SWINBURNE UNIVERSITY OF TECHNOLOGY

Topic 2 – Diodes

EEE20004 Analogue Electronics 1

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CRICOS 00111D
TOID 3069

Semiconductors

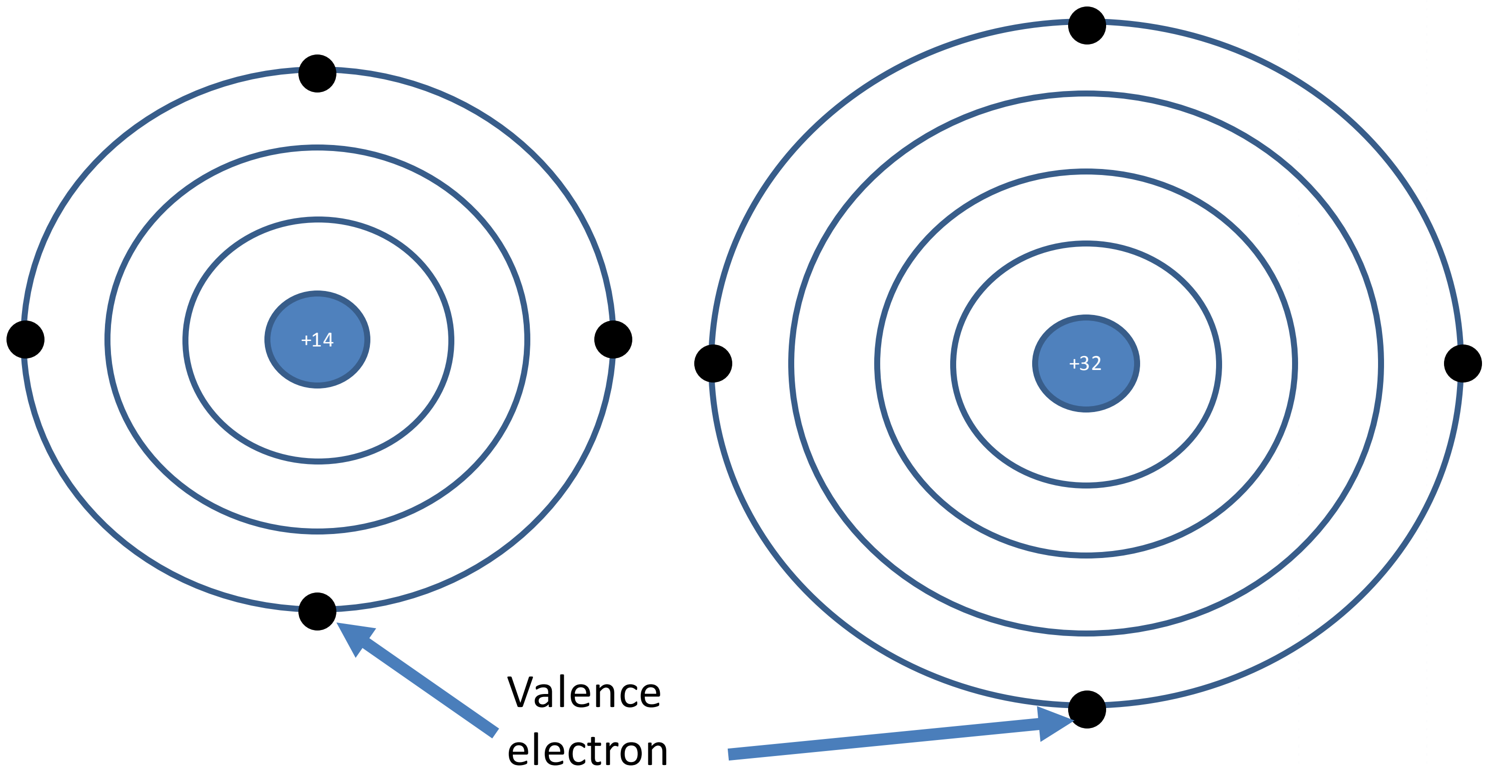
- Materials can be classified by their electrical conductivity:

- **Insulators**: very few free charge carriers. (Bad conductors)
- **Conductors**: Many free charge carriers. (Eg copper)
- **Semiconductors**: Conductivity is between insulators and conductors
  - Number of free charge carriers depends on:
    - Incident energy (heat, light, etc)
    - Impurities
    - Silicon, GaAs, and Germanium are examples semiconductors used in electonic devices
  - Note Semiconductors are typically Group IV element (4 valence electrons)

Semiconductors: Si and Ge

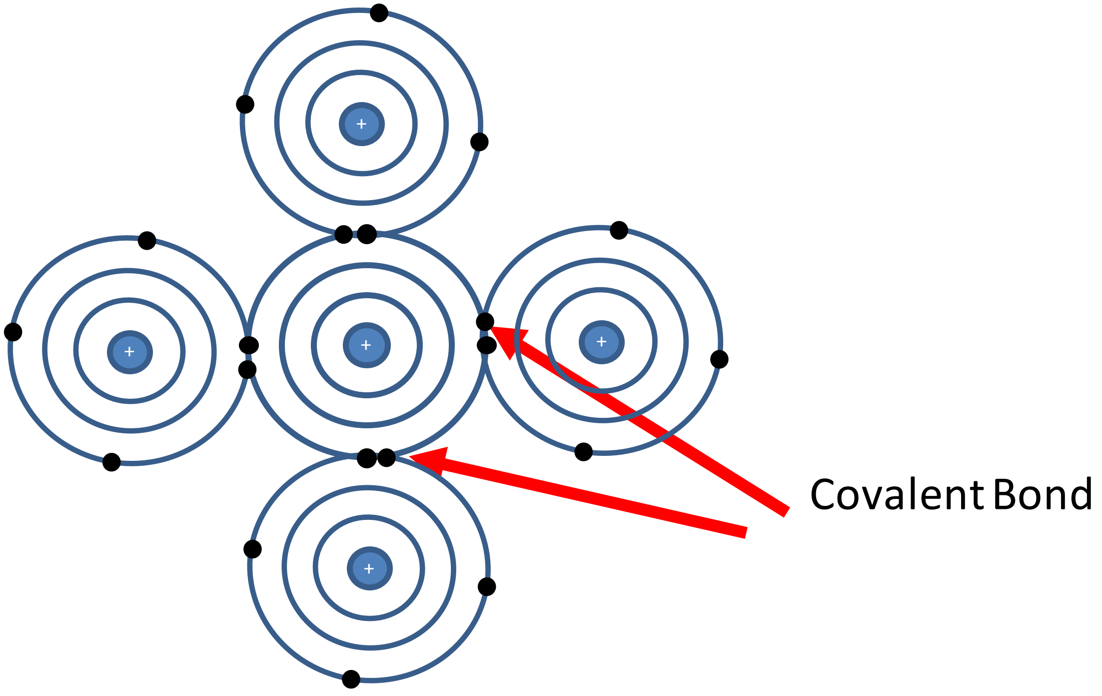
- Silicon

Germanium



Intrinsic Semiconductors

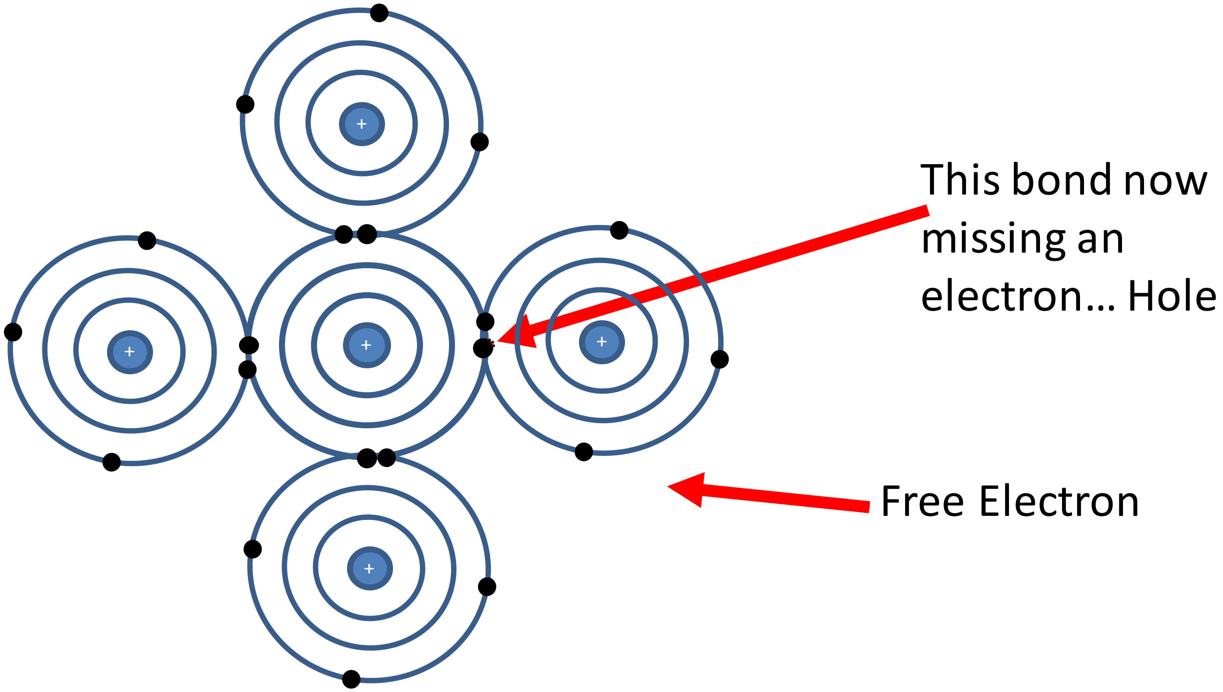
- Eg Pure silicon
- At room temperature Si atoms form covalent bonds
- The 4 valence electrons allow 4 covalent bonds to be formed.



- This bonding forms a 3 dimensional crystal

Intrinsic Semiconductors

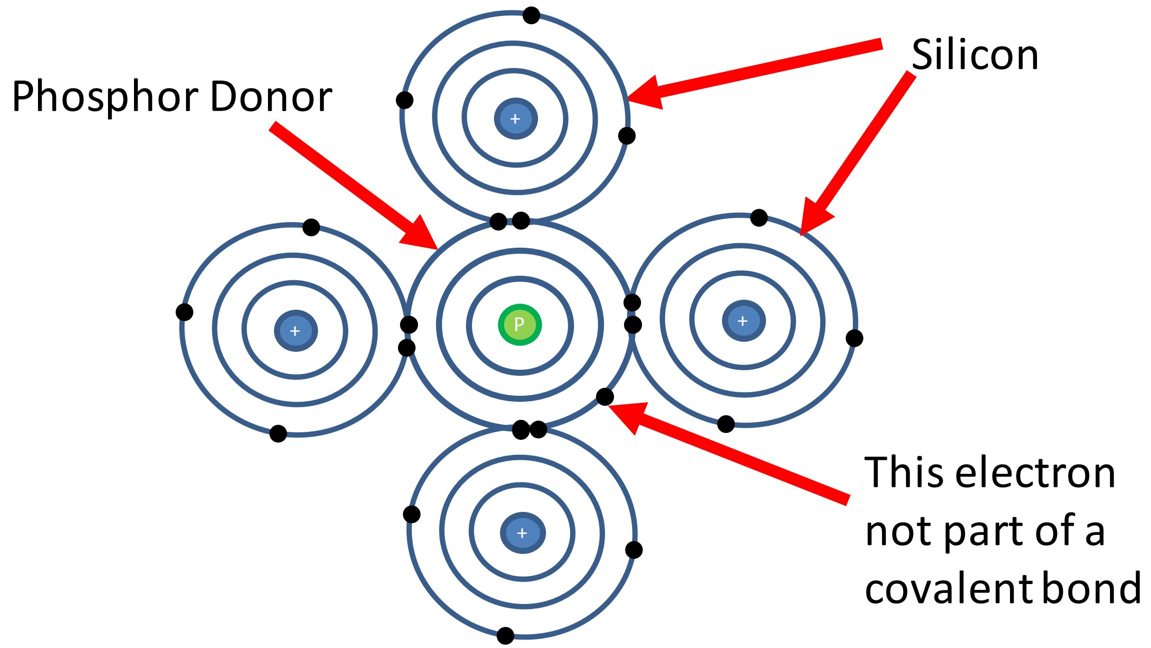
- At room temp, some of the valence electrons have enough energy escape the bonds and become free –ve charge carriers.



