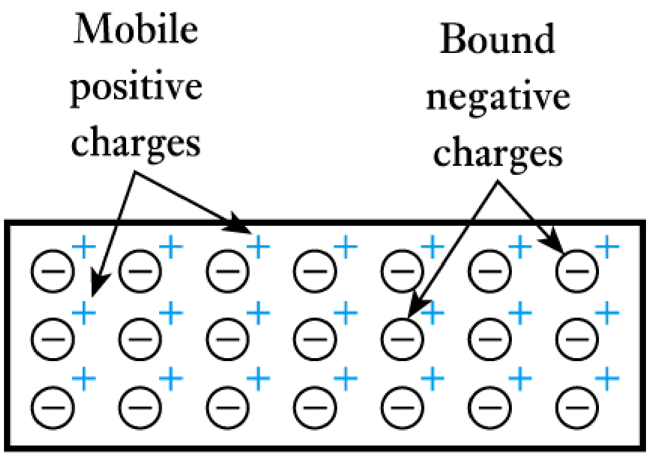
- ***n*-type materials contain an excess of conduction band electrons.**
- ***p*-type materials contain an excess of valence band holes.**

Doping of semiconductors

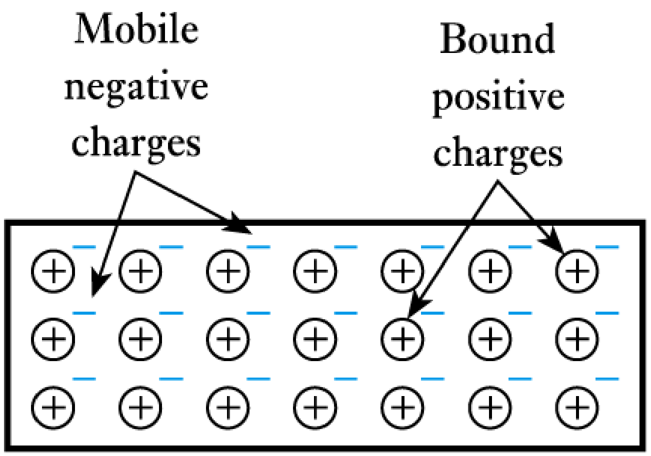
- **Doping**
  - the addition of small amounts of impurities drastically affects its properties
  - some materials form an excess of *electrons* and produce an ***n*-type semiconductor**
  - some materials form an excess of *holes* and produce a ***p*-type semiconductor**
  - both *n*-type and *p*-type materials have much greater conductivity than pure semiconductors
  - this is **extrinsic conduction.**

Doping of semiconductors (contd.)

- The dominant charge carriers in a doped semiconductor (e.g. electrons in *n*-type material) are called **majority charge carriers**. The other type are **minority charge carriers.**
- The overall doped material is electrically neutral.



(a) *p*-type semiconductor

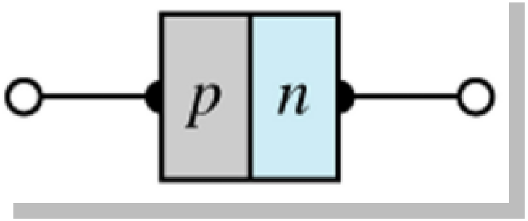


(b) *n*-type semiconductor

p-n Junctions

One end of a silicon or germanium crystal can be doped as a *p*-type material and the other end as an *n*-type material.

The result is a ***p-n* junction**.

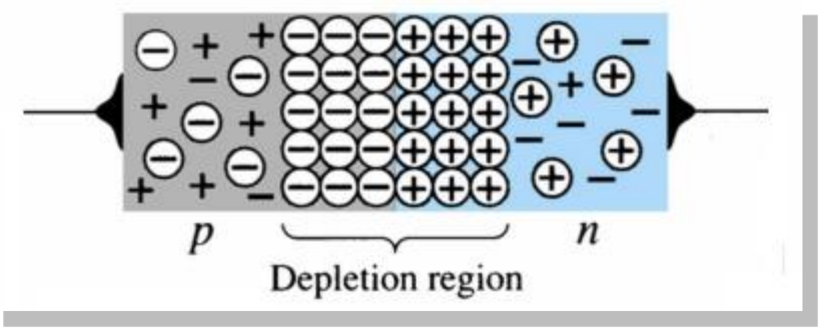


p-n Junctions

At the *p-n* junction, the excess conduction-band electrons on the *n*-type side are attracted to the valence-band holes on the *p*-type side.

The electrons in the *n*-type material migrate across the junction to the *p*-type material (electron flow).

The electron migration results in a **negative** charge on the p-type side of the junction and a **positive** charge on the n-type side of the junction.



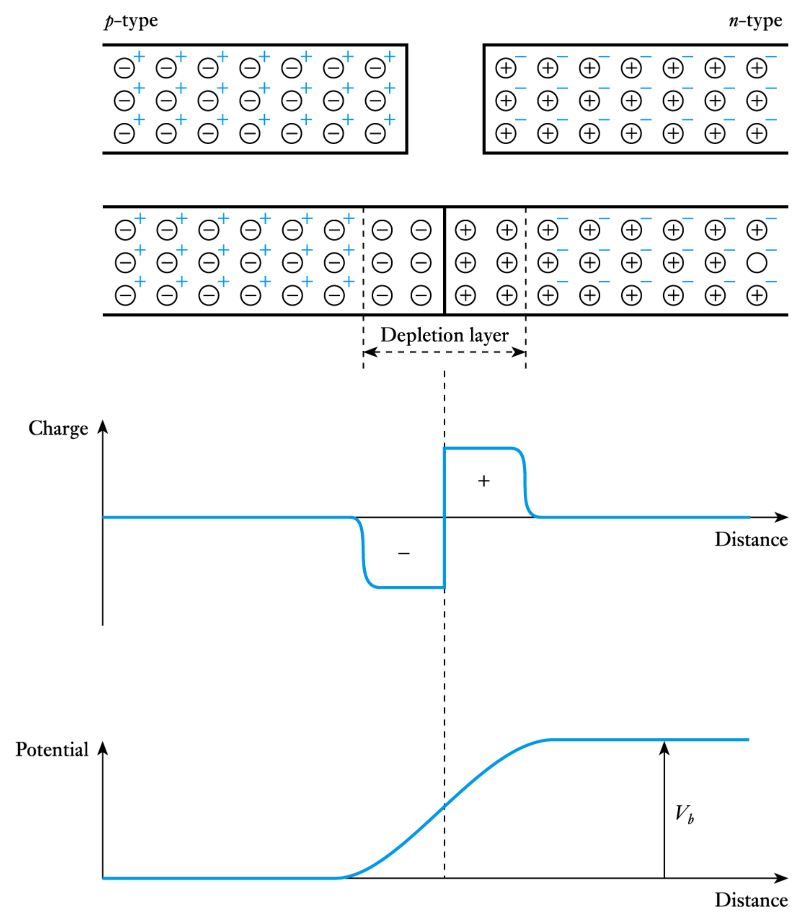
The result is the formation of a **depletion region** around the junction.

pn Junctions

- When *p*-type and *n*-type materials are joined, this forms a ***pn* junction**
  - the majority charge carriers on each side diffuse across the junction where they combine with (and remove) the charge carriers of the opposite polarity.
  - hence, around the junction there are few free charge carriers and we have a **depletion layer** (also called a **space-charge layer**).

pn Junctions (contd.)

- The diffusion of positive charge in one direction and negative charge in the other produces a charge imbalance
  - this results in a **potential barrier** across the junction.



pn Junctions (contd.)

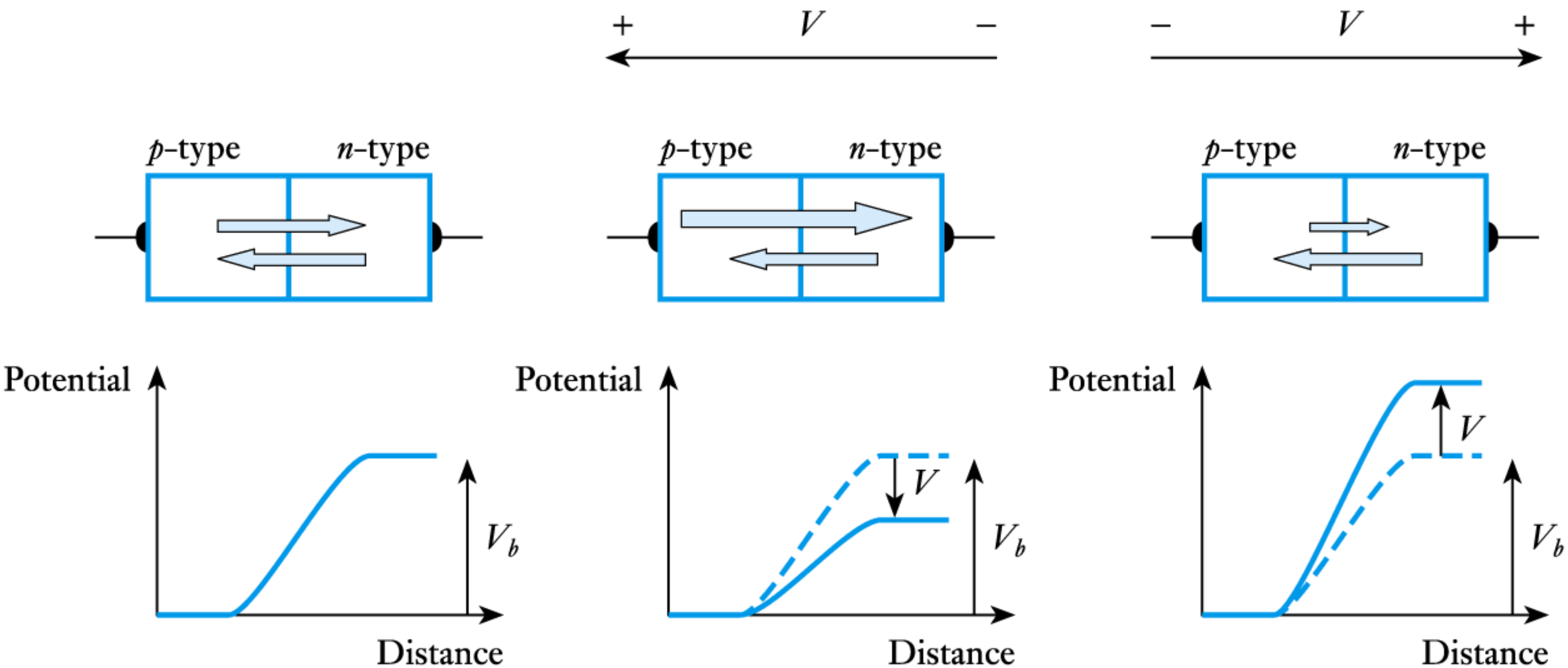
- **Forward bias**
  - if the *p*-type side is made *positive* with respect to the *n*-type side the height of the barrier is reduced
  - more majority charge carriers have sufficient energy to surmount it
  - the diffusion current therefore increases while the drift current remains the same
  - there is thus a net current flow across the junction which increases with the applied voltage.

pn Junctions (contd.)

- **Reverse bias**
  - if the *p*-type side is made *negative* with respect to the *n*-type side the height of the barrier is increased
  - the number of majority charge carriers that have sufficient energy to surmount it rapidly decreases
  - the diffusion current therefore vanishes while the drift current remains the same
  - thus the only current is a small leakage current caused by the (approximately constant) drift current
  - the leakage current is usually negligible (a few nA).

pn Junctions (contd.)

