BASIC ELECTRONIC CIRCUITS

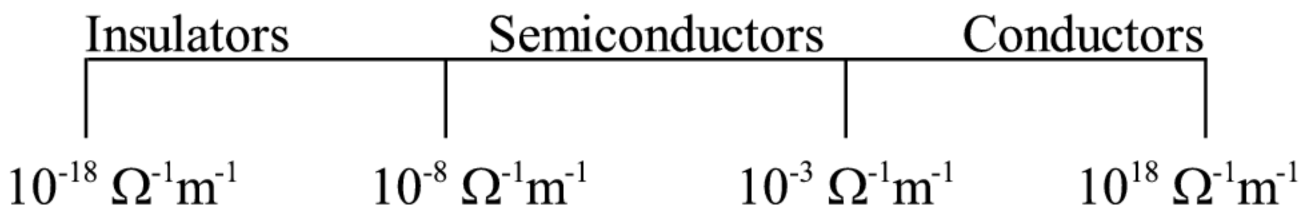
Chapter 3: DC Power Supply

Contents

- Diode Characteristics
- Regulated DC power supply
- Rectifiers: Half-wave and Full-wave
- Shunt capacitor filter
- Voltage regulator

Semiconductor Materials

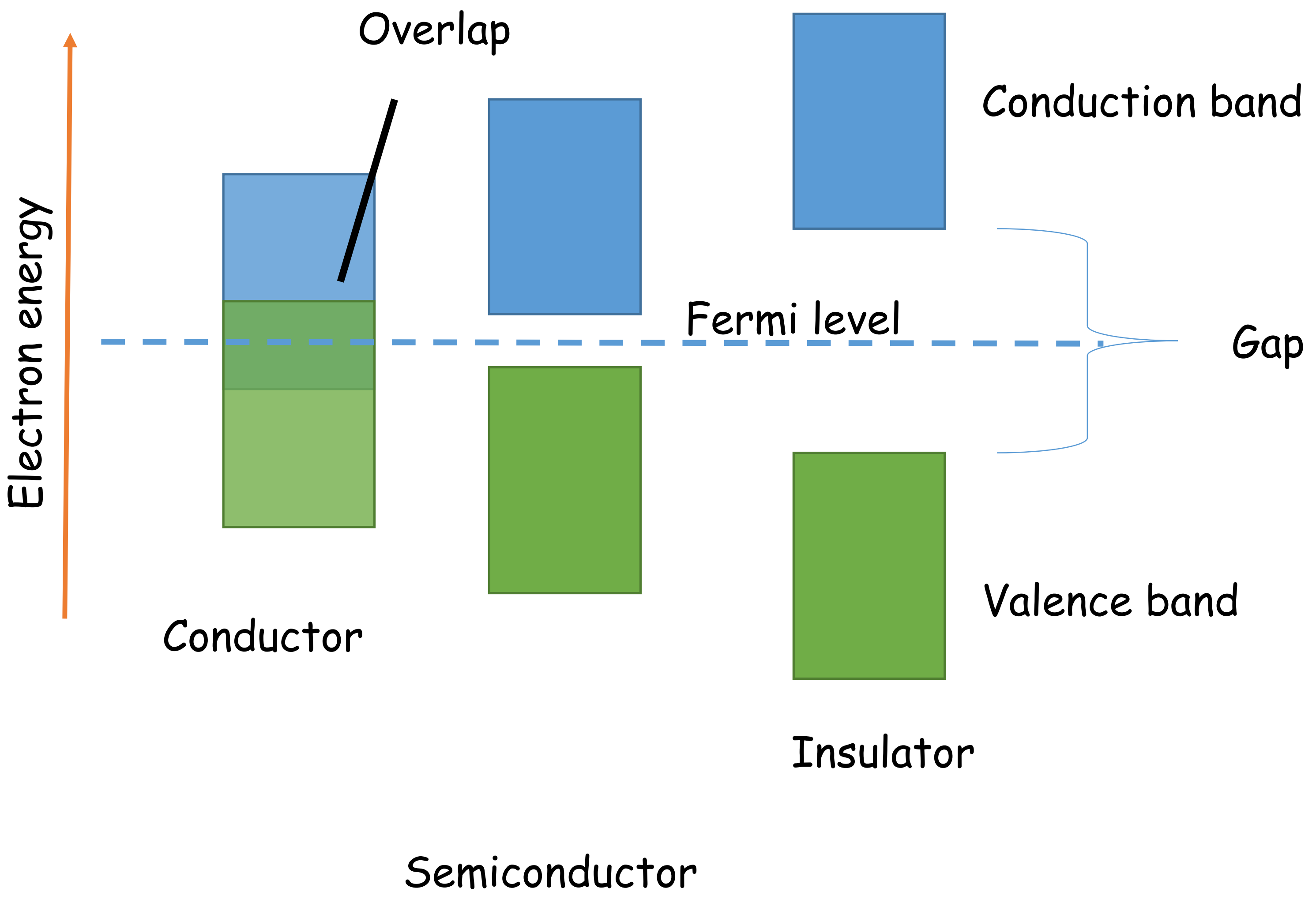
- Classification of materials



- They are used in, computers, laptops, cell phones, etc.

Silicon	**Si**	**14**	1. Cheap 2. Ultra High Purity 3. Oxide is amazingly perfect for IC applications
Germanium	**Ge**	**32**	1. High Mobility 2. High Purity Material 3. Oxide is porous to water/hydrogen (problematic)

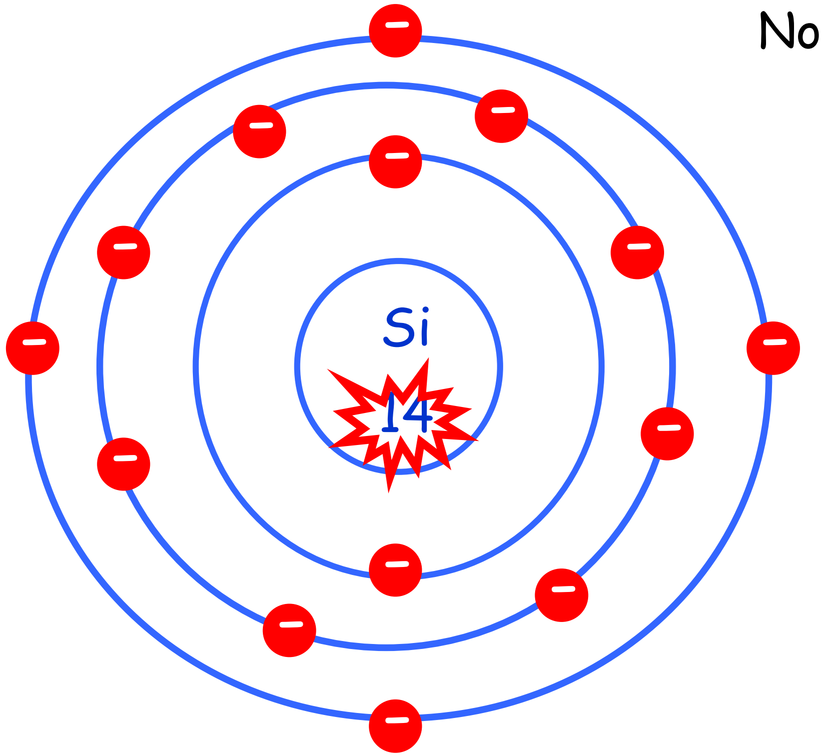
Energy band gap: Valence band and Conduction band



Silicon – 1.02 eV

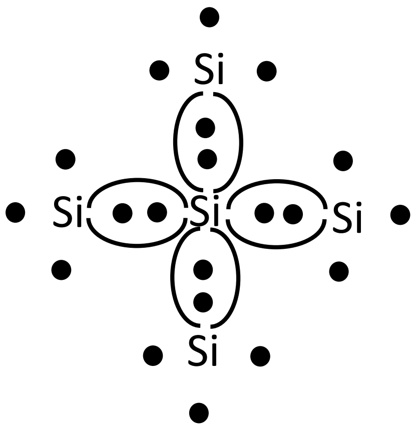
The Silicon Atomic Structure

No of electrons in each shell - $2(n^2)$



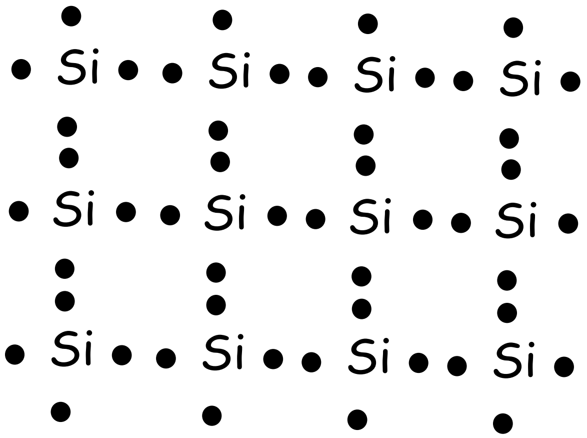
Silicon: Atomic no. 14
14 electrons in three shells: 2, 8, 4
i.e., 4 electrons in the outer "bonding" shell
Silicon forms strong covalent bonds with 4 neighbors

Intrinsic Semiconductor:

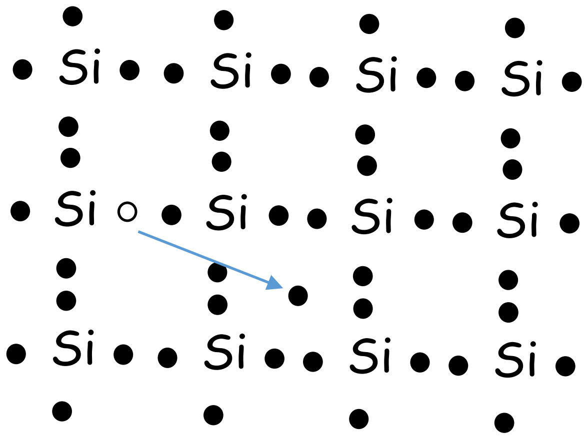


2D representation showing the covalent bond

- Each pair from strong covalent bond.
- Crystal of pure silicon has a rectangular lattice structure.
- At low temp. (0 K), all covalent bonds are intact and no electrons are available to conduct electric current.
- Intrinsic silicon crystal behaves as an insulator.



2D representation of single crystal silicon at T = 0 K; all the valence electrons are bound to the silicon atoms by covalent bonding.



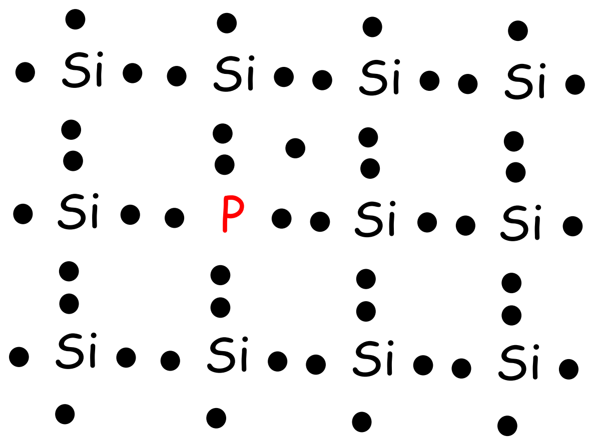
Breaking of the covalent bond for T > 0 K creating an electron in the conduction band and a positively charged "empty state".

- At room temp. ($\approx$ 300 K), sufficient thermal energy exists to break some of the covalent bonds, this is called **thermal generation**.
- This leads to breakage of covalent bond and an electron is **freed**.
- This free electron is available to conduct electric current when the electric field is applied to the crystal.

Doped Semiconductor

- In intrinsic semiconductor – equal concentration of free electrons and holes are generated by the thermal generation.
- These concentrations are far too small for silicon to conduct appreciable current at room temperature.
- A method was developed to change the carrier concentration in a semiconductor crystal substantially and in a precisely controlled manner.
- This process is called doping and the resulting silicon is referred to as doped silicon.
- What is Doping?
  - Introducing impurity atoms into the silicon crystal in sufficient numbers to substantially increase the concentration of either free electrons or holes but with little or no change in the crystal properties of silicon.