- If an electron leaves a covalent bond then a "hole" is created
- Holes are +ve charge carriers that can also move in the crystal
- Number of free electrons = number of holes

Doped Semiconductors: N-type

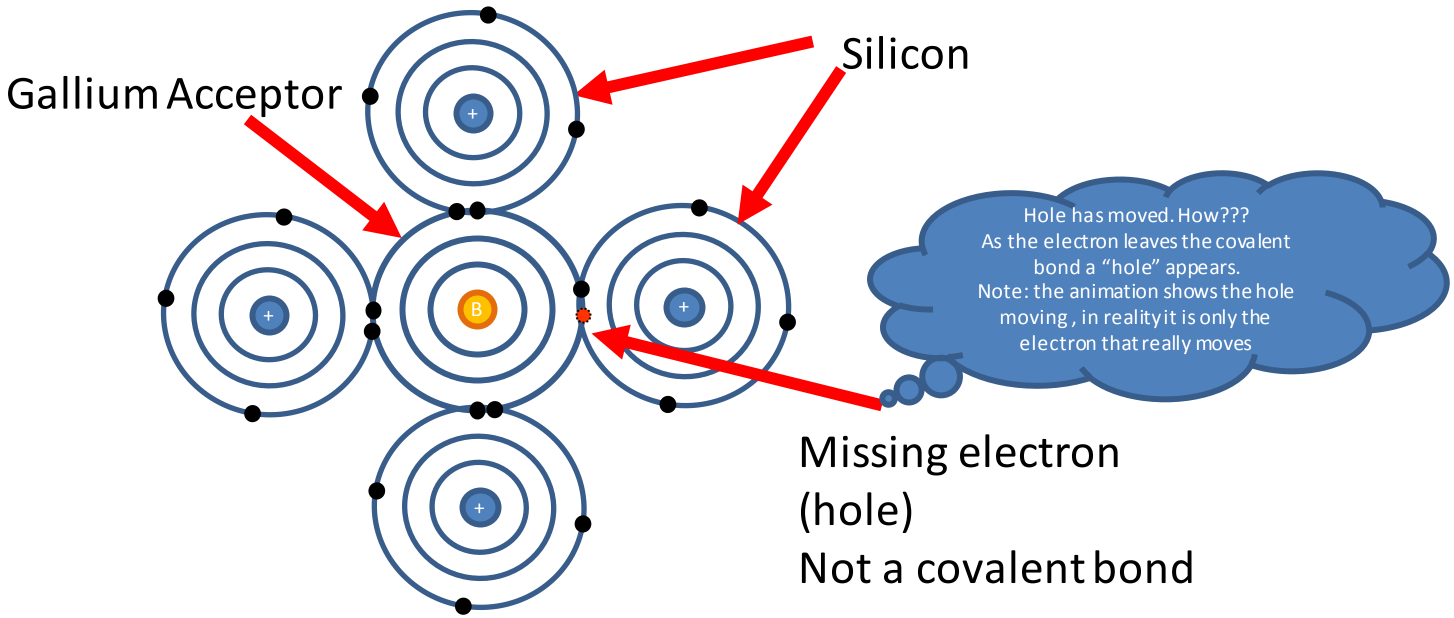
- Eg Silicon with added "Donor" Impurities
- Donor Impurities: Phosphorus (P), Arsenic (As) ... Group V elements
- Gp V elements have 5 valence electrons.