- **Currents in a *pn* junction**



(a) An isolated junction (b) Forward bias (c) Reverse bias

Diode Operating Conditions

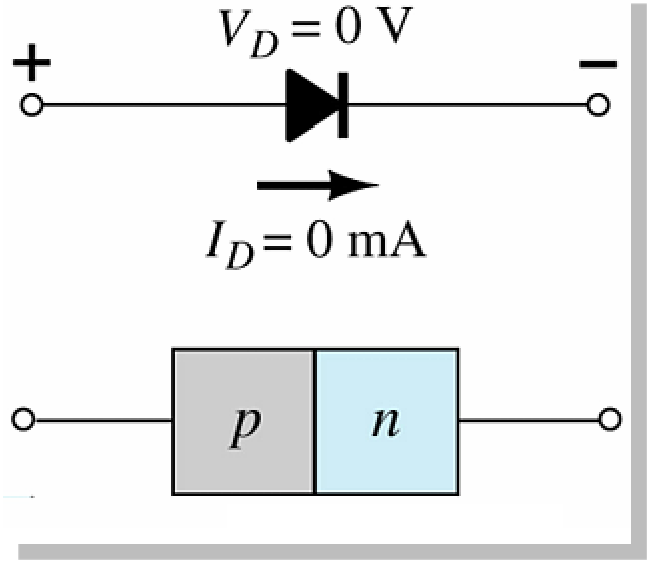
A diode has three operating conditions:

- **No bias**
- **Forward bias**
- **Reverse bias**

Diode Operating Conditions

No Bias

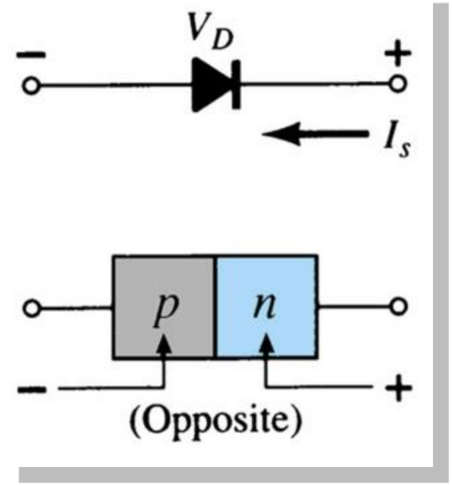
- No external voltage is applied: $V_D = 0$ V
    - No current is flowing: $I_D = 0$ A
- Only a modest depletion region exists

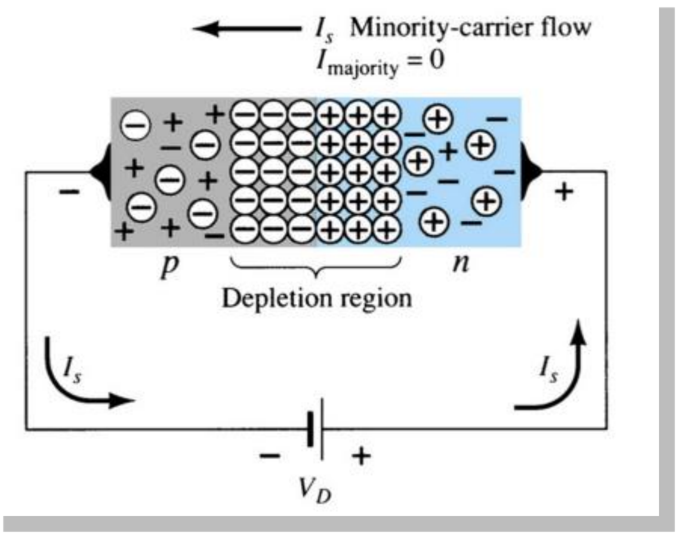


Diode Operating Conditions

Reverse Bias

External voltage is applied across the *p*-*n* junction in the opposite polarity of the *p*- and *n*-type materials.



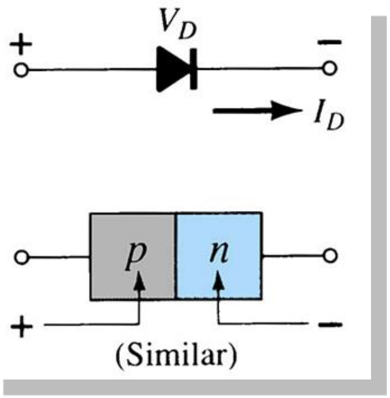


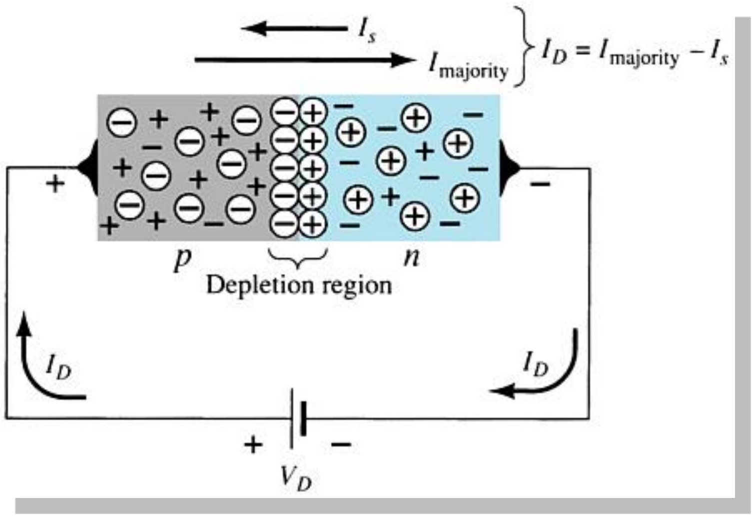
- **The reverse voltage causes the depletion region to widen.**
- **The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.**
- **The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.**

Diode Operating Conditions

Forward Bias

External voltage is applied across the *p-n* junction in the same polarity as the *p*- and *n*-type materials.



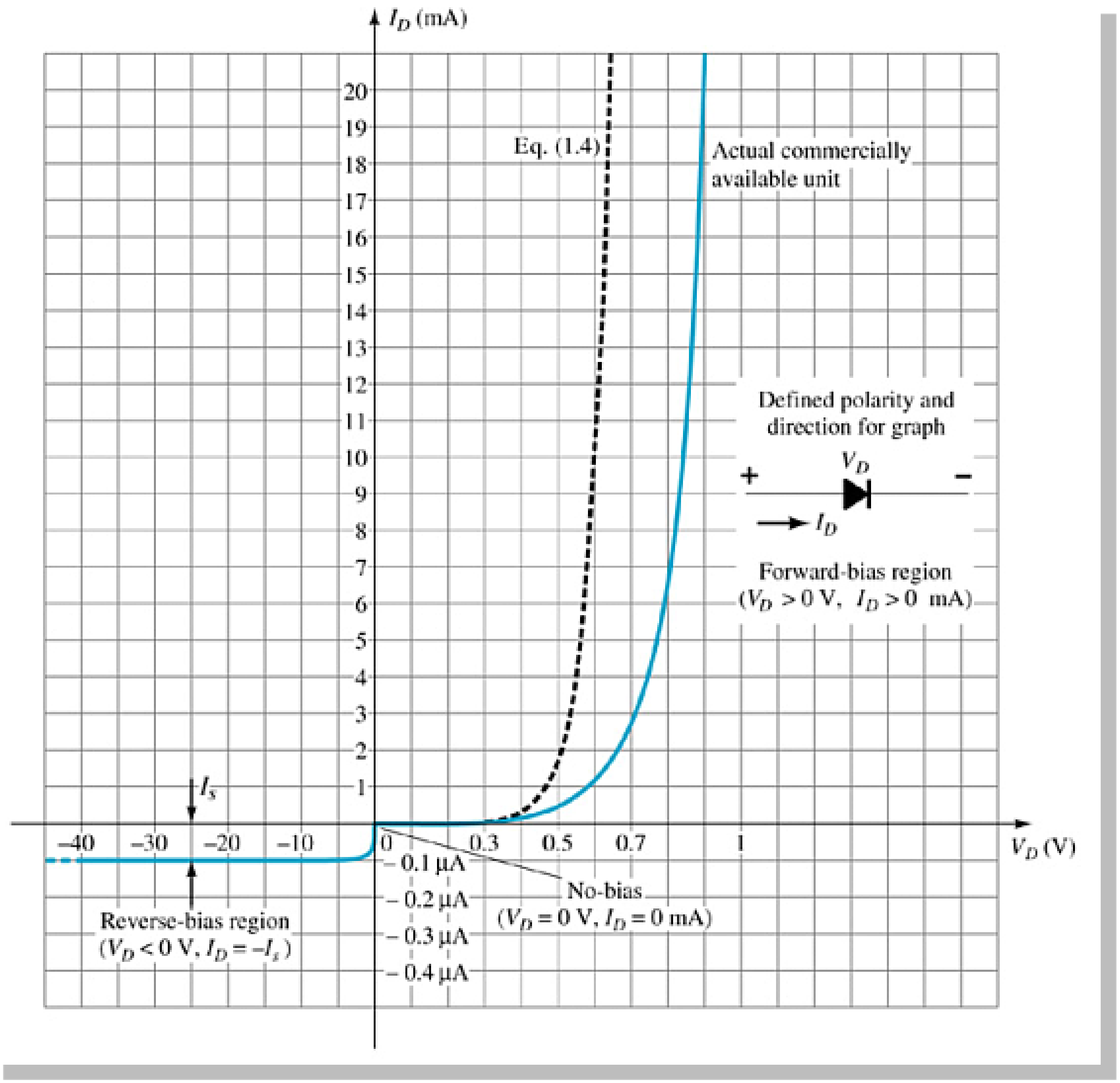


- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the *p-n* junction.
- The electrons and holes have sufficient energy to cross the *p-n* junction.

Actual Diode Characteristics

Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.

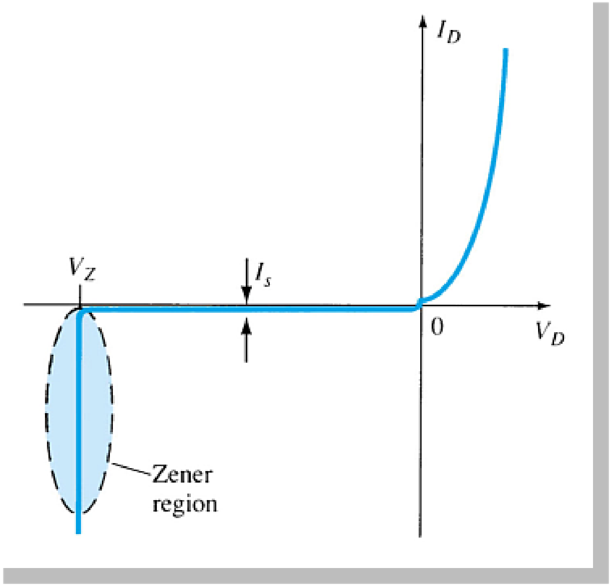


Zener Region

The Zener region is in the diode's reverse-bias region.

At some point the reverse bias voltage is so large the diode breaks down and the reverse current increases dramatically.

- The maximum reverse voltage that won't take a diode into the zener region is called the **peak inverse voltage** or **peak reverse voltage**.
- The voltage that causes a diode to enter the zener region of operation is called the **zener voltage (V_Z)**.