- Which concentration has to be improved?
  - To increase concentration of electrons 'n' silicon is doped with an element with a valence of 5, Eg. Phosphorus.
  - Leading to formation of n-type.
  - To increase the concentration of holes 'p' Silicon is doped with an element having a valence of 3, Boron.
  - Leading to the formation of p-type.



Dopant replace some of the silicon atoms in the crystal structure. Free electron donated by impurity atom. Pentavalent impurity atom called donor.

- Phosphorus has 5 valence electrons, 4 of these form covalent bonds with the neighboring atom and 5^{th} electron becomes the free electron.

- Hence one electron is donated by each phosphorus atom to the Silicon crystal and then P is called a Donor.

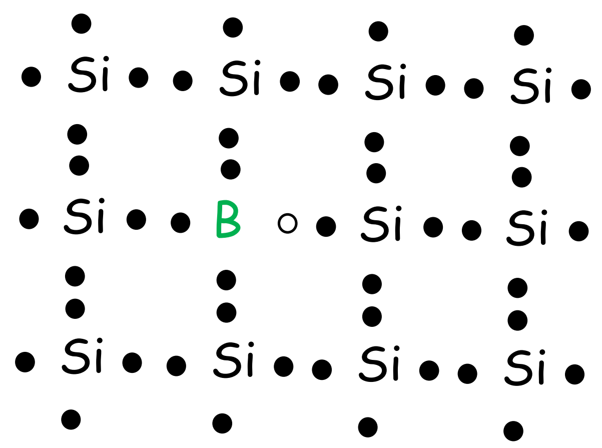
- Note that, there are **no-holes are generated** by this process.

- The +ve charge is a bound charge that does not move through crystal.

- Note that, in n-type silicon that concentration of free electrons will be much larger than that of holes.

- Electrons are said to be **majority** charge carries and holes the **minority** charge carriers in n-type silicon.

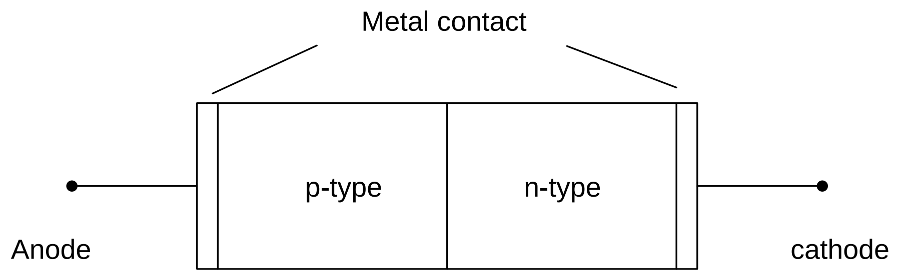
- To obtain the p-type silicon in which holes are the **majority** charge carriers, a trivalent impurity such as Boron is used.



Dopant replace some of the silicon atoms in the crystal structure. Each has 3 electrons in its outer shell, it accepts an electron from a neighboring atom, thus forming a covalent bond. The result is a hole in the neighboring atom and bound negative charge at the acceptor (Boron) atom. Each acceptor provides a hole.

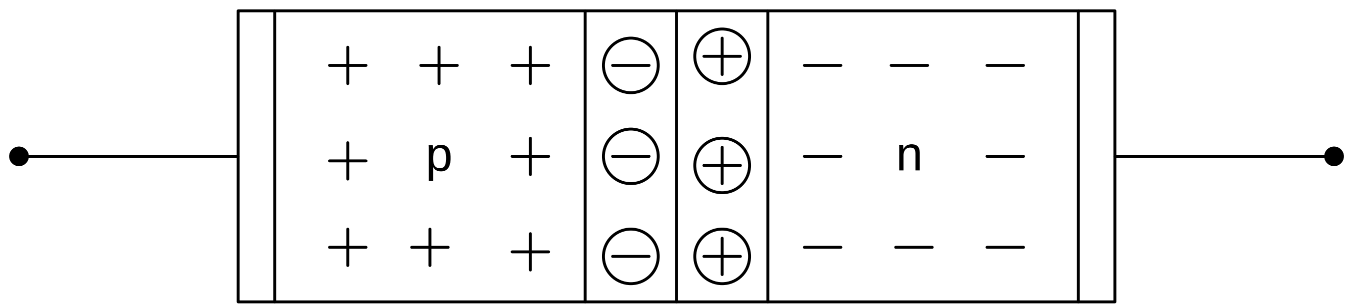
PN junction with open-circuit terminals

- pn junction is a practical semiconductor structure.



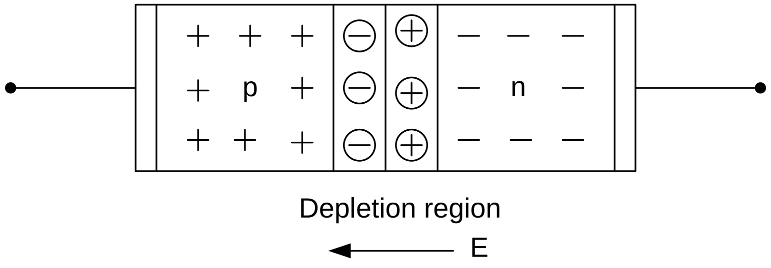
- Typically, p and n regions are part of the same silicon crystal, by creating regions of different doping (p and n regions)
- External contacts are made to the p and n regions through metal.
- Terminals of the pn junction are labeled as anode and cathode.

Operation with open-circuit terminals



- In p, majority holes (+) are neutralized by an equal amount of bound –ve charges of the acceptor atom, and minority charge carriers (electrons).
- In n, majority electrons (-) are neutralized by an equal amount of bound +ve charges of the donor atom, and minority charge carriers (holes).

Depletion region



- Holes diffuse across the junction into the n region quickly recombine with the majority electrons, and disappear.
- This also leads to disappearance of some free electrons from the n-type material.
- Thus some of the bound +ve charges will no longer be neutralized by the free electrons, thus these are called '**uncovered**' charges.

PN junction with an applied voltage

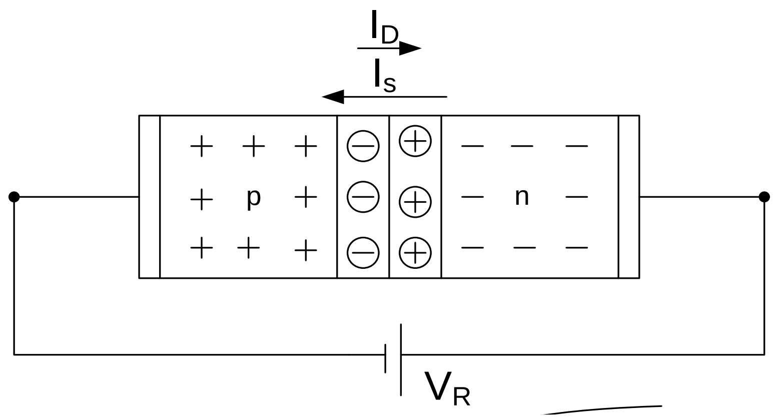
- To study the electrical conduction properties, apply a dc voltage between its two terminals of a pn junction.
- Forward-bias voltage – if the voltage applied so that the p side is made more positive than the n side.
- Reverse-bias voltage – if the n side is made more positive than the p side.
- pn junction exhibits vastly different conduction properties in its forward and reverse bias.

Reverse bias case

- The externally applied voltage is in the direction to add to the barrier voltage, and increases the effective barrier voltage.

- Leads to reduction in Diffusion current I_D, i.e., this reduces the no. of holes that diffuse into the n region and the number of electrons that diffuse in the p region.

- If I_D = 0, the current across the junction through the external circuit will be I_s.



- I_s, is due to thermally generated minority carrier drift and it is expected that I_s should be small and strongly dependent on temperature.

- Hence in the reverse-bias direction, pn junction conducts a very small and almost constant current I_s.

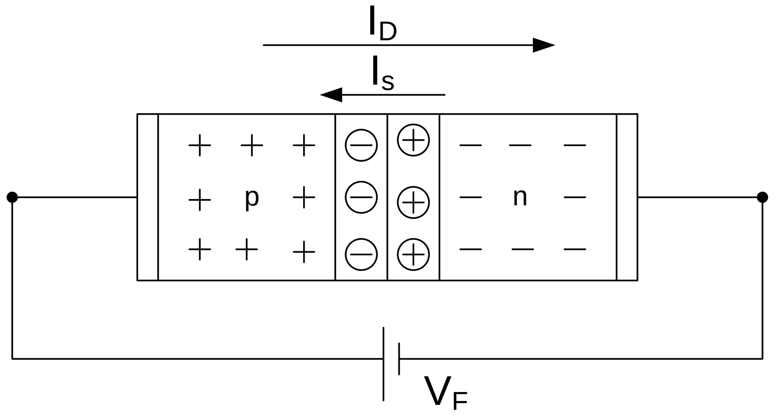
- Increase in the barrier voltage is accompanied by the corresponding increase in the strong uncovered charges on both sides of the depletion region.

- A wider depletion region needed to uncover the additional charge required to support the larger barrier voltage.

Forward-bias condition

- Applied voltage V_F is in the direction that subtracts from the built-in voltages V_o, resulting in a reduced barrier voltage.

- Reduction in barrier voltage will be accompanied by the reduced depletion region charge and corresponding narrower depletion region width W.



- Lowering of the barrier voltage will enable more holes to diffuse from p to n and more electrons from n to p.

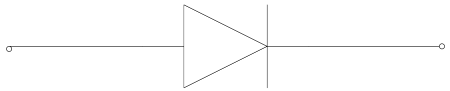
- Hence the diffusion current I_D increases substantially and can become many orders of magnitude larger than the drift current I_s.

- Current in the external circuit, $I = I_D - I_s$, flows in the forward direction of the junction from p to n.

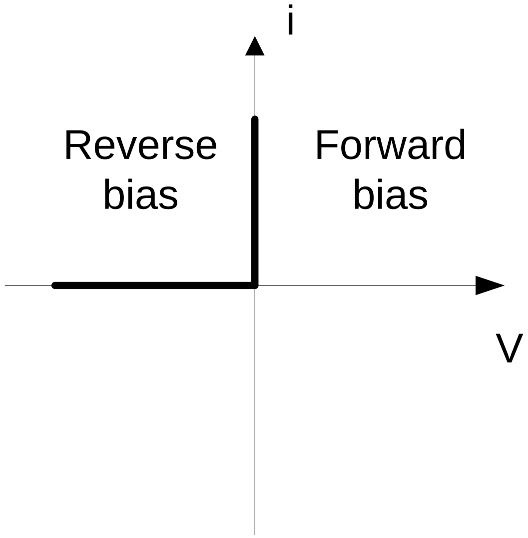
Diodes

- A simple and fundamental nonlinear circuit element
- has nonlinear i-v characteristics
- Application of the nonlinear elements in generating:
  - DC voltage from AC voltage, rectifier circuits.
  - Signals of various waveforms
  - Digital logic and memory circuits