- Not much energy is required to ionise the P atom as the 5th electron is not part of a covalent bond
- At room temp, essentially all the donor atoms will be ionised. Hence the free electron density will be higher the hole density.
- Call this **N-type** semiconductor

Doped Semiconductors: P-type

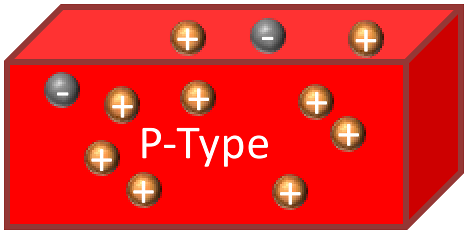
- Eg Silicon with added “Acceptor” Impurities
- Acceptor Impurities: Boron (B), Gallium (Ga)... Group III elements
- Gp III elements have 3 valence electrons.



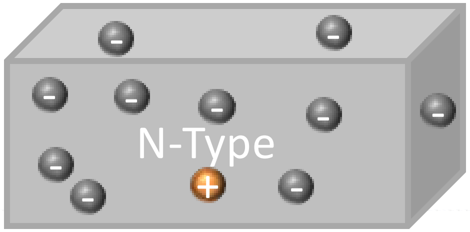
- Only three covalent bonds can be formed as there is a “missing” valence electron.
- The acceptor atom may acquire an electron, hence make the covalent bond. This allows the hole to move.
- At room temp, essentially all the acceptor atoms will be ionised. Hence the free hole density will be higher the electron density.
- Call this **P-type** semiconductor

Carriers

- Will have both free electrons and holes in both extrinsic semiconductors
- In **p-type** semiconductor the number of free holes exceeds the number of free electrons.
  - Holes are termed "majority" carriers
  - Electrons are termed "minority" carriers

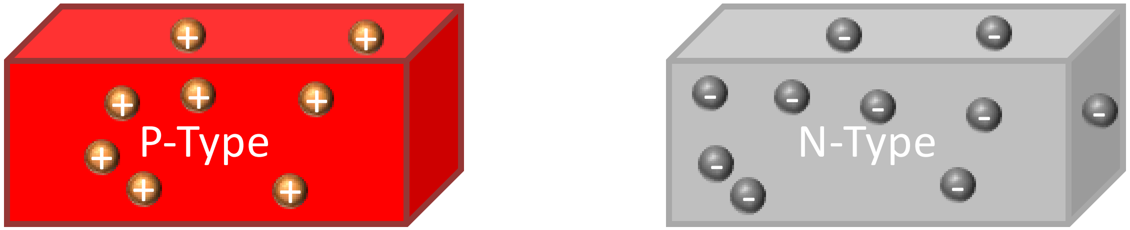


- In **n-type** semiconductor the number of free electrons exceeds the number of free holes.
  - Electrons are termed "majority" carriers
  - Holes are termed "minority" carriers

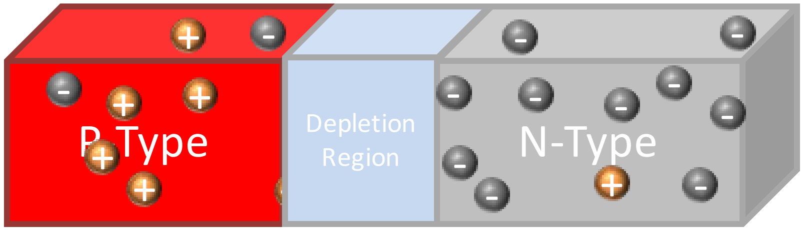


PN Junction

- What happens if join **P-type and N-type** semiconductor?