Forward Bias Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the *p-n* junction. This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:

- **gallium arsenide diode ≅ 1.2 V**
- **silicon diode ≅ 0.7 V**
- **germanium diode ≅ 0.3 V**

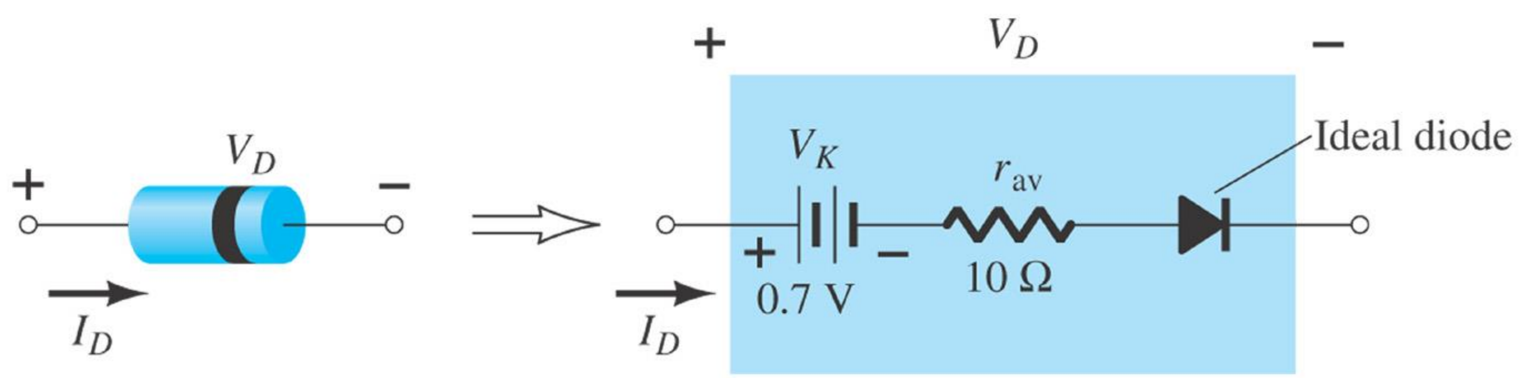
Temperature Effects

As temperature increases it adds energy to the diode.

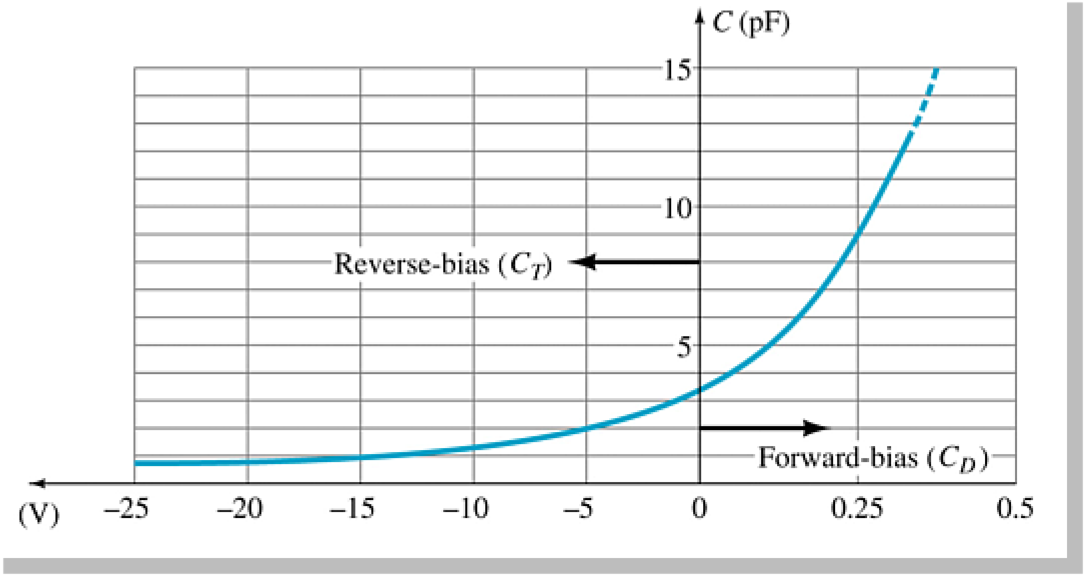
- **It reduces the required forward bias voltage for forward-bias conduction.**
- **It increases the amount of reverse current in the reverse-bias condition.**
- **It increases maximum reverse bias avalanche voltage.**

Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.

Diode Equivalent Circuit



Diode Capacitance

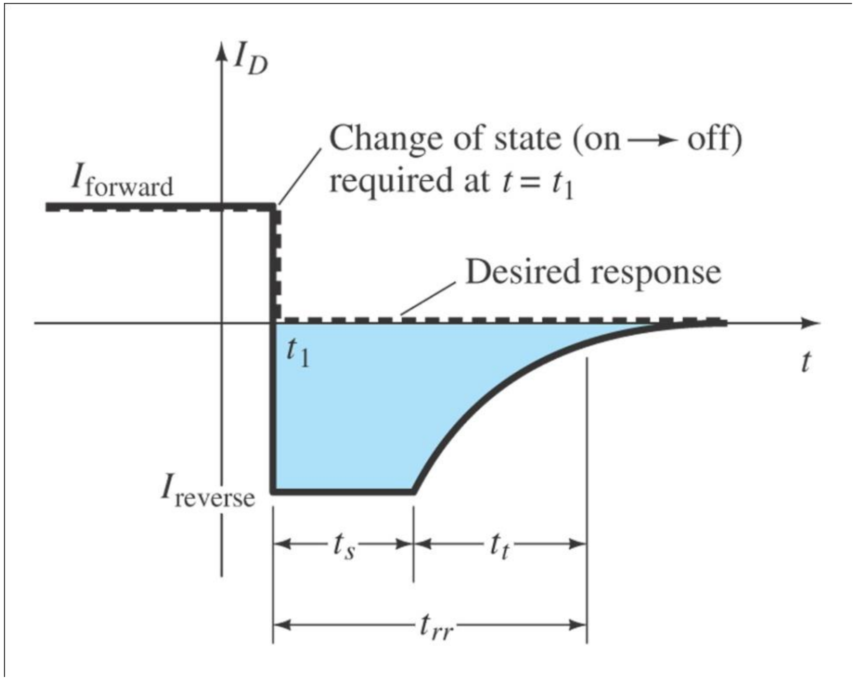


In reverse bias, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance, C_T. The amount of capacitance depends on the reverse voltage applied.

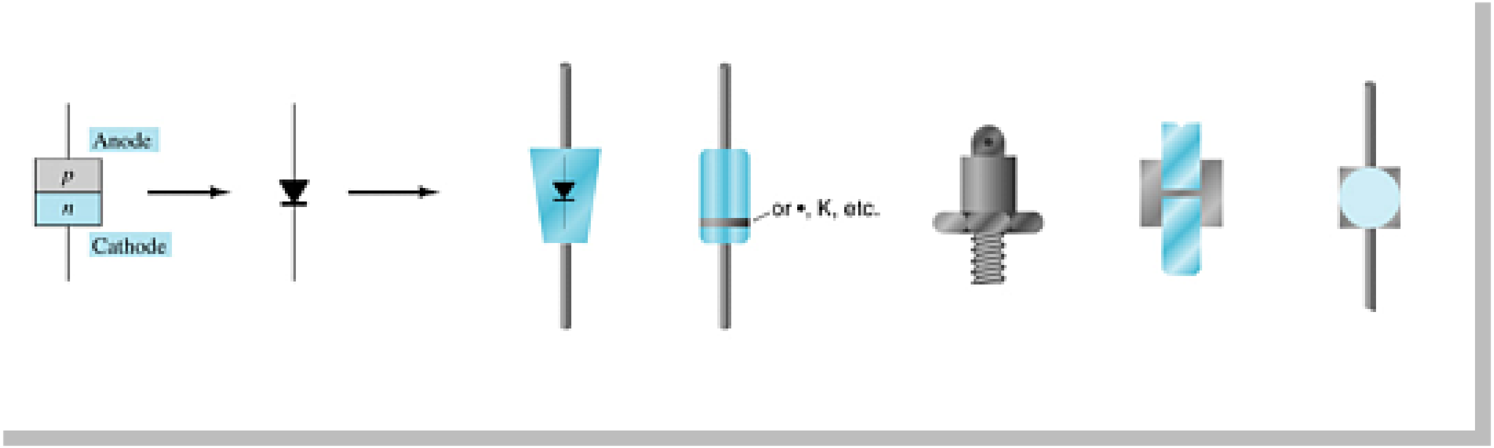
In forward bias storage capacitance or diffusion capacitance (C_D) exists as the diode voltage increases.

Reverse Recovery Time (t_{rr})

Reverse recovery time is the time required for a diode to stop conducting once it is switched from forward bias to reverse bias.



Diode Symbol and Packaging



The anode is abbreviated A
The cathode is abbreviated K

Diode Testing

Diode checker
Ohmmeter
Curve tracer

Diode Checker

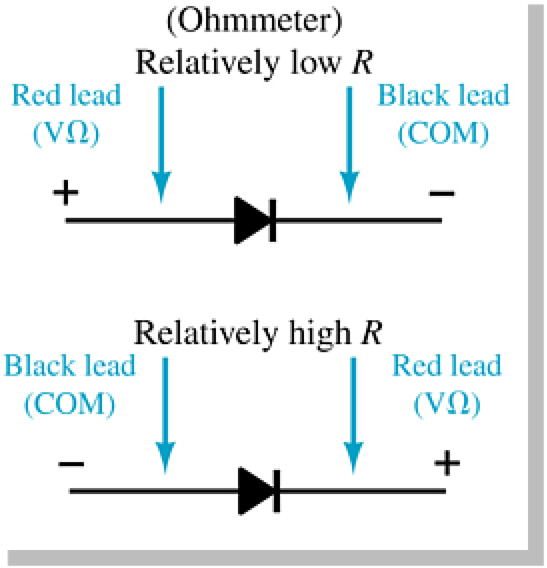
Many digital multimeters have a diode checking function.
The diode should be tested out of circuit.

A normal diode exhibits its forward voltage:

- **Gallium arsenide ≅ 1.2 V**
- **Silicon diode ≅ 0.7 V**
- **Germanium diode ≅ 0.3 V**

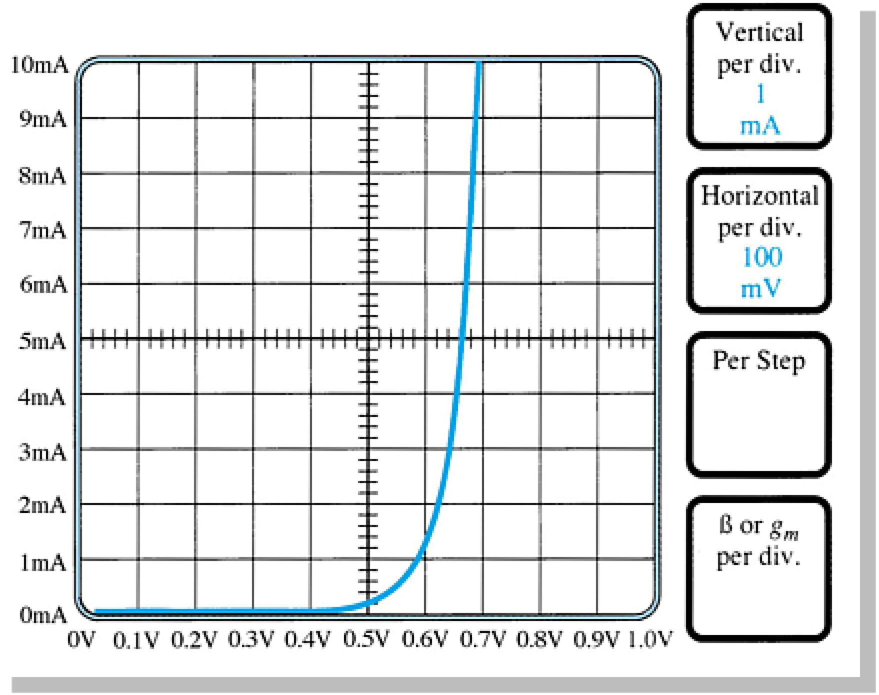
Ohmmeter

An ohmmeter set on a low Ohms scale can be used to test a diode. The diode should be tested out of circuit.



Curve Tracer

A curve tracer displays the characteristic curve of a diode in the test circuit. This curve can be compared to the specifications of the diode from a data sheet.