The Ideal Diode

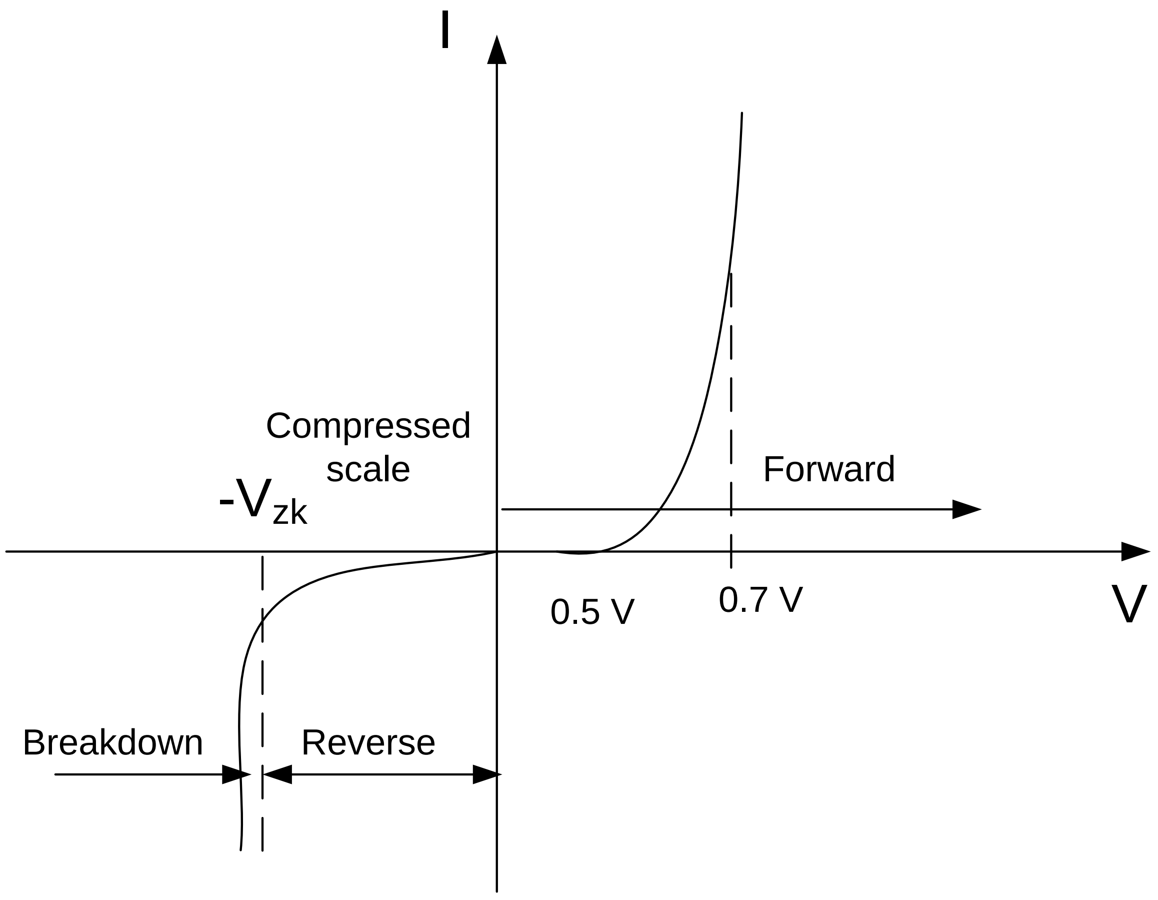


- The most fundamental nonlinear circuit element.
- For –ve voltage, no current flows and the diode behaves as open circuit, then the diode operation mode is said to be reverse biased.
- It has '0' current in the reverse operation, and said to be "cut-off" or "off".
- If a +ve current is applied, 0 voltage drop appears, it behaves as a short circuit in forward direction.
- A forward-biased circuit is said to be "turned on" or "on".



Terminal characteristics of a junction diodes

- The most common implementation of the diode utilizes a pn junction.
- PN junction can conduct substantial amount of current in forward direction and almost no current in the reverse direction.
- i-v char. of pn junction has three regions:
  - Forward V > 0
  - Reverse V < 0
  - Breakdown V < $-V_{zk}$



The forward region $I = I_s\left(e^{V/nV_T} - 1\right)$

- n varies between 1 and 2, depending on material and physical construction.
- I_s is constant for given diode for given temp., Saturation current, scale current-> due to directly proportional to the cross-sectional area of the diode.
- I_s is very strong function of temp., of the order of 10^{-15} A, it gets double for each 5 ^oc rise in temperature.
- The voltage (V_T) is a thermal voltage = kT/q.
- At room temp. (20 ^oC), V_T = 25.3 mV.

$$V = V_T \ln \frac{I}{I_s}$$

- the exponential relation of the current i to the voltage V holds over many decades of the current (10^7), remarkable property of junction diodes.

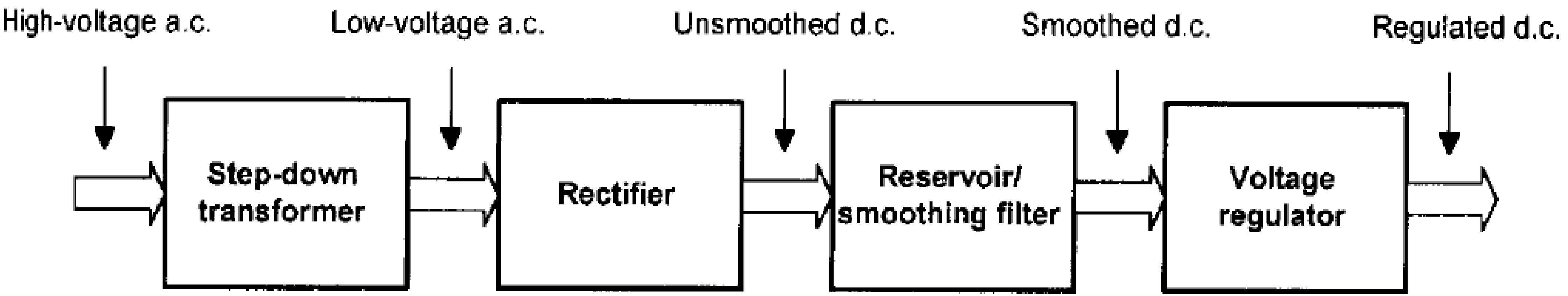
The reverse bias region

- In the RB region, the diode voltage is made negative.
- For V negative and few times grater than thermal voltage, leads to corresponding exponential function becomes much less than unity.
- $i = -I_s$.
- Real diodes exhibit reverse currents that though quite small, and much larger than I_s.
- Large part of the reverse current due to leakage effects, and they are proportional to junction area, the reverse current gets double for every 10 deg. Rise in temp.

The Breakdown region

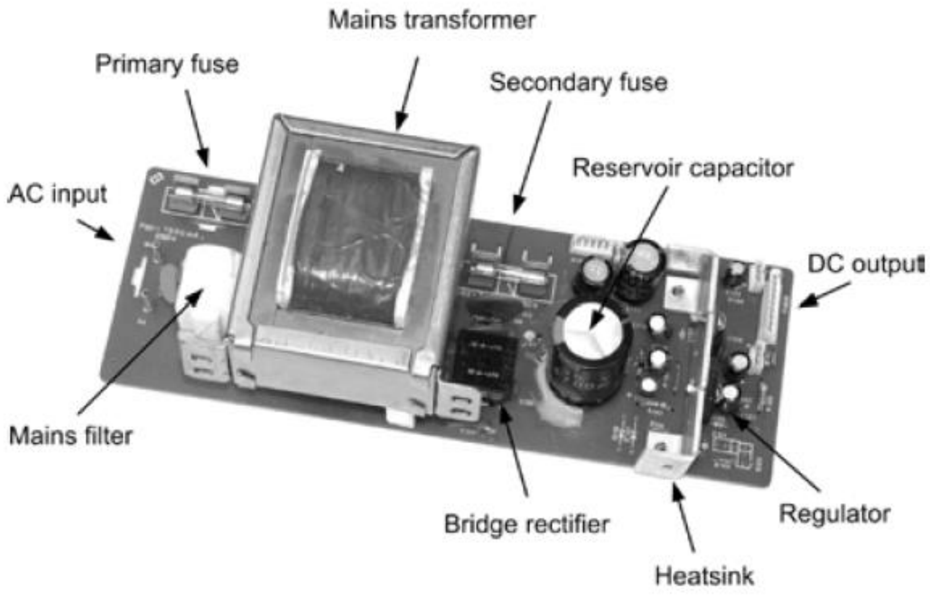
- The magnitude of the reverse voltage exceeds a threshold value that is specific to the particular diode breakdown voltage.
- This is the voltage at the 'knee' of the i-v curve, and is denoted by V_{zk}.
- In the breakdown region the reverse current increases rapidly with the associated increase in voltage drop being very small.

DC Power Supply:



Block diagram of a dc power supply.

- Power supply is fed from the V_s volts ac line, and it delivers a dc voltage V_o to an electronic circuit called load.
- V_o required to be as constant as possible in spite of variations in the ac line voltage and current drawn by the load.



- **Diode rectifier**: converts the input sinusoid V_s to a unipolar output, this wave form has a non zero average or dc component, this pulsating nature makes it **unsuitable** as a dc source for electronic circuits, **needs filtering**.

- **Filter:** the variations in the magnitude of the rectifier o/p are considerably reduced by the filter block.

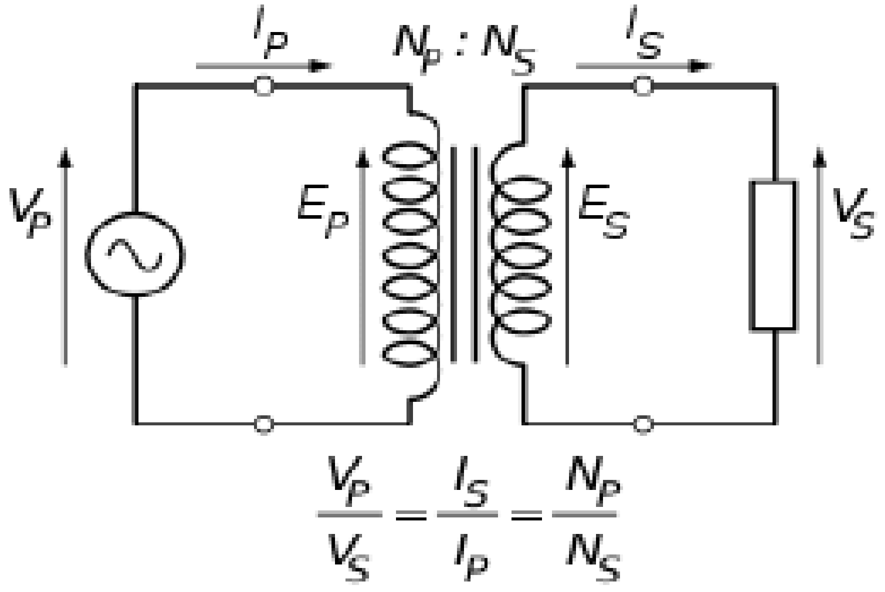
- The o/p of the rectifier filter, though much more constant than without the filter, still contains a time-dependent component known as ripple.

- A voltage regulator is employed to reduce the ripple and also to stabilize the magnitude of the dc o/p voltage. Such regulator can be implemented by using the Zener shunt regulator.

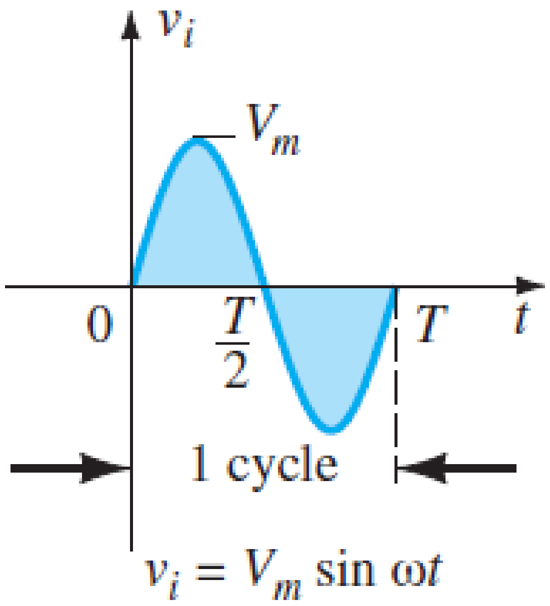
- **<u>Power transformer</u>**: consists of two separate coils wound around an iron core that magnetically couples the two windings.

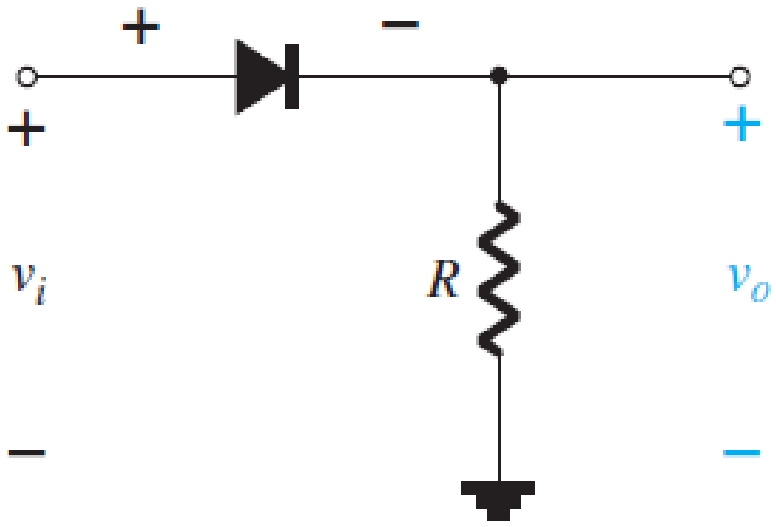
- The primary winding having N_P turns is connected to V_P supply, and the secondary winding having N_S turns is connected to the circuit of the dc power supply. An ac voltage V_s (= V_s N_2/N_1) develops between the two terminals of the secondary winding.