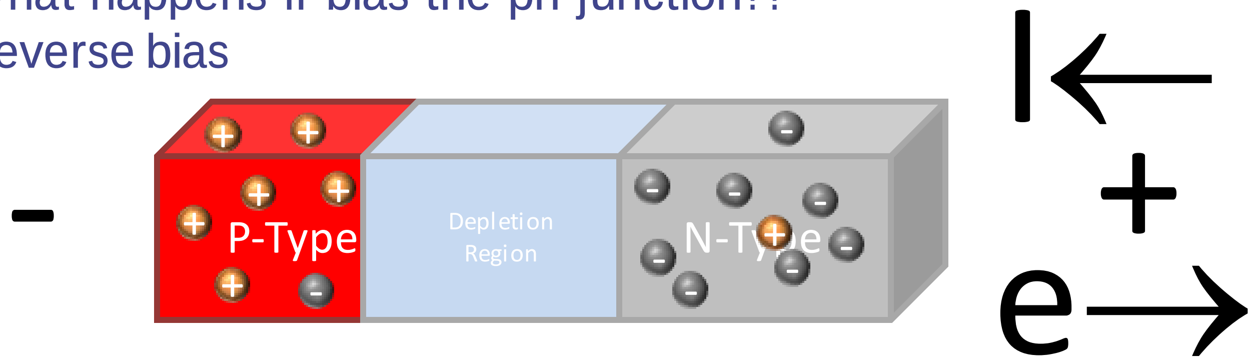
- Majority carriers that cross the PN junction will encounter majority carries of the opposite type and recombine
- This causes a region that is depleted of free carriers either side of the junction



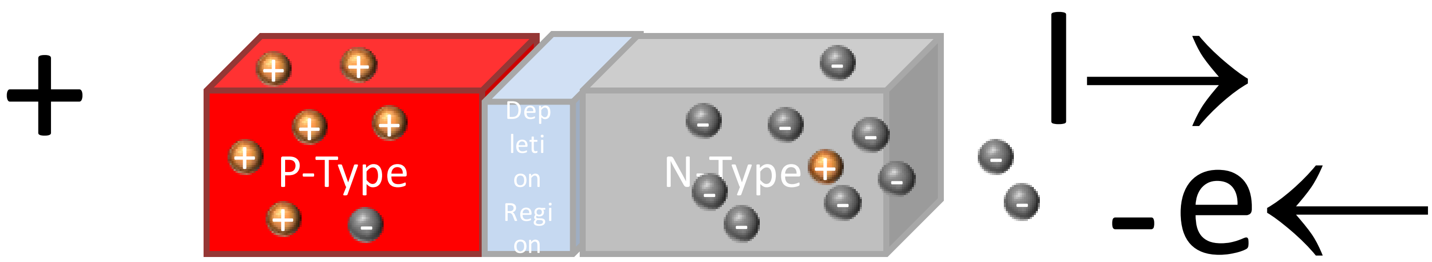
- Note the depletion region has a barrier potential across it