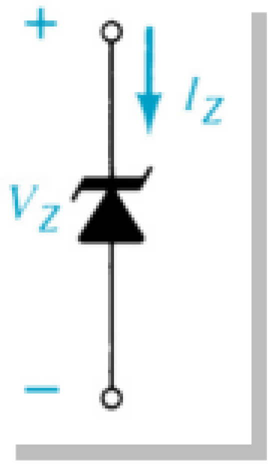
Other Types of Diodes

Zener diode
Light-emitting diode
Diode arrays

Zener Diode

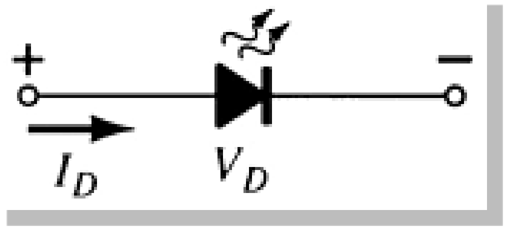
A Zener is a diode operated in reverse bias at the Zener voltage (V_Z).

Common Zener voltages are between 1.8 V and 200 V



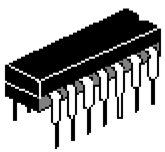
Light-Emitting Diode (LED)

An LED emits photons when it is forward biased.
These can be in the infrared or visible spectrum.
The forward bias voltage is usually in the range of 2 V to 3 V.



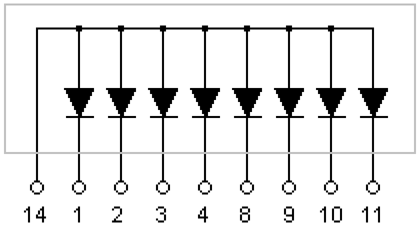
Diode Arrays

Multiple diodes can be packaged together in an integrated circuit (IC).

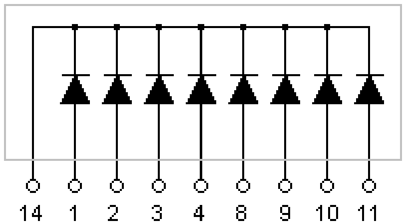


A variety of combinations exist.

Common Anode

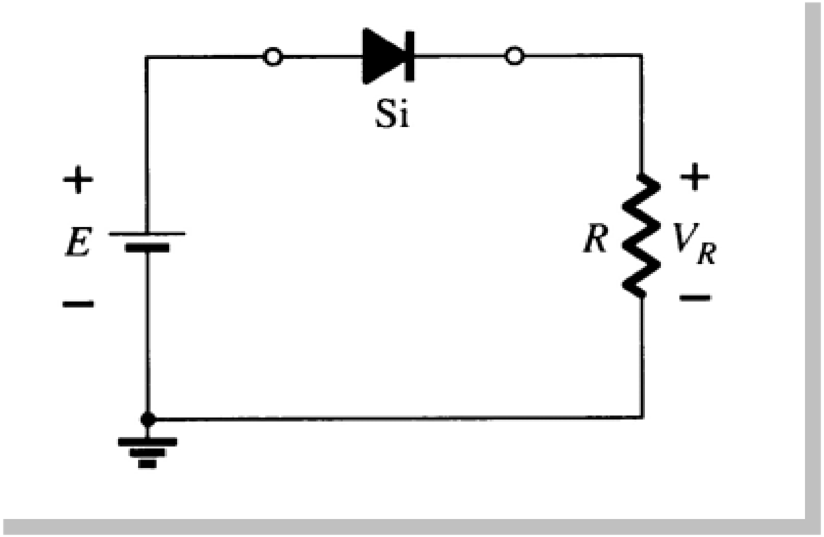


Common Cathode



Series Diode Configurations

Forward Bias



Constants

- **Silicon Diode: V_D = 0.7 V**
- **Germanium Diode: V_D = 0.3 V**

Analysis (for silicon)

- $V_D = 0.7$ V (or $V_D = E$ if $E < 0.7$ V)
- $V_R = E - V_D$
- $I_D = I_R = I_T = V_R / R$

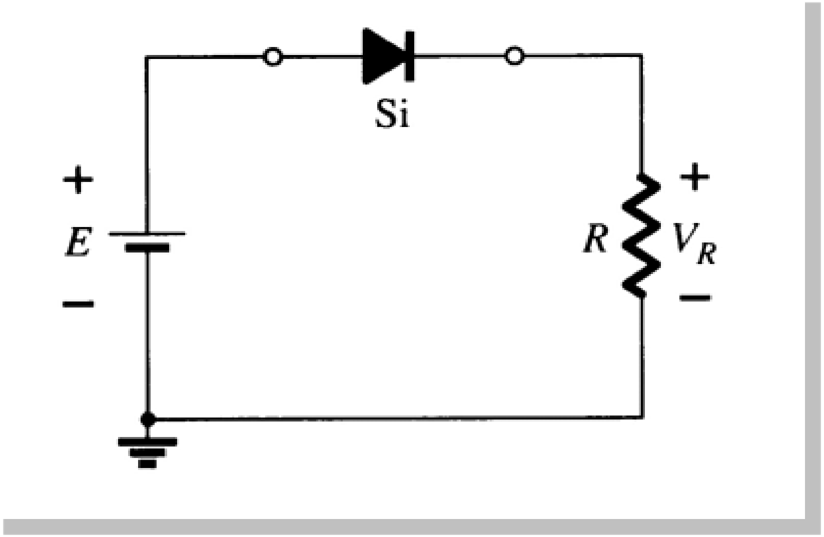
Series Diode Configurations

Reverse Bias

Diodes ideally behave as open circuits

Analysis

- $V_D = E$
- $V_R = 0\ \mathrm{V}$
- $I_D = 0\ \mathrm{A}$



Parallel Configurations

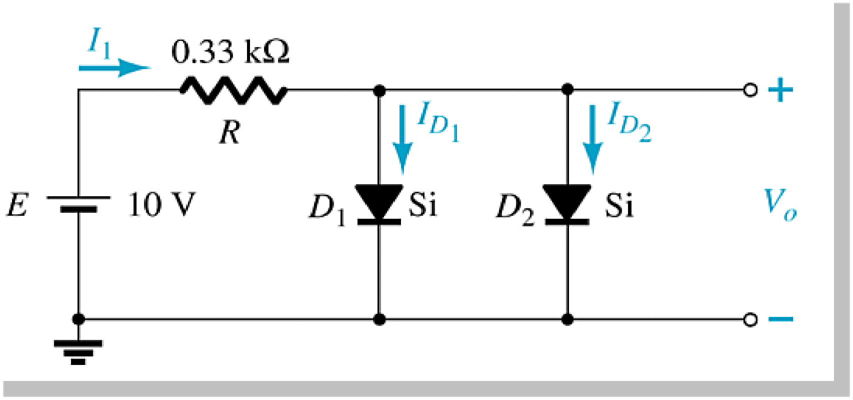
$$V_D = 0.7\,V$$

$$V_{D1} = V_{D2} = V_O = 0.7\,V$$

$$V_R = 9.3\,V$$

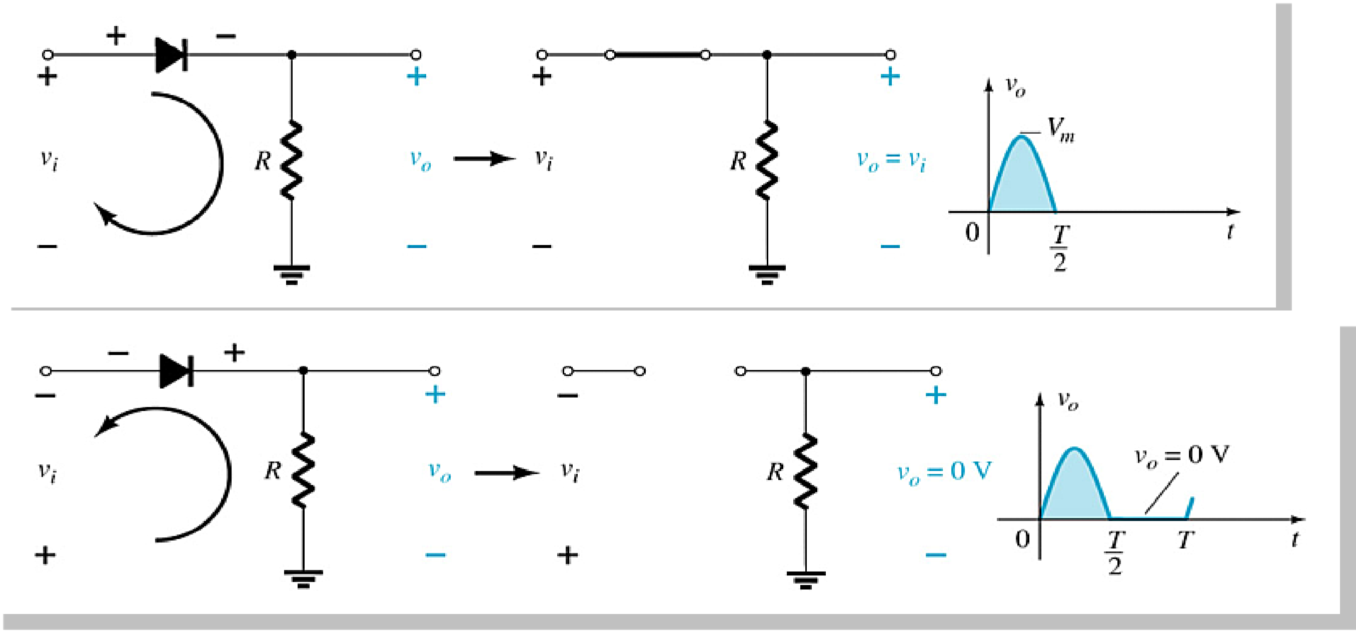
$$I_R = \frac{E - V_D}{R} = \frac{10\,V - .7\,V}{.33\,k\Omega} = 28\,mA$$

$$I_{D1} = I_{D2} = \frac{28\,mA}{2} = 14\,mA$$



Half-Wave Rectification

The diode only conducts when it is forward biased, therefore only half of the AC cycle passes through the diode to the output.



The DC output voltage is $0.318V_m$, where V_m = the peak AC voltage.

PIV (PRV)

Because the diode is only forward biased for one-half of the AC cycle, it is also reverse biased for one-half cycle.