- It provides electrical isolation between the electronic equipment and power line circuit, this minimizes the electric shock to the equipment user.

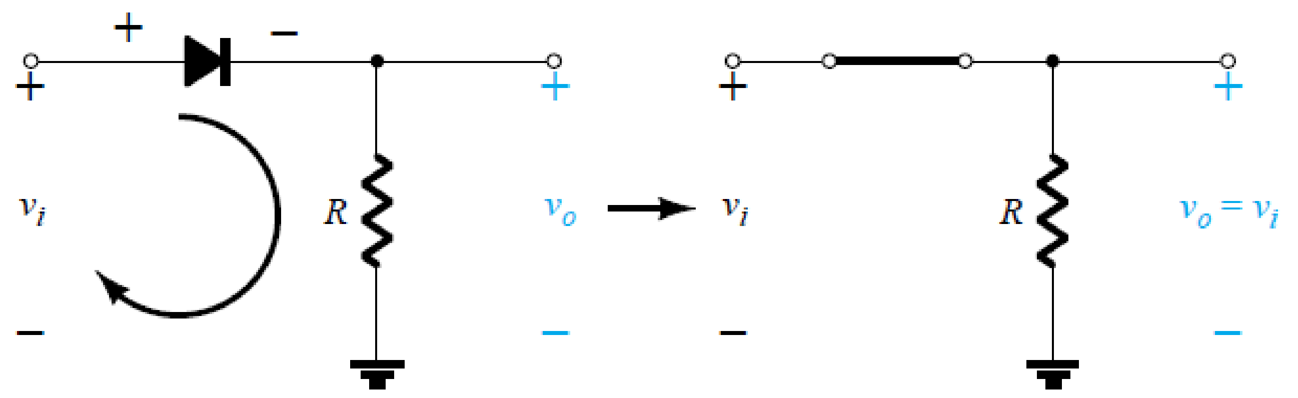


The half-wave rectifier

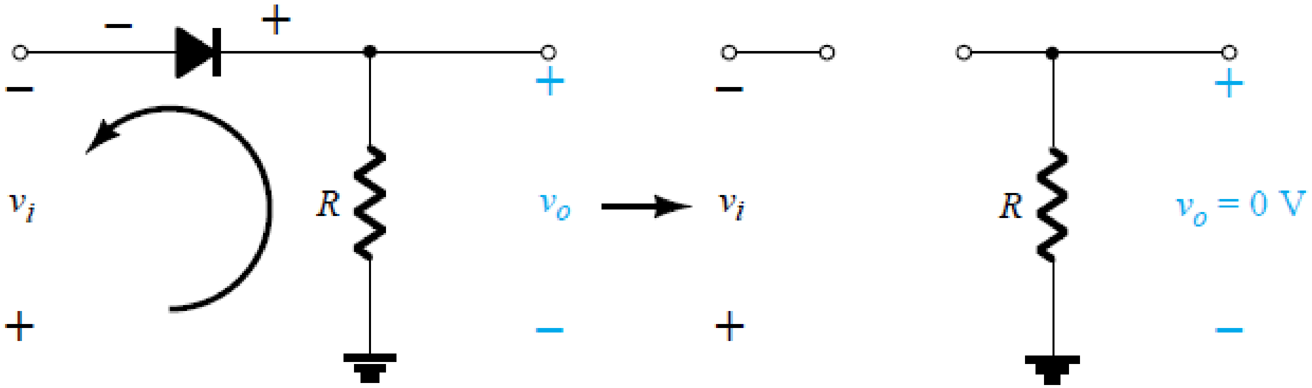


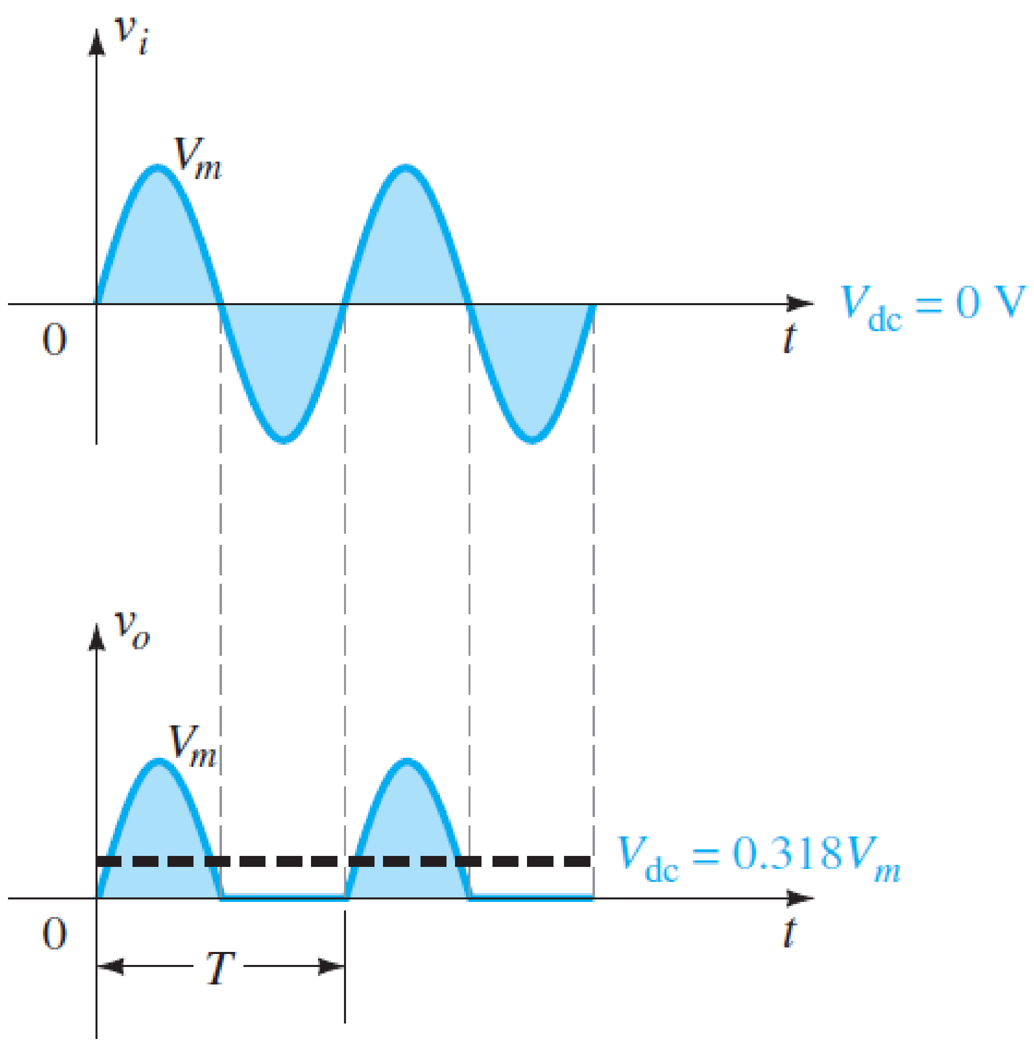


For the +ve half cycle: 0 to T/2



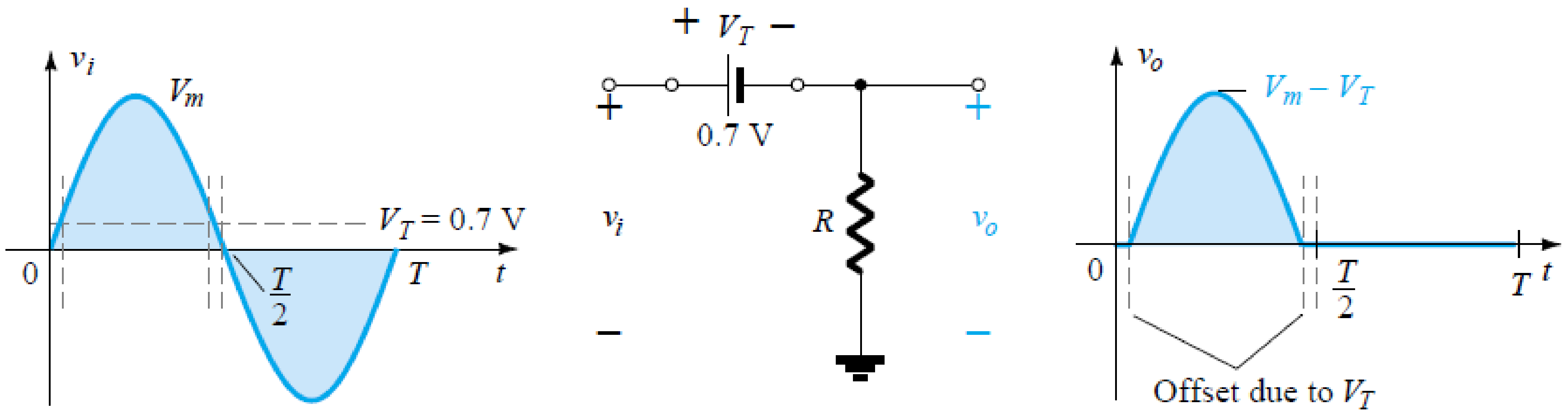
For the -ve half cycle: T/2 to T





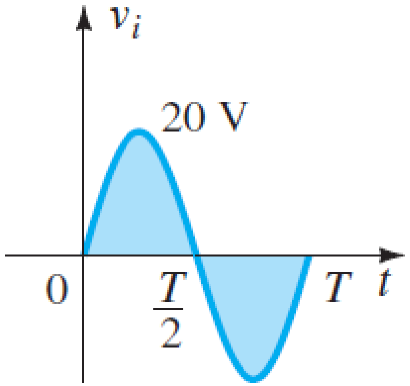
$$V_{avg} = V_{dc} = \frac{1}{T}\int_0^T V_m \sin wt dt = \frac{V_m}{\pi}$$

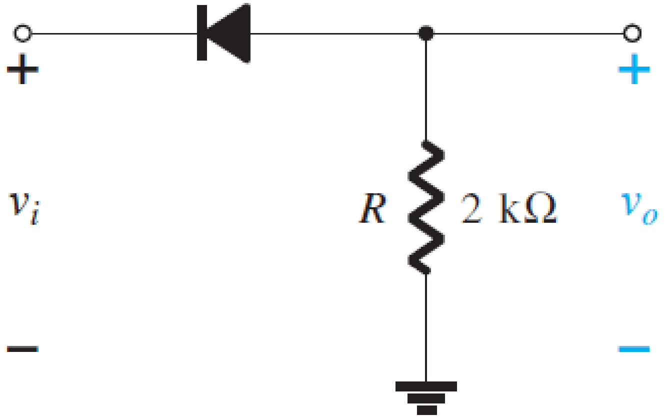
Silicon diode with cut-in voltage: 0.7 V.



$$V_{avg} = V_{dc} = \frac{(V_m - VT)}{\pi}$$

Example: Draw the wave-form of v_o, determine its dc value, and amplitude.