PN Junction

- What happens if bias the pn junction??
- Reverse bias



- Depletion region grows → higher barrier potential → small current flows

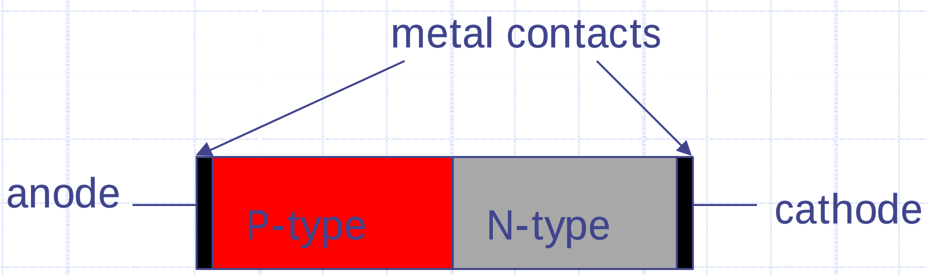


- Depletion region shrinks → lower barrier potential → large current flows

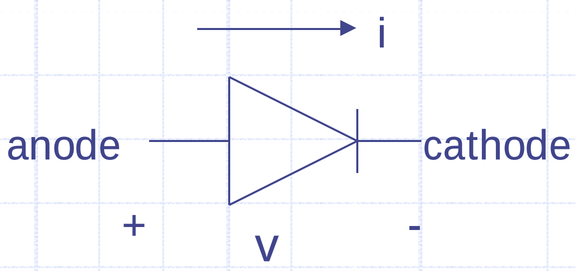
Diodes – Physical structure

- The diode consists of a p-n junction. It is a two terminal device that permits current to flow easily in one direction whilst almost completely preventing current flow in the other direction.

- Its physical structure, and circuit symbol are shown in the figures below :



physical structure



circuit symbol

Diodes – i-v characteristic

The i-v characteristic of a diode is given by the **non-linear** expression

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) \qquad (1)$$

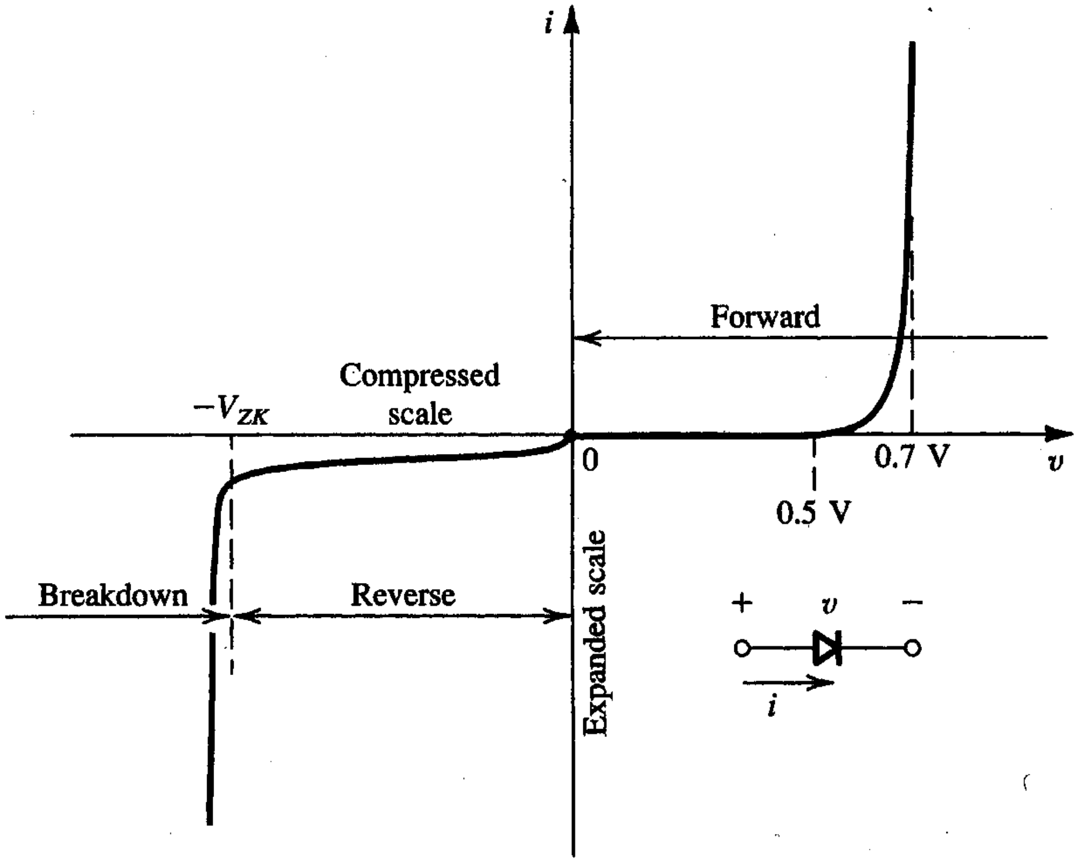
where i_D is the diode current,

I_S is the reverse saturation current, and is a constant (10^{-9}A to 10^{-15}A) at a given temperature,

η is a constant, η=1 for diodes in standard integrated circuits, and η=2 for discrete diodes,

V_T is the thermal voltage, and is a constant for a given temperature, ≈ 25 mV at 25^{0}C.