It is important that the reverse breakdown voltage rating of the diode be high enough to withstand the peak, reverse-biasing AC voltage.

$$\textbf{PIV (or PRV)} > V_m$$

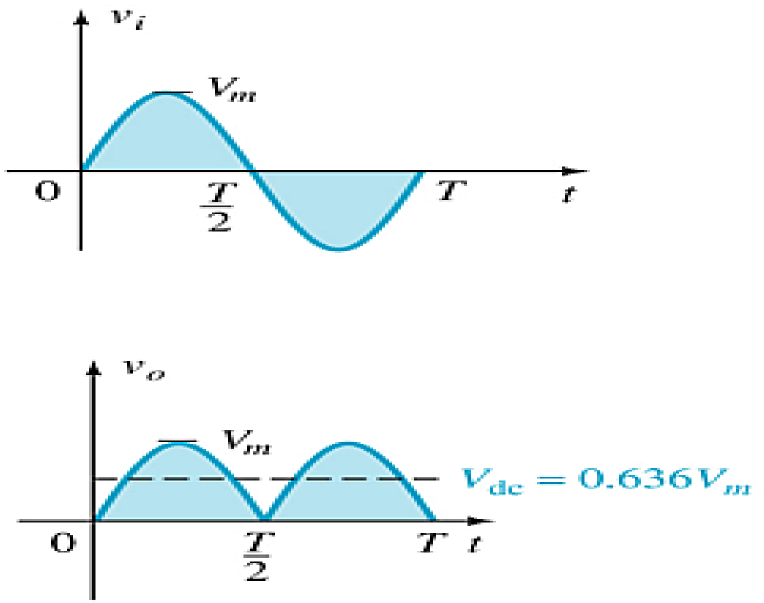
- **PIV = Peak inverse voltage**
- **PRV = Peak reverse voltage**
- V_m **= Peak AC voltage**

Full-Wave Rectification

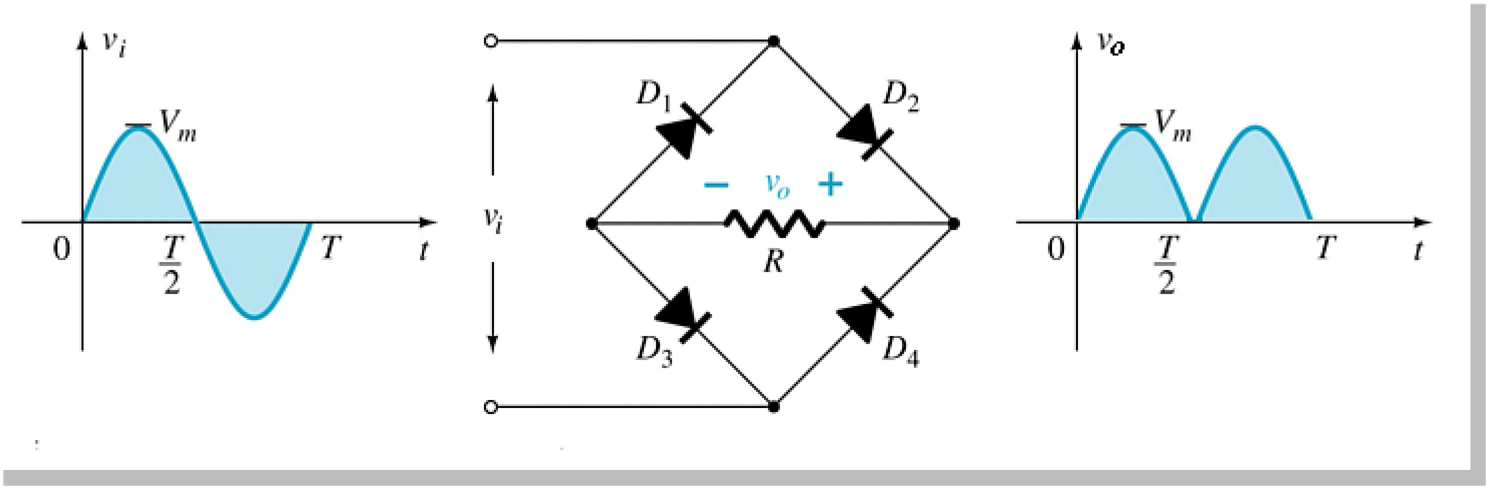
The rectification process can be improved by using a full-wave rectifier circuit.

Full-wave rectification produces a greater DC output:

- **Half-wave: $V_{dc} = 0.318V_m$**
- **Full-wave: $V_{dc} = 0.636V_m$**

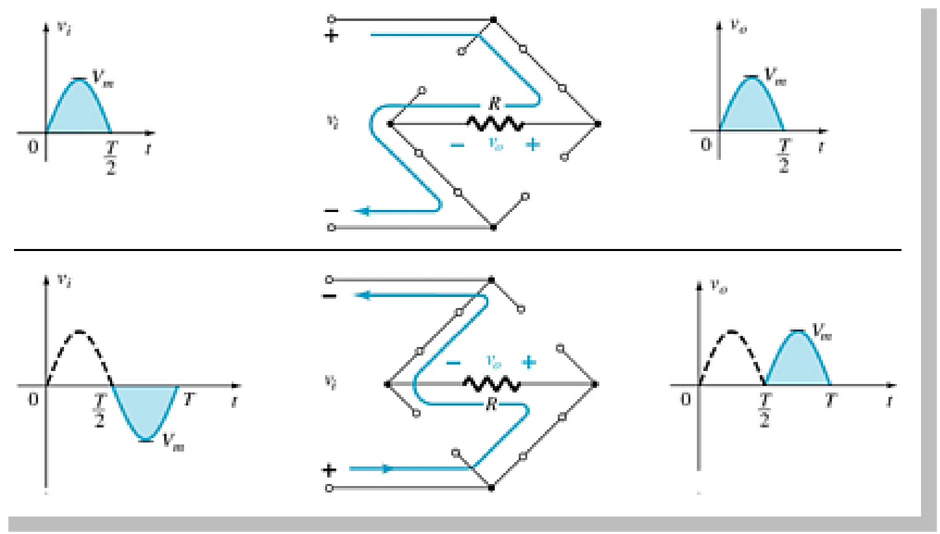


Full-Wave Rectification

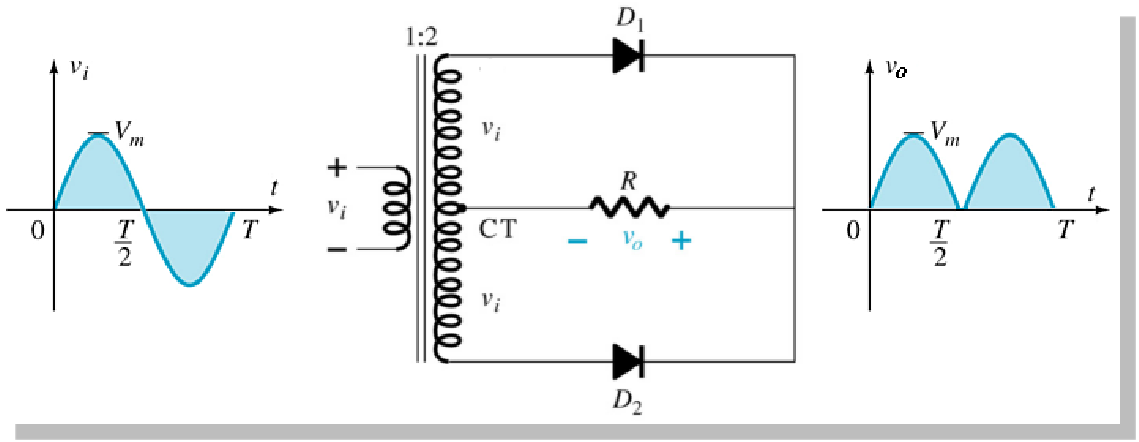


Bridge Rectifier

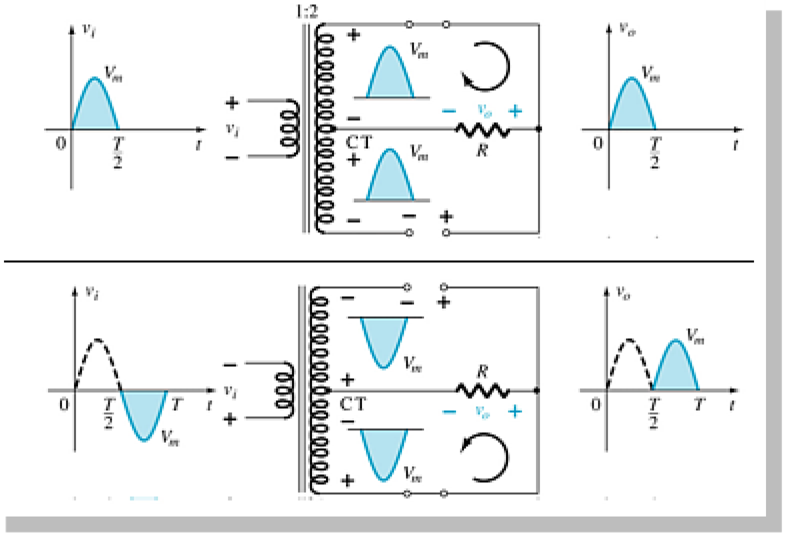
- Four diodes are connected in a bridge configuration
- $V_{DC} = 0.636V_m$



Full-Wave Rectification



Center-Tapped Transformer Rectifier



Requires

- **Two diodes**
- **Center-tapped transformer**

$$V_{DC} = 0.636V_m$$

Summary of Rectifier Circuits

Rectifier	Ideal V_{DC}	Realistic V_{DC}
Half Wave Rectifier	$V_{DC} = 0.318V_m$	$V_{DC} = 0.318V_m - 0.7$
Bridge Rectifier	$V_{DC} = 0.636V_m$	$V_{DC} = 0.636V_m - 2(0.7\text{ V})$
Center-Tapped Transformer Rectifier	$\mathrm{V}_{DC} = 0.636V_m$	$V_{DC} = 0.636V_m - 0.7\text{ V}$

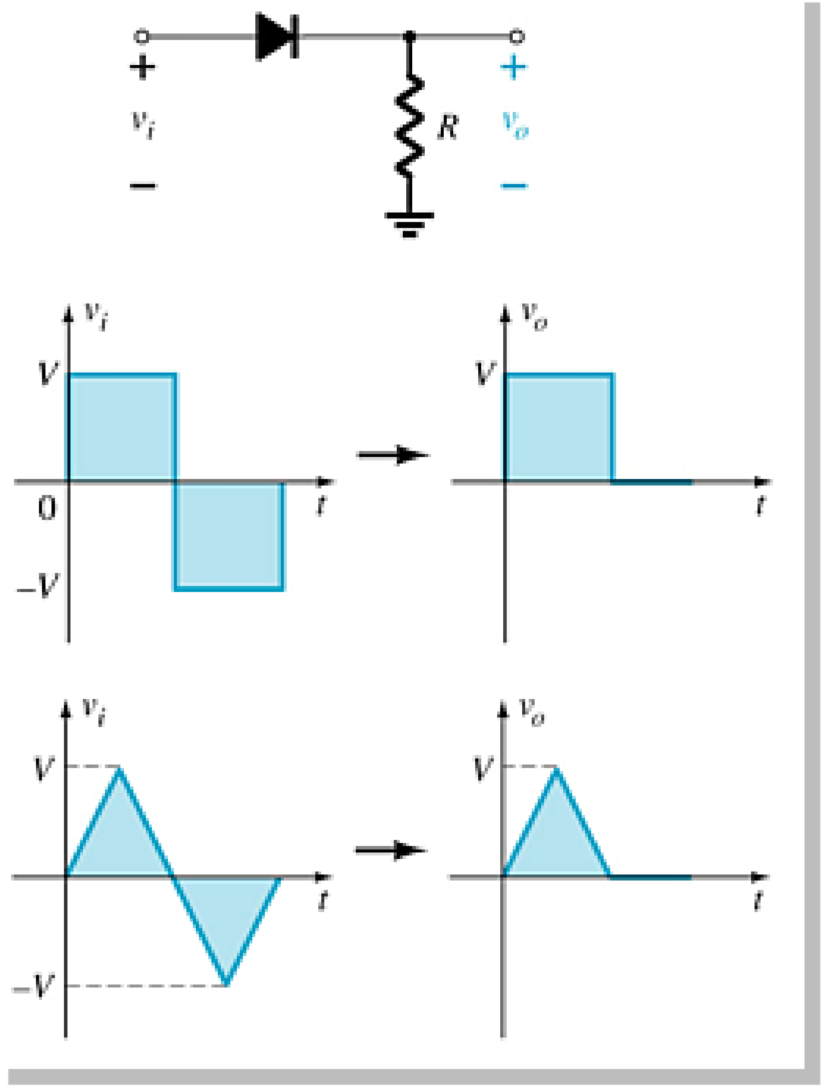
V_m = peak of the AC voltage.

In the center tapped transformer rectifier circuit, the peak AC voltage is the transformer secondary voltage to the tap.