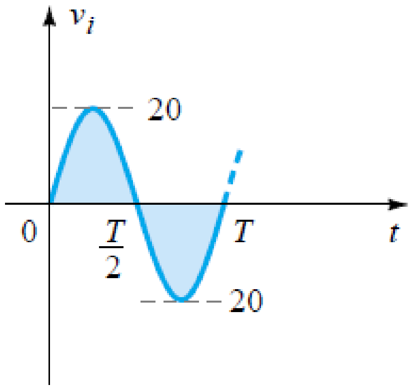


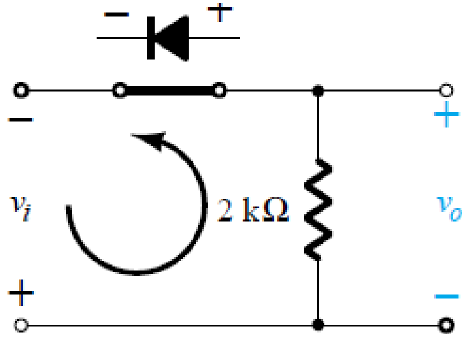


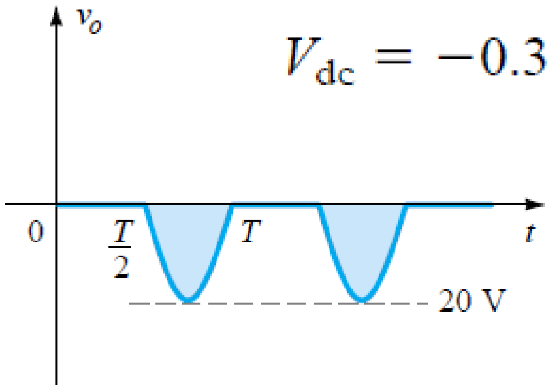
If the diode is replaced with a silicon diode then the Avg. Or DC voltage

$$V_{dc} \cong -0.318(V_m - 0.7\text{ V}) = -0.318(19.3\text{ V}) \cong \mathbf{-6.14\text{ V}}$$

Sol:

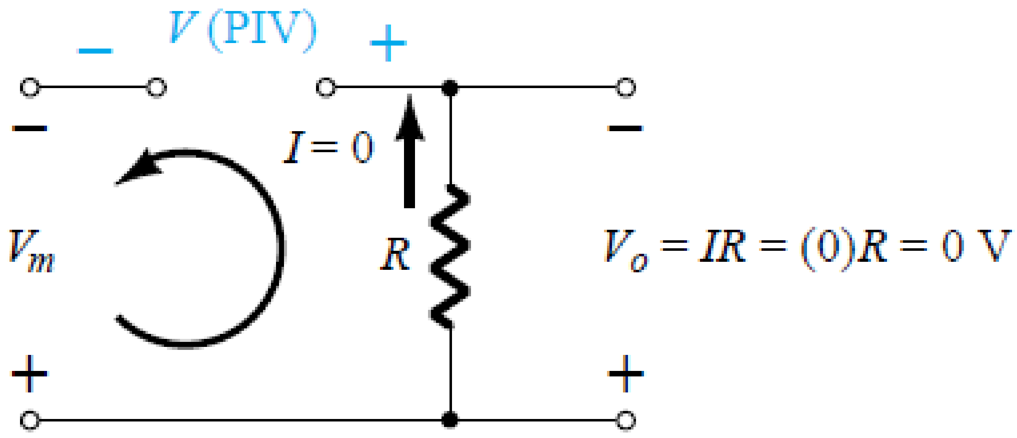






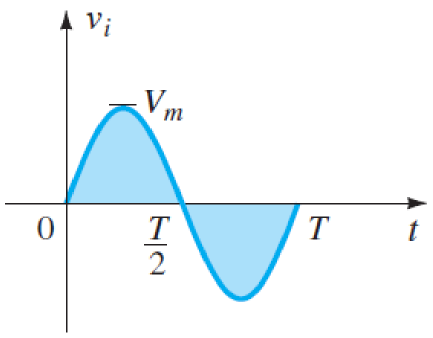
$$V_{dc} = -0.318V_m = -0.318(20\text{ V}) = \mathbf{-6.36\text{ V}}$$

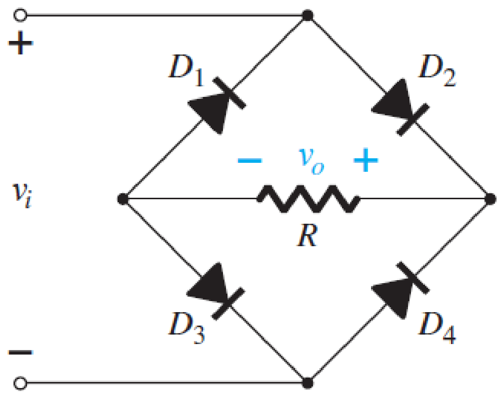
- **Peak inverse voltage (PIV) or Peak reverse Voltage (PRV):**
- PIV or PRV rating is of primary importance in the design of rectification systems.
- Diode must be able to with stand without breakdown, which is determined by the largest reverse voltage that is expected to appear across the diode.

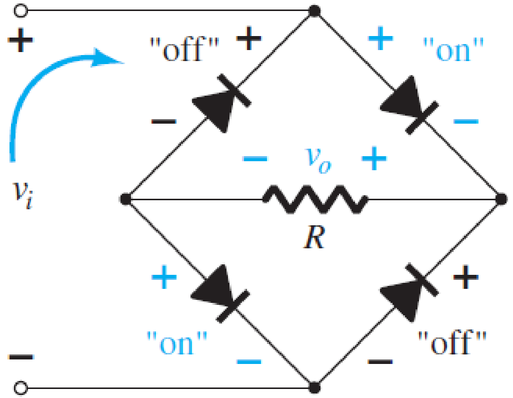


$$\boxed{\text{PIV rating} \geqq V_m}$$

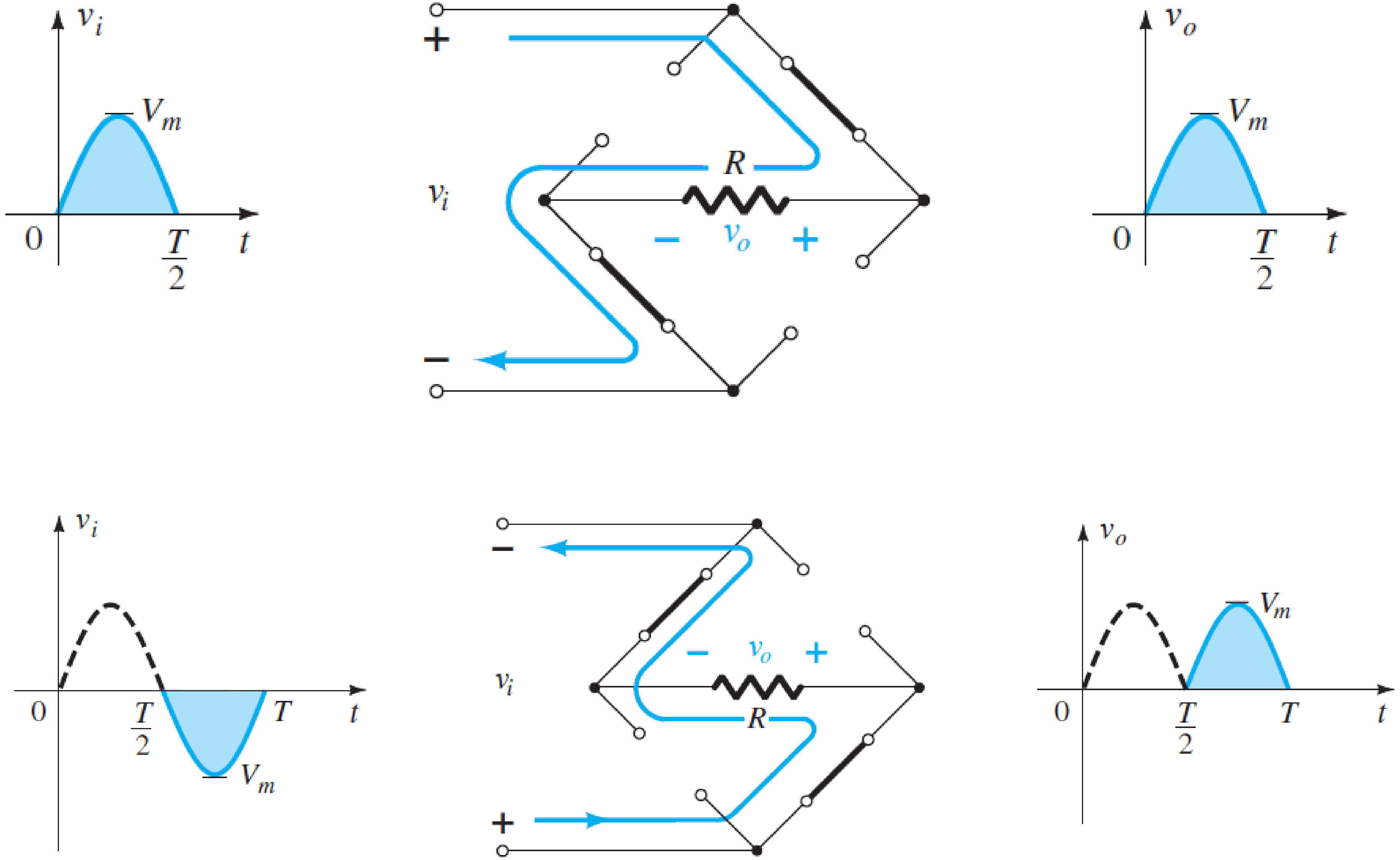
Full wave rectification: The bridge rectifier



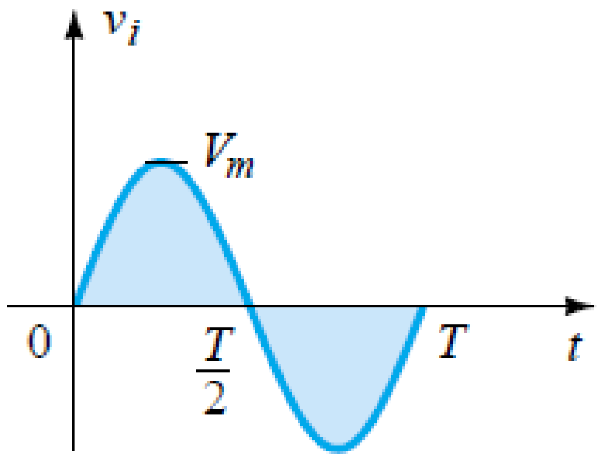


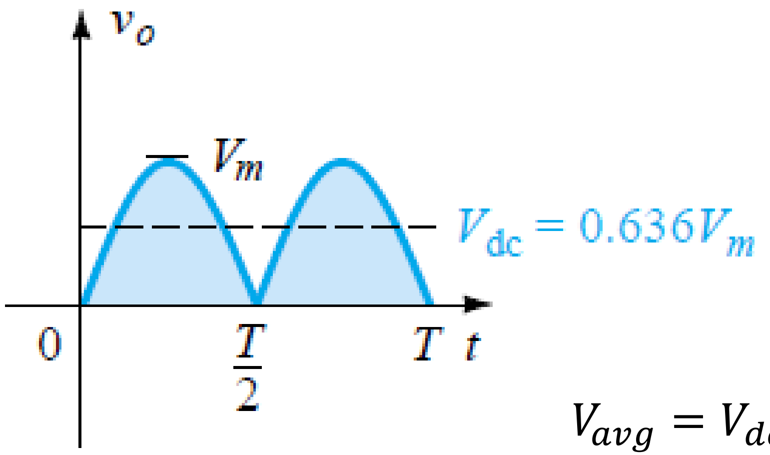


- Utilizes both halves of the input sinusoid, to provide unipolar output.
- Inverts the negative halves of the sine wave.
- During the positive half-cycles, current is conducted through D_2, R, and D_3.
- Since two diodes are ideal, the load voltage Vo = V_i .
- During the negative half-cycle current is conducted through D_4, R, and D_1.
- During both half-cycles, current flows through R in the same direction and thus Vo will always be +ve.



v_i
V_m
0
$\frac{T}{2}$
t
+
−
R
v_o
v_o
V_m
T



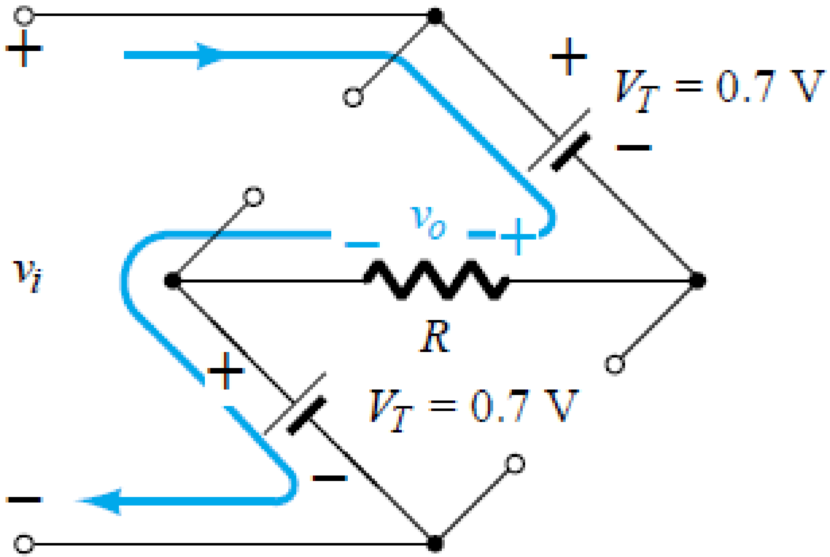


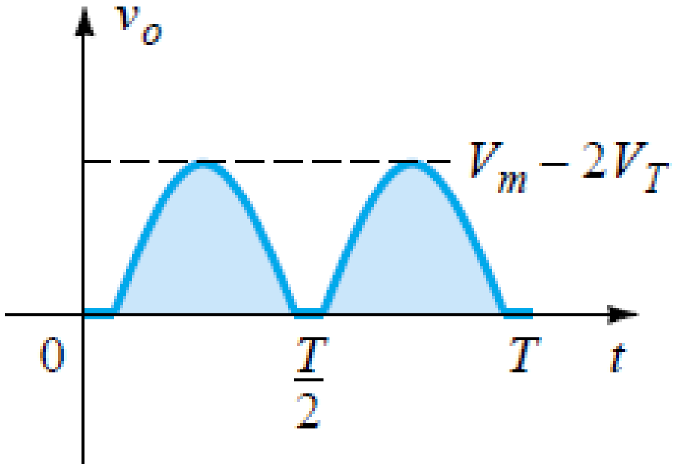
$$V_{avg} = V_{dc} = \frac{2}{T}\int_0^{T/2} V_m \text{sin} wtdt = \frac{2V_m}{\pi}$$

- PIV: during the positive half-cycle, the reverse voltage across D_1 can be determined from the loop formed by D_1, R, and D_2 as, $V_{D1} = v_o$

- Thus the maximum value of V_{D1} occurs at the peak of Vo and is given by, PIV = V_m.

- If Silicon diode is used in bridge rectifier circuit:
- For the case of +ve half cycle:

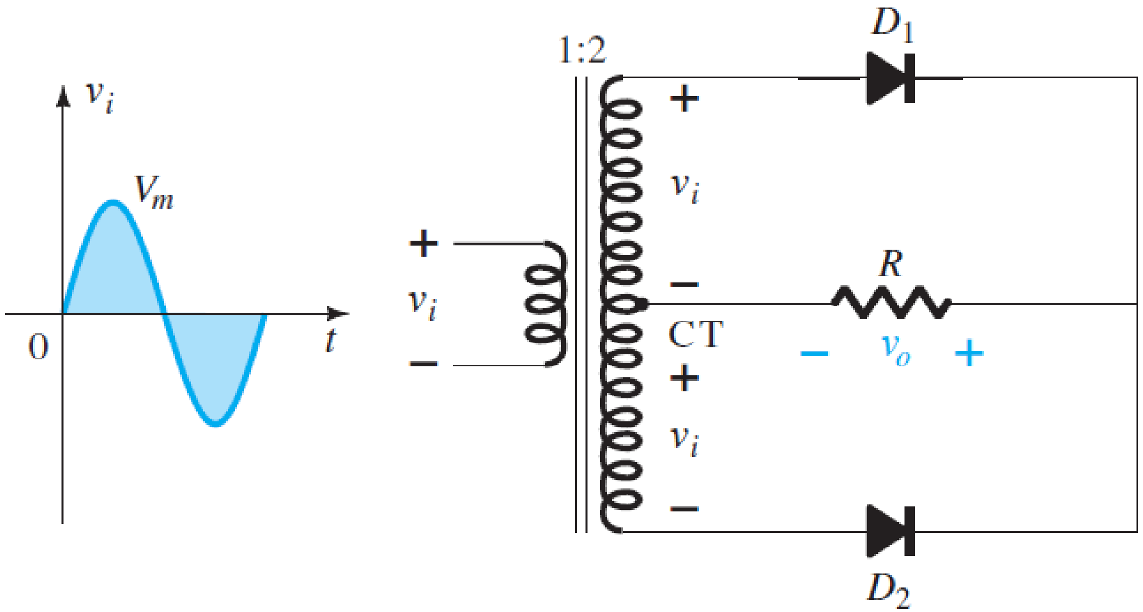




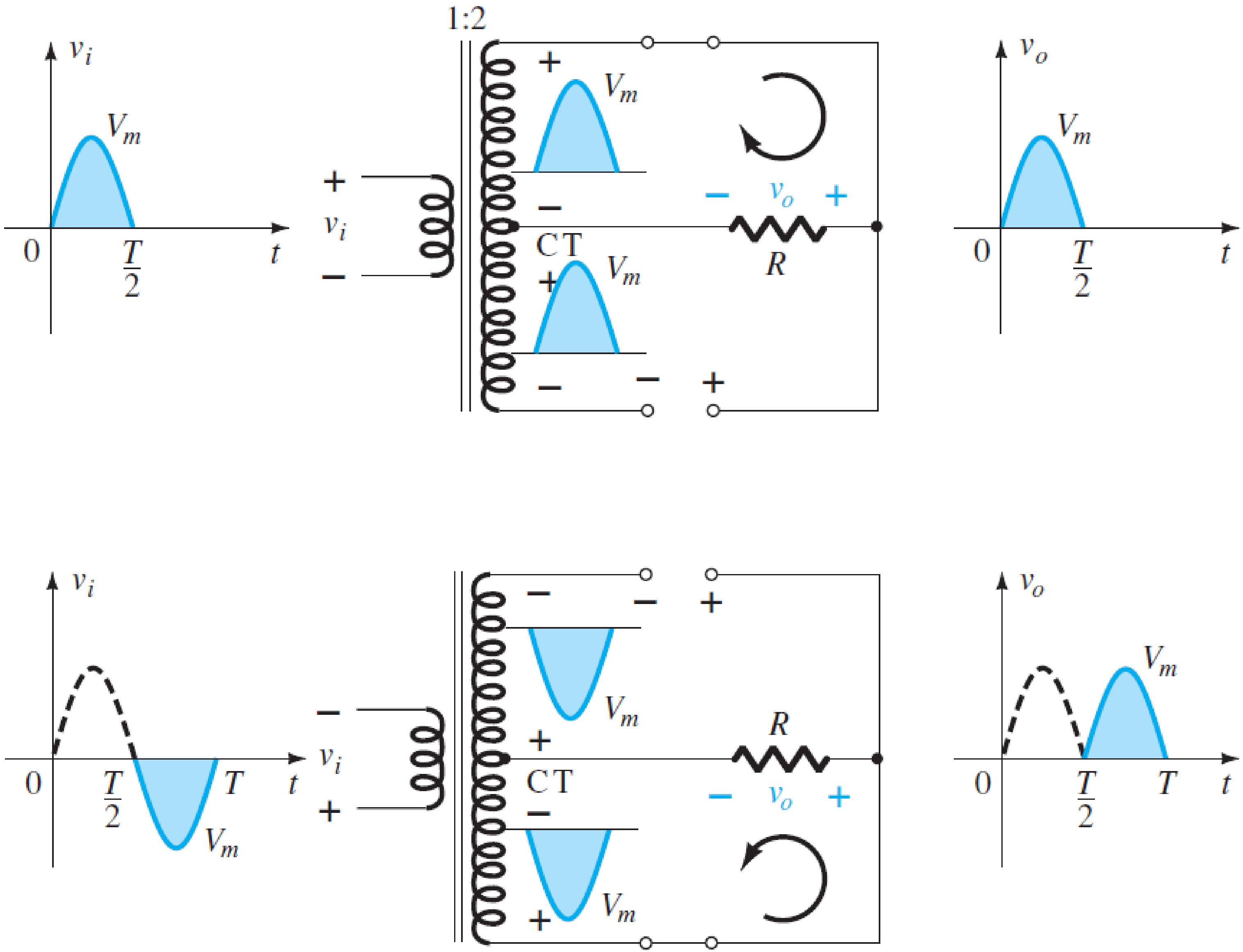
$$v_i - V_T - v_o - V_T = 0$$

$$v_o = v_i - 2V_T$$

The full-wave rectifier



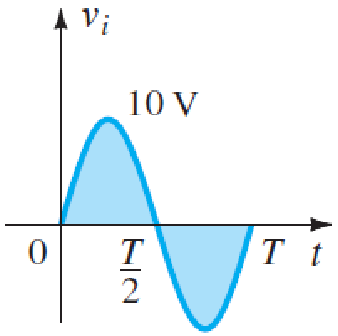
- The transformer was center-tapped to provide two equal voltages V_i, across the two halves of the secondary winding.
- During the positive half cycle only D_1 will conduct and D_2 will be off.

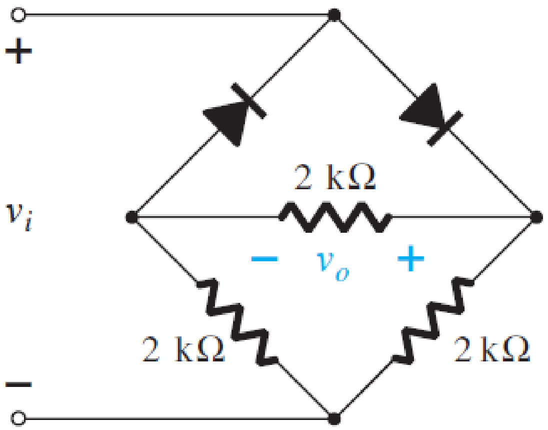


1:2
vi
Vm
0
T/2
t
+
vi
−
CT
R
vo
T

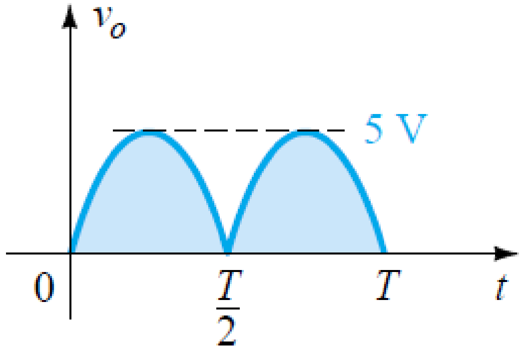
- During the negative half cycle D_1 will be cut-off and D_2 will conduct.
- Note that, current through 'R' always flows in the same direction and Vo will be unipolar.
- The full wave rectifier obviously provides a more energetic wave form than that of a half-wave rectifier.
- **PIV**: during the positive half cycle D_1 on and D_2 off and the reverse voltage across D_2 will be V_m+V_R.
- Reaches maximum when V_R at its peak value V_m and V_m at its peak value, PIV = $2V_m$.

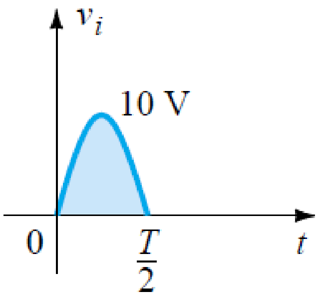
- Determine the o/p wave-form of the network, calculate the o/p dc level, and required PIV of each diode.