Diode Clippers

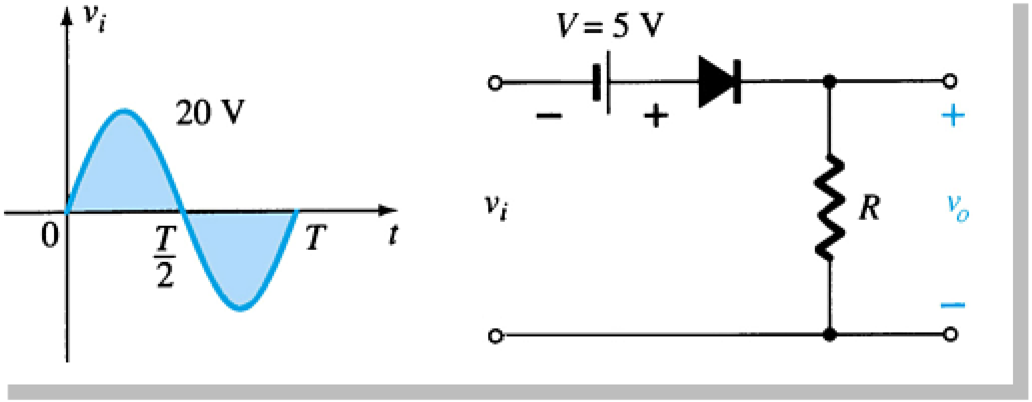
The diode in a series clipper "clips" any voltage that does not forward bias it:

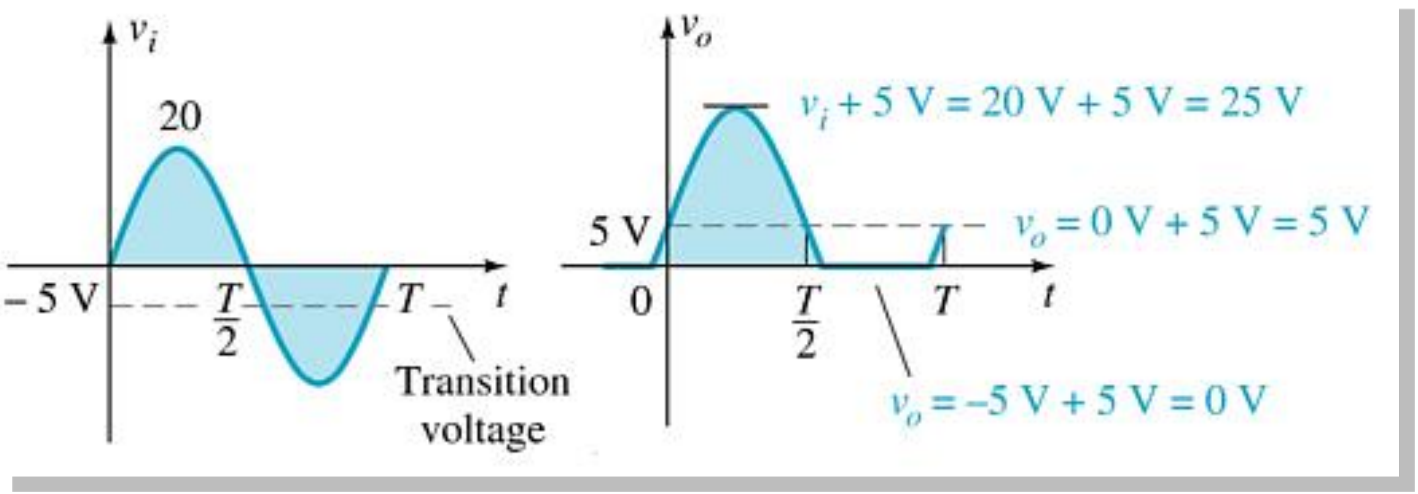
- A reverse-biasing polarity
- A forward-biasing polarity less than 0.7 V (for a silicon diode)



Biased Clippers

Adding a DC source in series with the clipping diode changes the effective forward bias of the diode.

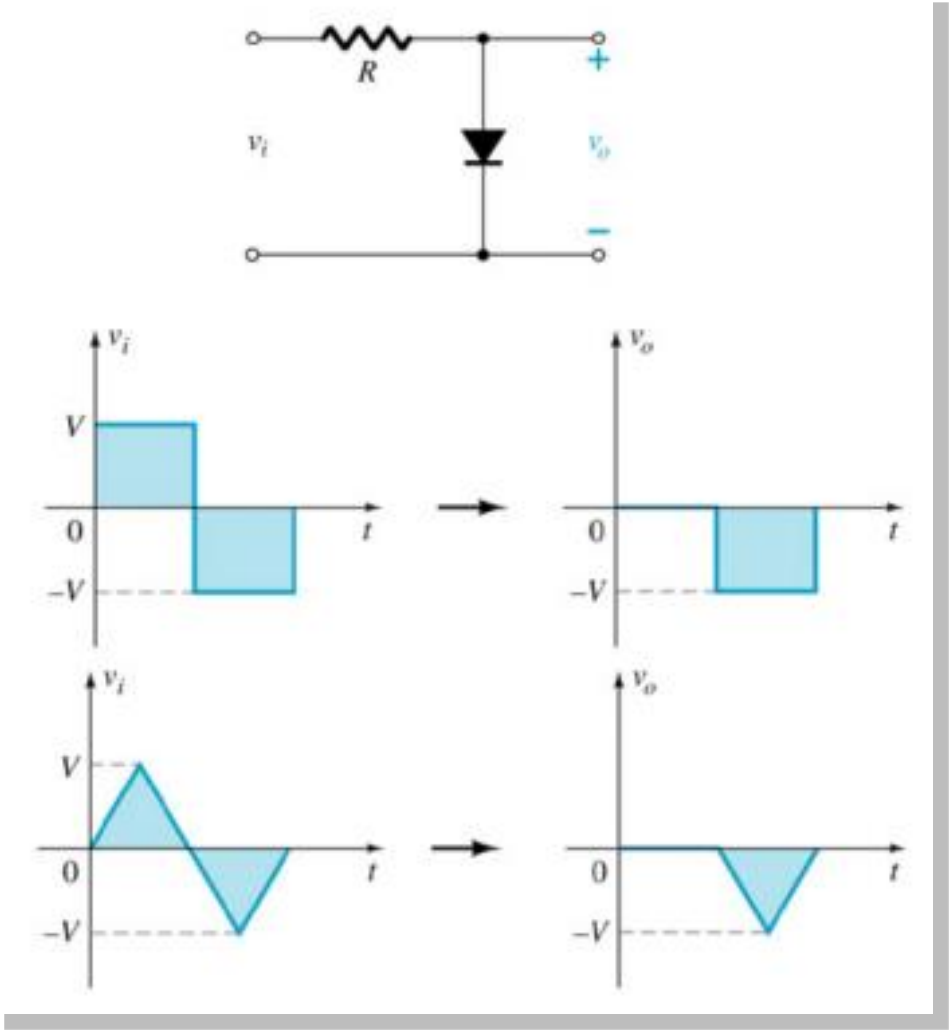




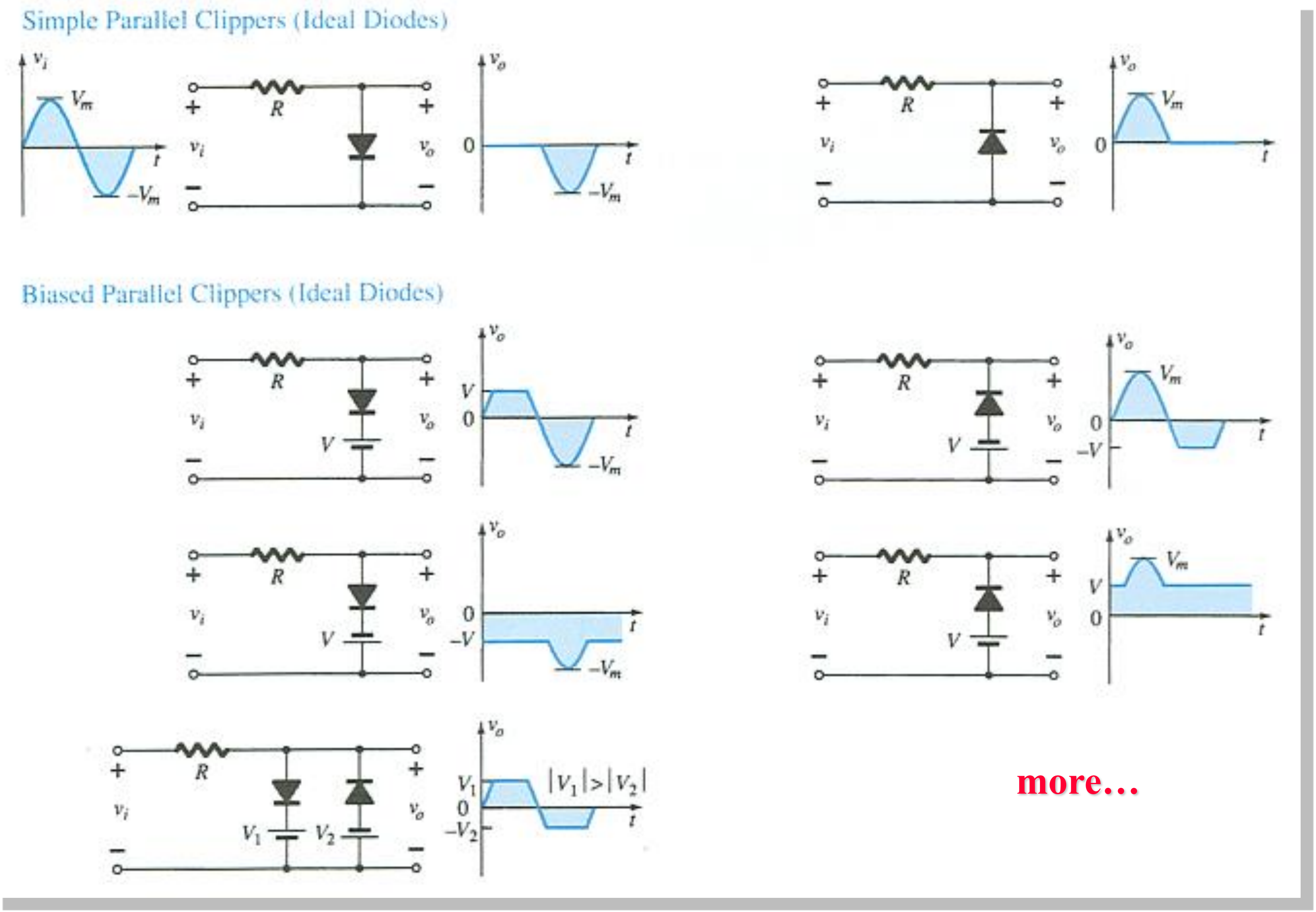
Parallel Clippers

The diode in a parallel clipper circuit "clips" any voltage that forward bias it.

DC biasing can be added in series with the diode to change the clipping level.