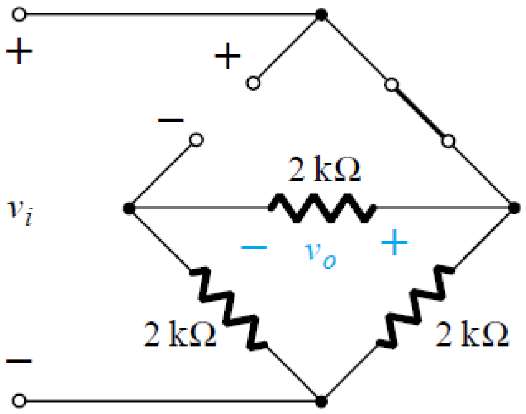


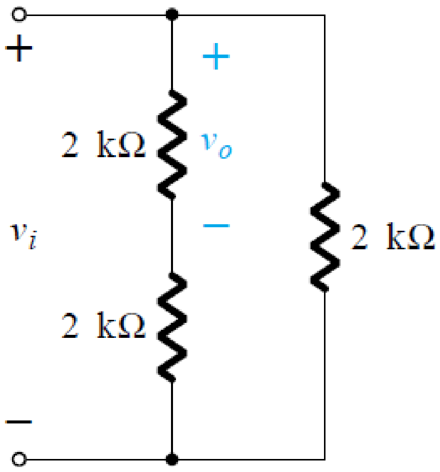


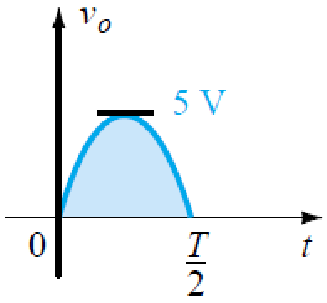
$V_{dc} = 0.636(5\text{ V}) = \mathbf{3.18\ V}$



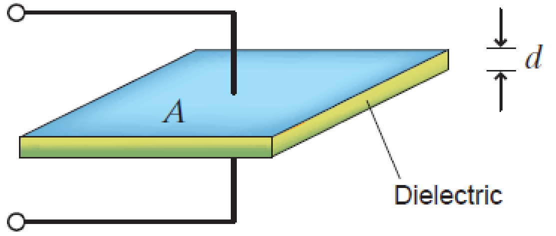








Capacitor as a Filter



$$q = Cv \qquad C = \frac{\varepsilon A}{d}$$

- Stores electric energy

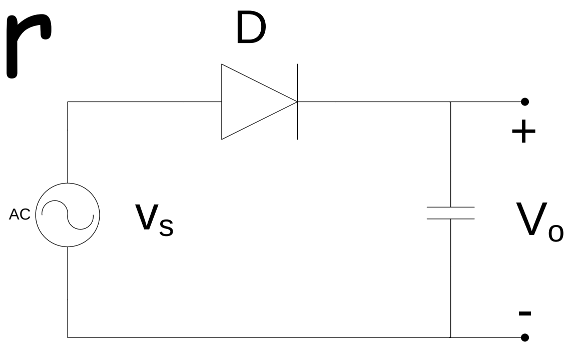
- Current i is given by, $i = C\dfrac{dv}{dt}$

- Power delivered to the element is given by, $p(t) = v(t)i(t) = Cv(t)\dfrac{dv(t)}{dt}$

- Energy stored will be,

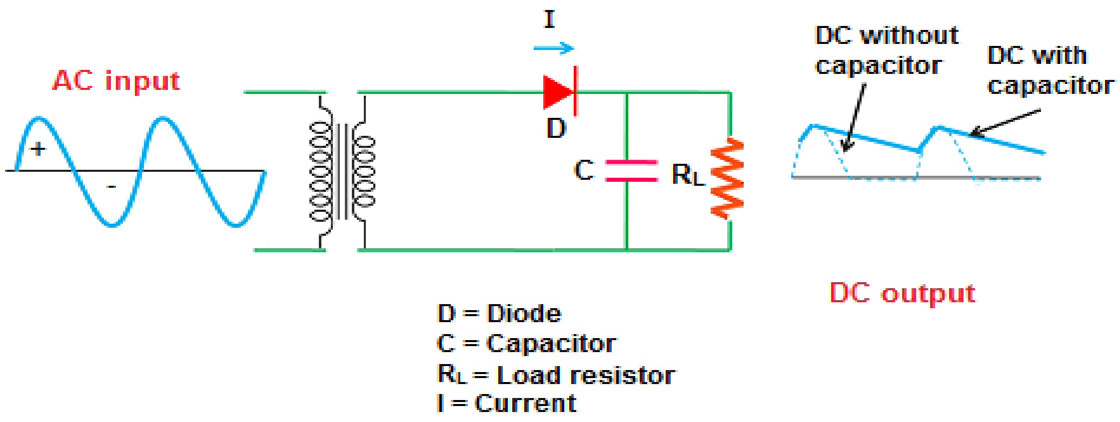
$$w_c(t) = \int_{-\infty}^{t} Cv(x)\frac{dv(x)}{dx}dx = \int_{v(-\infty)}^{v(t)} Cv(x)dv(x) = \frac{1}{2}Cv^2(t)$$

Rectifier with a filter capacitor – the peak rectifier

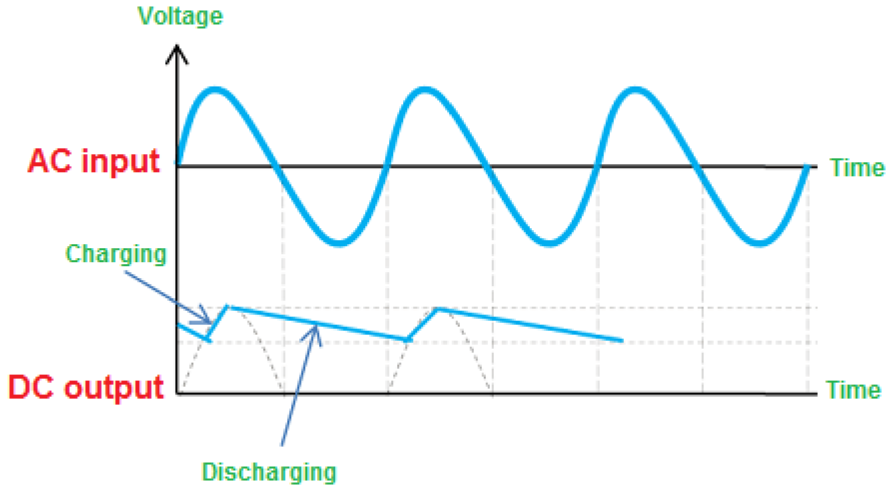


- The pulsating nature of rectifier output voltage produced by the rectifier circuits makes it unsuitable as a dc supply for electronic circuits.
- Variation of the output voltage can be reduced by placing a capacitor across the load.
- The filter capacitor serves to reduce substantially the variations in the rectifier output voltage.
- The capacitor charges until V_i reaches its peak values, as V_i reduces diode becomes reverse biased and the output voltage remains constant at the peak value.
- Theoretically, capacitor retains its charge, since there is no way for the capacitor to discharge.
- Hence the circuit produces a dc voltage output equal to the peak value of the input ac signal.

- In practice, when the load resistor is connected across the capacitor C, First, the capacitor charges to the peak value of the input, then, the diode cuts-off and the capacitor discharges through the resistor 'R'.
- This discharge operation continues for entire cycle until the input excessed the capacitor.
- Then the diode turns-on again and charges the capacitor up to the peak of V_i, and the process repeats.

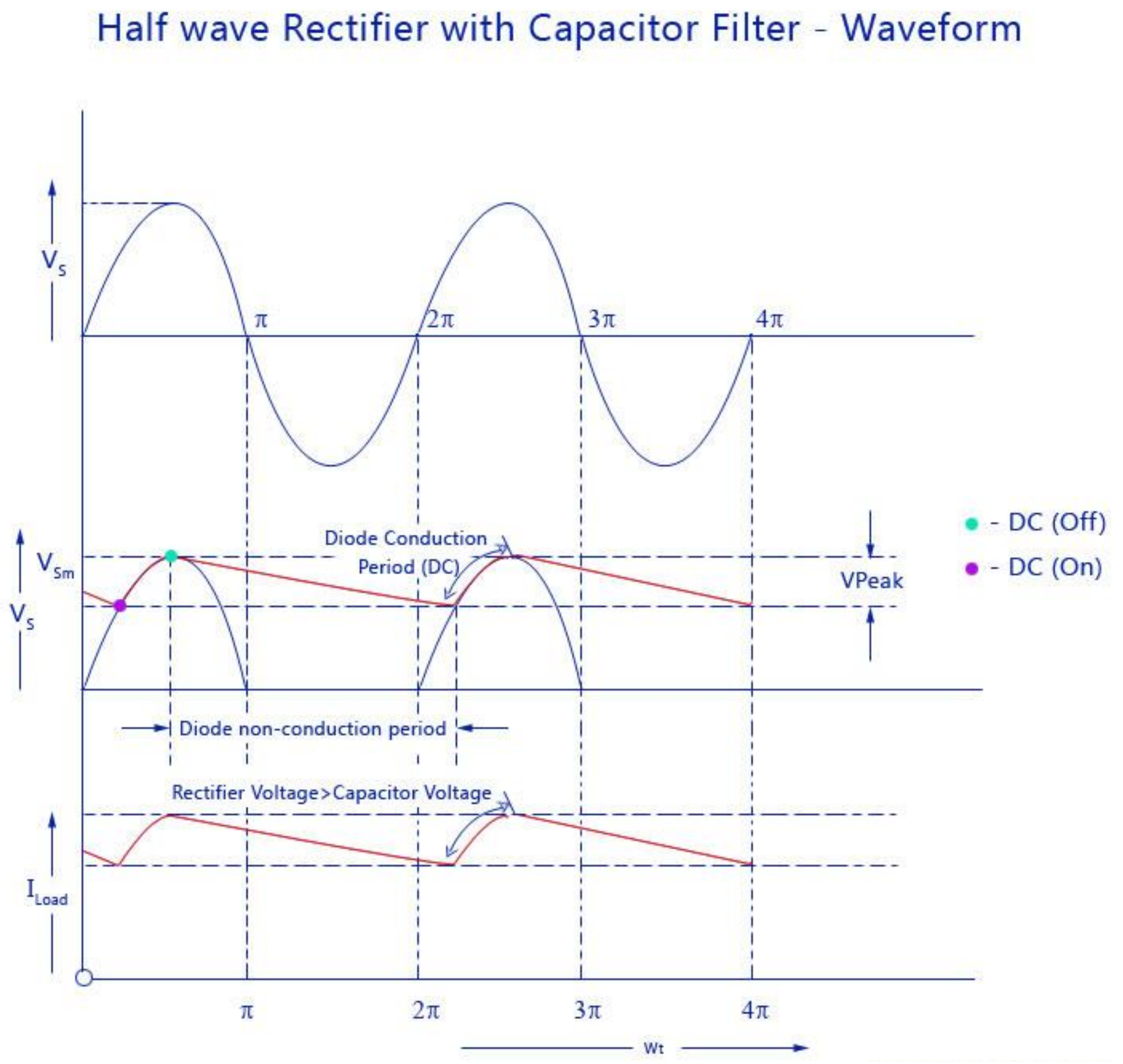


Half wave rectifier with capacitor filter



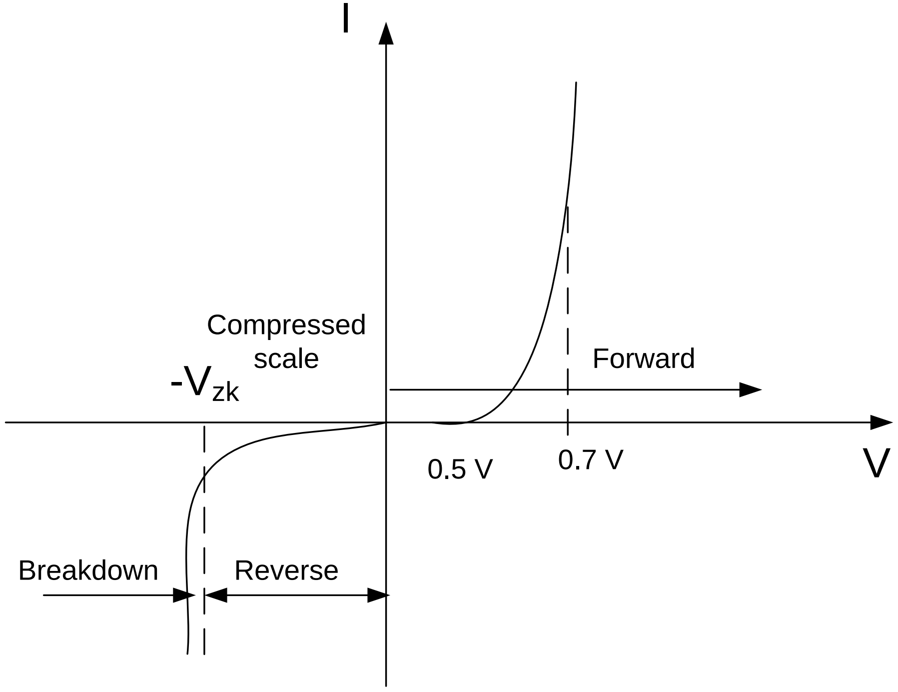
Half wave rectifier with filter o/p waveforms

- To keep the output voltage from decreasing too much during the capacitor discharge, one selects a value for 'C' so that the time constant 'CR' must be much greater than the discharge interval.
- The load current, $i_L = v_o/R$.
- The diode current (during its conduction cycle), $i_D = i_R + i_C$



Reverse Breakdown: Not a destructive Phenomenon

- A PN junction can be repeatedly operated in the breakdown region
- Provided the mag. of the reverse breakdown currents is limited to a safe value.
- Two possible mechanisms:
  - Zener effect (V_z < 5 V)
  - Avalanche effect (V_z > 7 V)

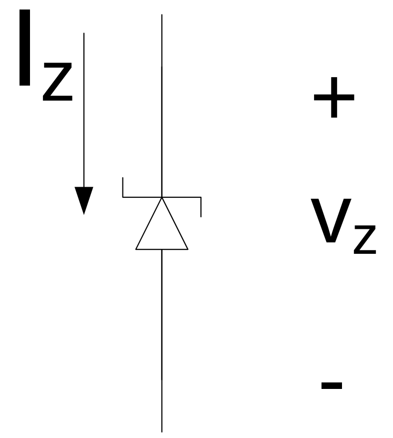


Operation in the reverse breakdown region

- In the breakdown region diode exhibits very steep i-v characteristics, and almost constant voltage drop that indicates the diodes operate in breakdown region can be used in design of voltage regulator.