Summary of Clipper Circuits



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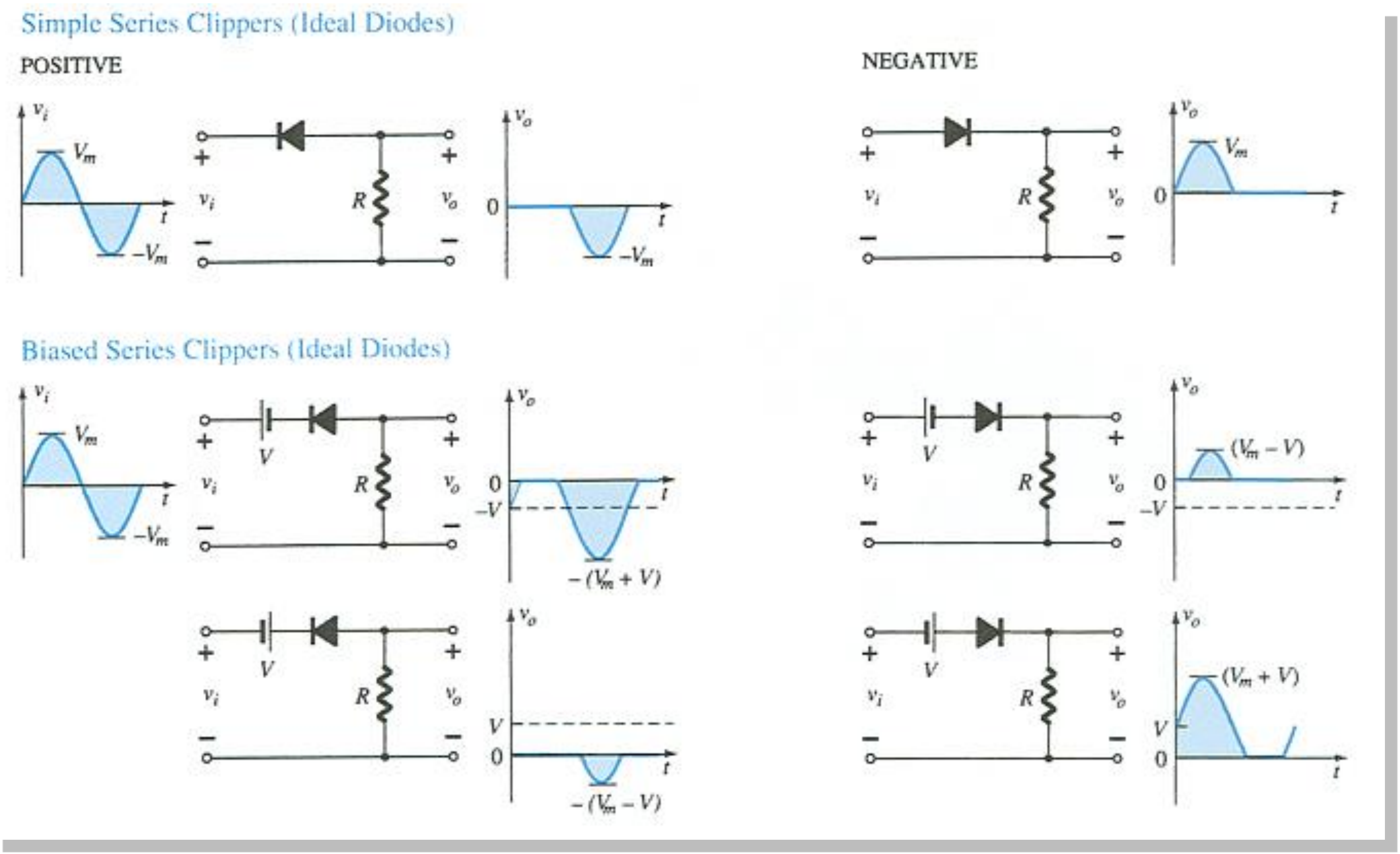
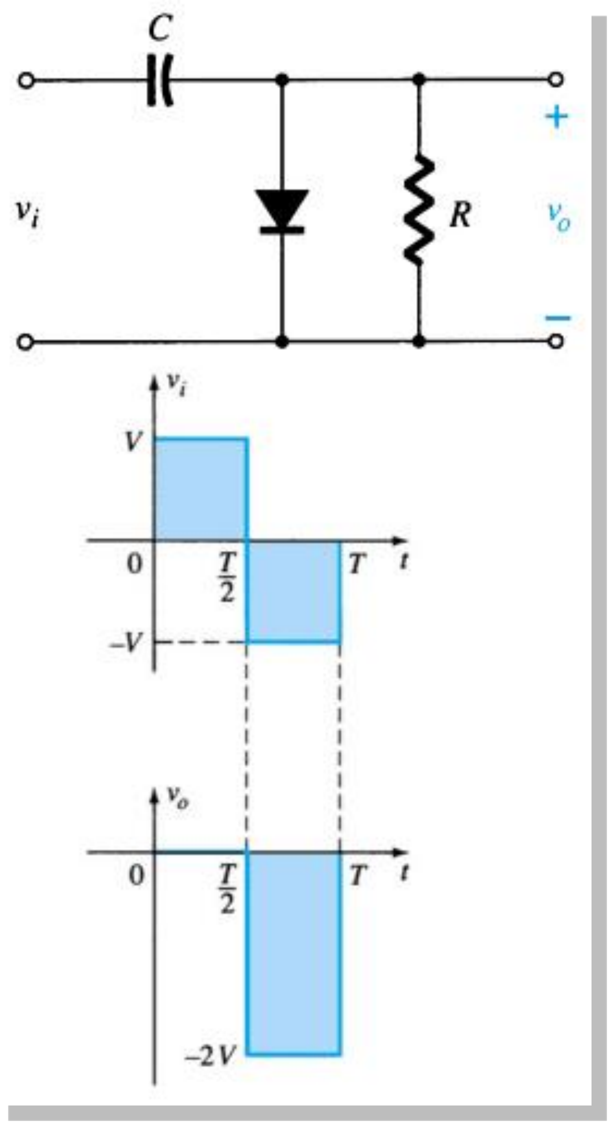
Summary of Clipper Circuits



Clampers

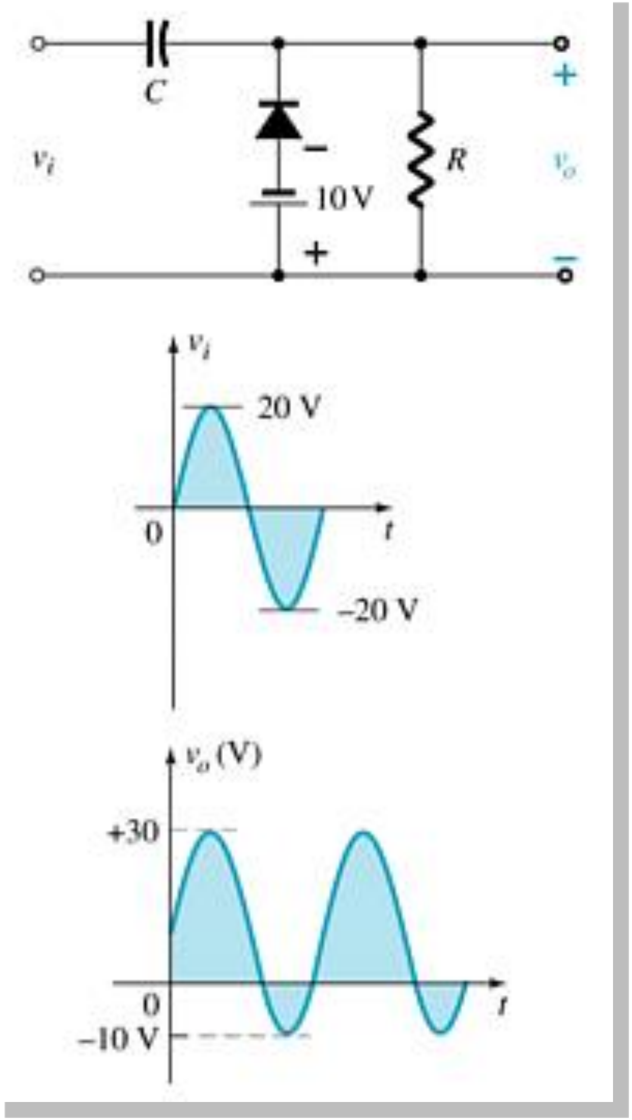
A diode and capacitor can be combined to "clamp" an AC signal to a specific DC level.



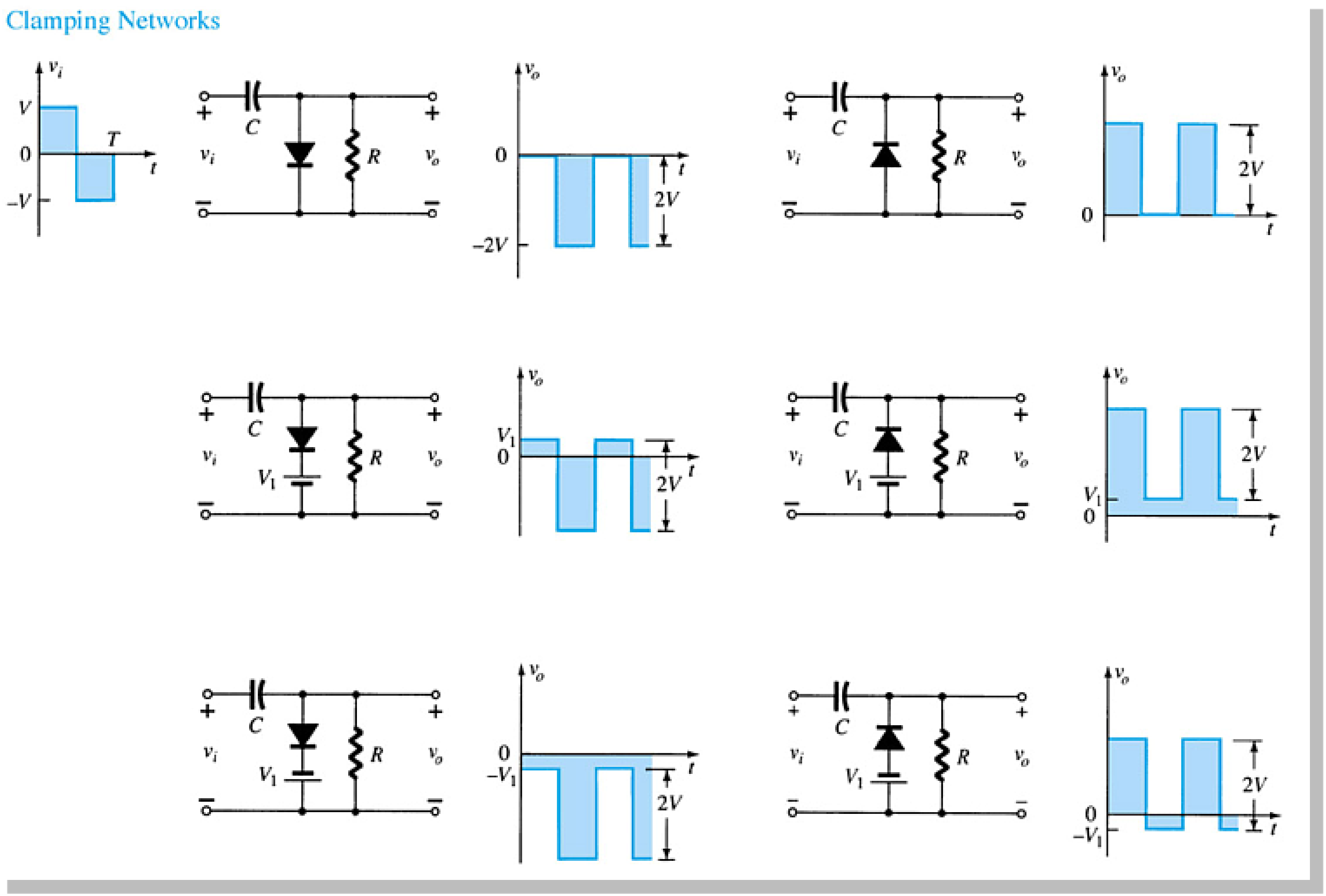
Biased Clamper Circuits

The input signal can be any type of waveform such as sine, square, and triangle waves.

The DC source lets you adjust the DC clamping level.

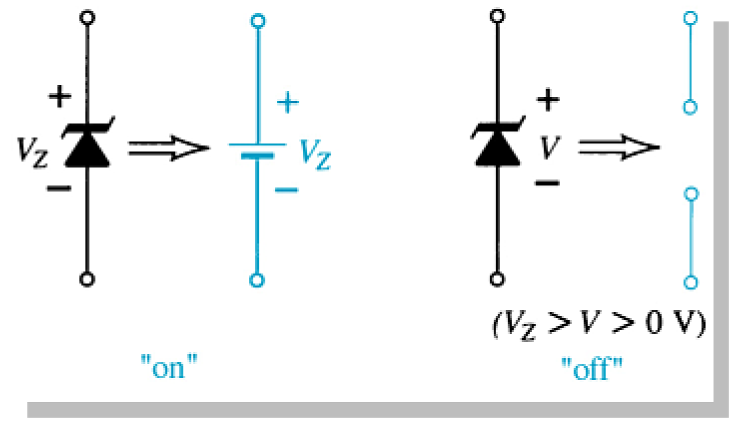


Summary of Clamper Circuits

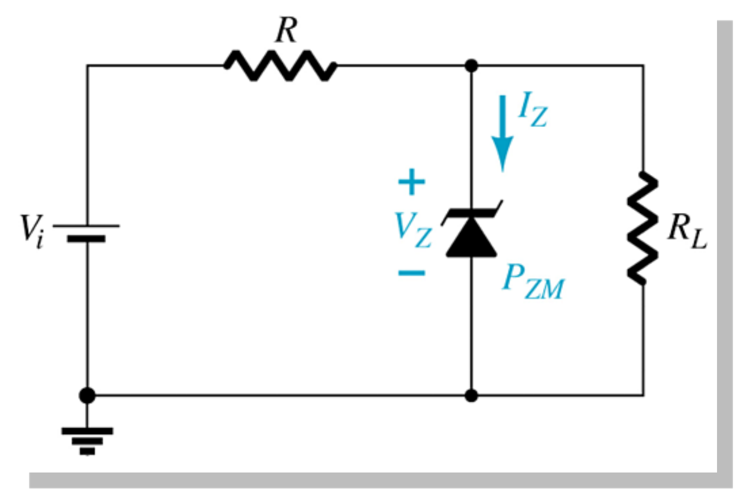


Zener Diodes

The Zener is a diode operated in reverse bias at the Zener Voltage (V_z).



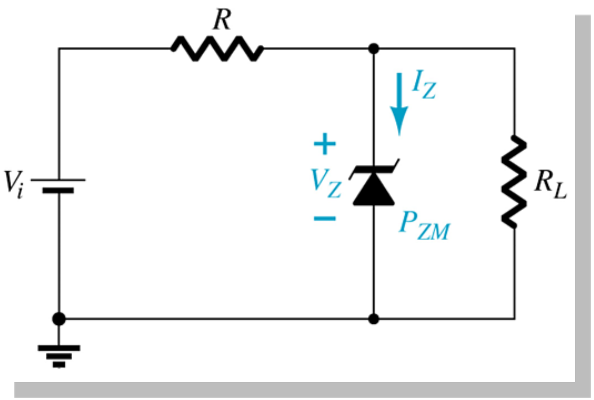
- When $V_i \geq V_Z$
  - The Zener is on
  - Voltage across the Zener is V_Z
  - Zener current: $I_Z = I_R - I_{RL}$
  - The Zener Power: $P_Z = V_Z I_Z$



- When $V_i < V_Z$
  - The Zener is off
  - The Zener acts as an open circuit

Zener Resistor Values

If *R* is too large, the Zener diode cannot conduct because the available amount of current is less than the minimum current rating, I_{ZK}. The minimum current is given by:



$$I_{L\min} = I_R - I_{ZK}$$

The *maximum* value of resistance is:

$$R_{L\max} = \frac{V_Z}{I_{L\min}}$$

If *R* is too small, the Zener current exceeds the maximum current rating, I_{ZM}. The maximum current for the circuit is given by:

$$I_{L\max} = \frac{V_L}{R_L} = \frac{V_Z}{R_{L\min}}$$

The *minimum* value of resistance is:

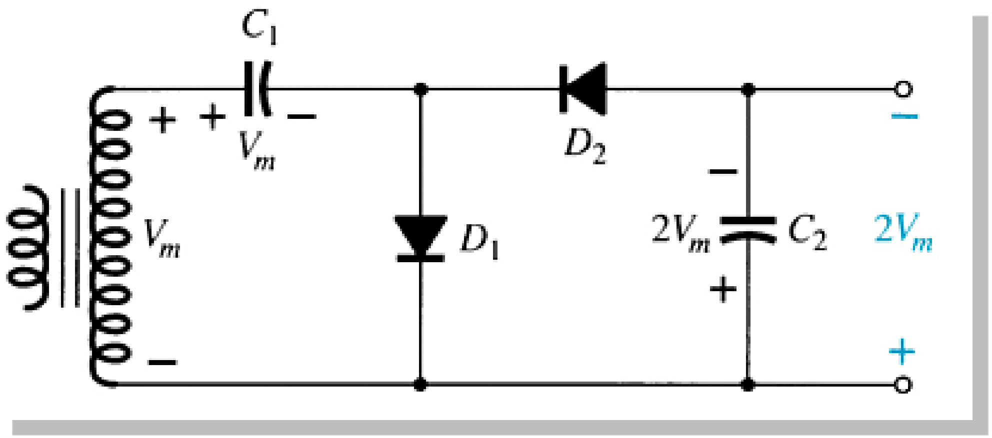
$$R_{L\min} = \frac{RV_Z}{V_i - V_Z}$$

Voltage-Multiplier Circuits

Voltage multiplier circuits use a combination of diodes and capacitors to step up the output voltage of rectifier circuits.

- **Voltage Doubler**
- **Voltage Tripler**
- **Voltage Quadrupler**

Voltage Doubler



This half-wave voltage doubler's output can be calculated by:

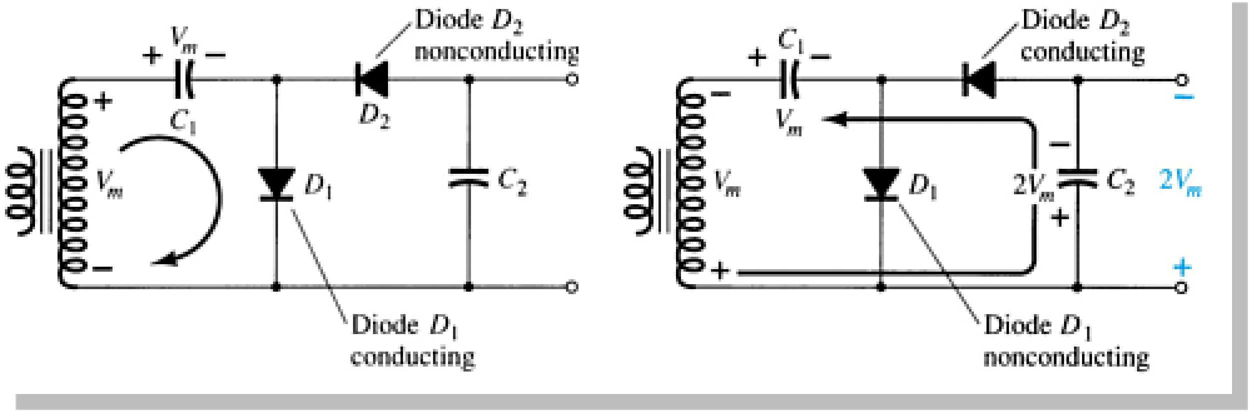
$$\mathbf{V_{out} = V_{C2} = 2V_m}$$

where V_m = peak secondary voltage of the transformer

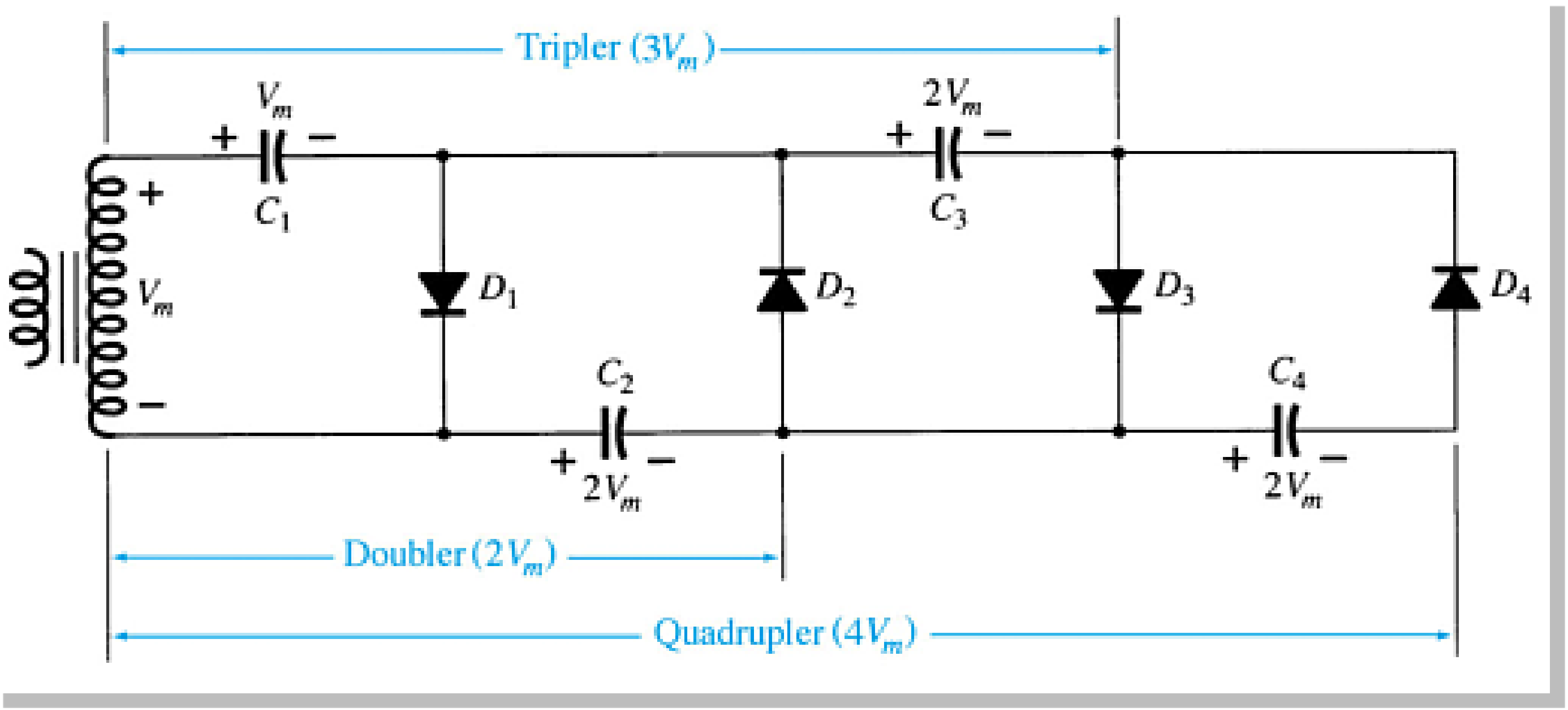
Voltage Doubler

- **Positive Half-Cycle**
  - **D_1 conducts**
  - **D_2 is switched off**
  - **Capacitor C_1 charges to V_m**

- **Negative Half-Cycle**
  - **D_1 is switched off**
  - **D_2 conducts**
  - **Capacitor C_2 charges to V_m**



Voltage Tripler and Quadrupler



Practical Applications

- **Rectifier Circuits**
  - **Conversions of AC to DC for DC operated circuits**
  - **Battery Charging Circuits**

- **Simple Diode Circuits**
  - **Protective Circuits against**
    - **Overcurrent**
    - **Polarity Reversal**
    - **Currents caused by an inductive kick in a relay circuit**

- **Zener Circuits**
  - **Overvoltage Protection**
  - **Setting Reference Voltages**