- This turn out to be an important application of diodes operating in the reverse breakdown region and special diodes are manufactured to operate specifically in the breakdown region.

- They are breakdown diodes, Eg: Zener diode.
- Current flows into cathode and cathode is positive with respect to the anode.



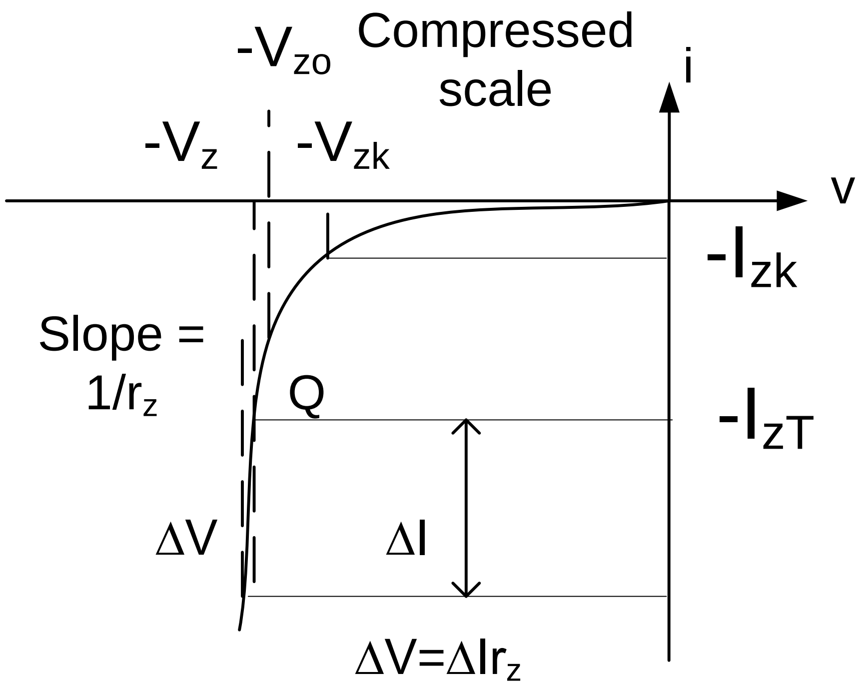
Circuit symbol for Zener Diode

Modeling the Zener diode

- Current greater than knee current is almost a straight line.
- As the current through the zener deviates from I_{ZT}, the voltage across it will change, though slightly,

$$r_z = \frac{\Delta V}{\Delta I}$$

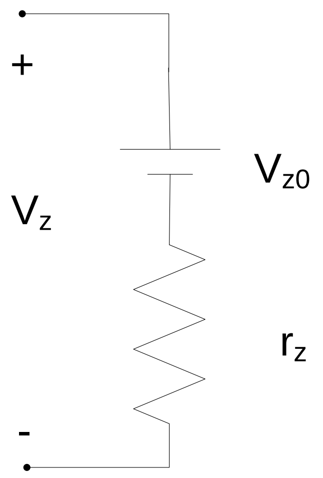
- r_z – incremental resistance, or dynamic resistance.
- Range: few ohms to few tens of ohms.



- Lower the value of r_z, the more constant the voltage remains constant as its current varies, hence more ideal its performance becomes in the design of **voltage regulators**.
- Almost linear char. of the zener diode suggests that the device can be modeled as shown in fig.
- V_{z0} denotes the point at which the straight line of slope $1/r_z$ intersect the voltage axis.
- The equivalent circuit model can be analytically described by

$$V_z = V_{z0} + r_z I_z$$

- applicable for $V_z > V_{z0}$ and $I_z > I_{zk}$.

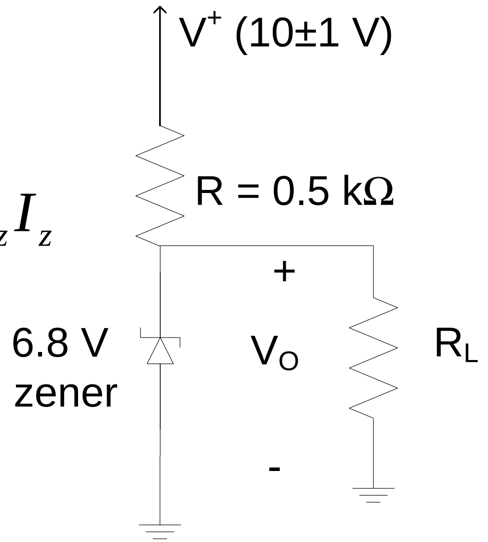


Use of zener as a shunt regulator

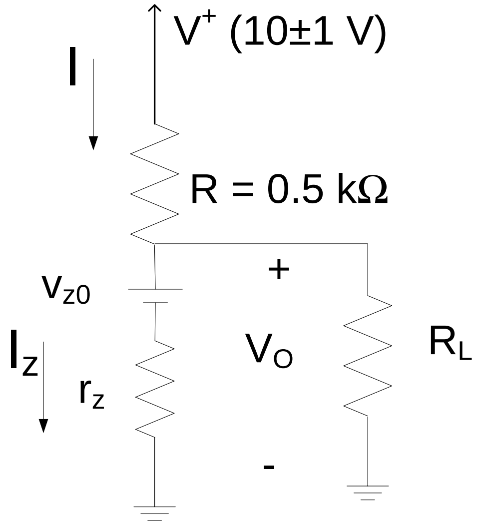
- Example: the 6.8 V zener diode in the circuit is specified to have V_z = 6.8 V at I_z = 5 mA, r_z = 20 Ω, and I_{ZK} = 0.2 mA. The supply voltage V^+ is normally 10 V but can vary by 1V.

$$V_z = V_{z0} + r_z I_z$$

$$V_{Zo} = V_z - r_z I_z = 6.7V$$



- (a) find V_0 with no load and with V^+ at its normal value.



With no load , the current through the zener is,

$$I_z = I = \frac{V^+ - V_{z0}}{R + r_z} = 6.35mA$$

$$V_o = V_{z0} + r_z I_z = 6.7 + 6.35 \times 0.02 = 6.83V$$

(b) Find the change in V_0 resulting from the ± 1V change in V^+. Note that ($\Delta V_O/\Delta V^+$), usually expressed in mV/V, is known as **line regulation**.

$$\Delta V_O = \Delta V^+ \frac{r_z}{R + r_z} = \pm 1 \frac{20}{500 + 20} = \pm 38.5 mV$$

Thus the line regulation is 38.5 mV/V.

(c) Find the change in V_O resulting from connecting a load resistance R_L that draws a current I_L = 1 mA, and hence find the **load regulation** ($\Delta V_O/\Delta I_L$) in mV/mA.

When the load draws a current 1 mA, then the zener current will be decreased by 1 mA. The corresponding change in zener voltage can be found from

$$\Delta V_O = r_z \Delta I_z = 20 \times -1 = -20 mV$$

Thus the load regulation is

$$\frac{\Delta V_O}{\Delta I_L} = -20\, mV/mA$$

(d) Find the change in V_O when R_L = 2 KΩ?

The load current will be approximately, 6.8V/2KΩ = 3.4 mA.

Thus the change in zener current will be, - 3.4 mA. And corresponding change in zener voltage will thus be,

$$\Delta V_O = r_z \Delta I_z = 20 \times -3.4 = -68mV$$

(e) Find the value of V_O when R_L = 0.5 kΩ?

The load current will be , 6.8/0.5 = 13.6 mA. **This is not possible**, since the current I supplied through R is only 6.4 mA. Therefore zener must be cutoff, if that is the case, then V_O will be determined by the voltage divider circuit.

$$V_O = V^+ \frac{R_L}{R + R_L} = 10 \frac{0.5}{0.5 + 0.5} = 5V$$

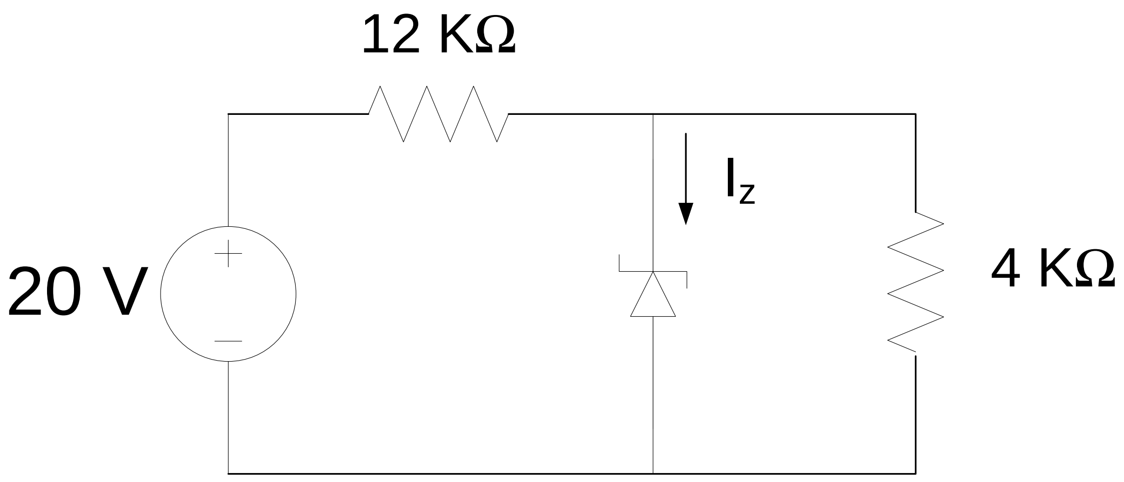
(f) What is the minimum value of R_L for which the diode still operate?

$$I_z = I_{zk} = 0.2mA \qquad V_z = V_{zk} = 6.7V$$

The lowest current supplied through R is (9-6.7)/0.5 = 4.6 mA, and thus the load current is 4.6 – 0.2 = 4.4 mA.
The corresponding value of R_L is

$$R_L = \frac{6.7}{4.4} = 1.5k\Omega$$

- The zener diode voltage in Fig. 1. is V_z = 3.9 V. Assuming r_z =0. Determine I_z and I_L. What is the power dissipated in the Zener diode?



- Consider the zener diode circuit shown in Fig. 1. Assume V_z = 12 V and r_z =0.
- (a) Calculate the zener diode current and the power dissipated in the Zener diode for RL = ∞.
- (b) What is the value of R_L such that the current in the zener is one-tenth of the current supplied by the 40 V source?
- (c) Determine the power dissipated in the Zener diode for the conditions of part (b)?