Diode – Operating modes



Source : Sedra/Smith – Microelectronic circuits

i-v characteristic of the pn junction diode

Diode – Operating modes

Forward-biased region ($v_D > 0$)

Current i_D increases exponentially with v_D. Normal operation is above the knee of the curve, where v_D is ≈ 0.7V = V_γ (or V_F).

V_γ is the turn-on or cut-in voltage.

Reverse-biased region ($v_D < 0$ but $v_D > -V_{zk}$)

$i_D = -I_S$, i.e. diode current is constant, and very small in value (nA to fA). Note : f = 10^{-15}

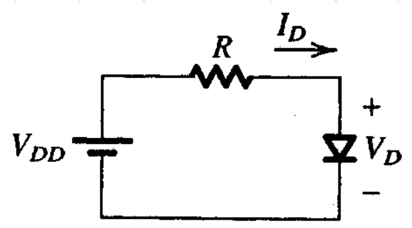
Breakdown region ($v_D < -V_{zk}$)

Breakdown occurs when the reverse voltage across the diode exceeds V_{ZK}. The reverse current increases rapidly with only a small increase in voltage drop. For most applications, operation of the diode in the breakdown region is undesirable.

Zener diodes are diodes specifically designed to operate in this portion of the i-v curve.

DC Load line and operating point

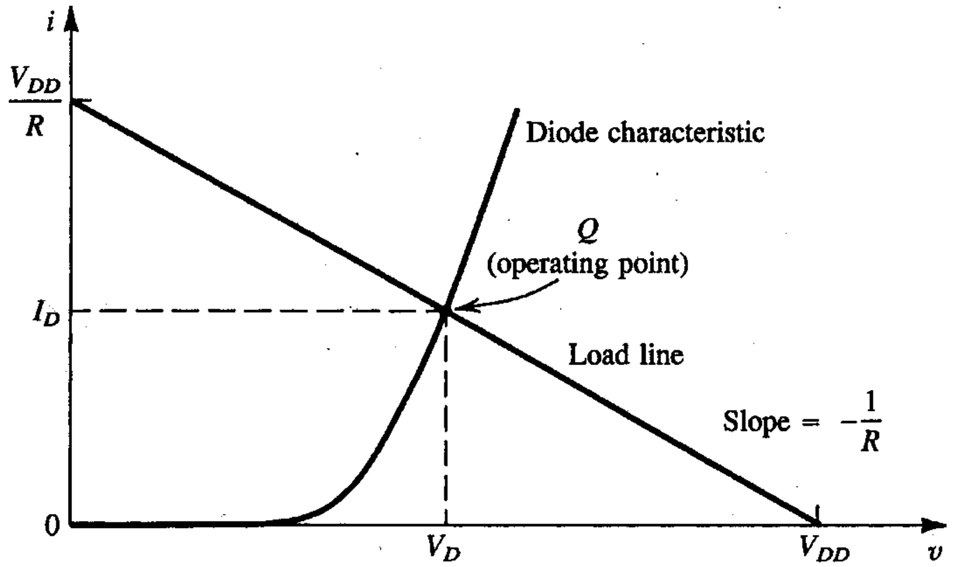
Consider simple diode circuit below:



$$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}} - 1\right) \quad i - v \text{ equation of the diode}$$

$$V_D = V_{DD} - I_D R \quad DC \text{ load line equation}$$

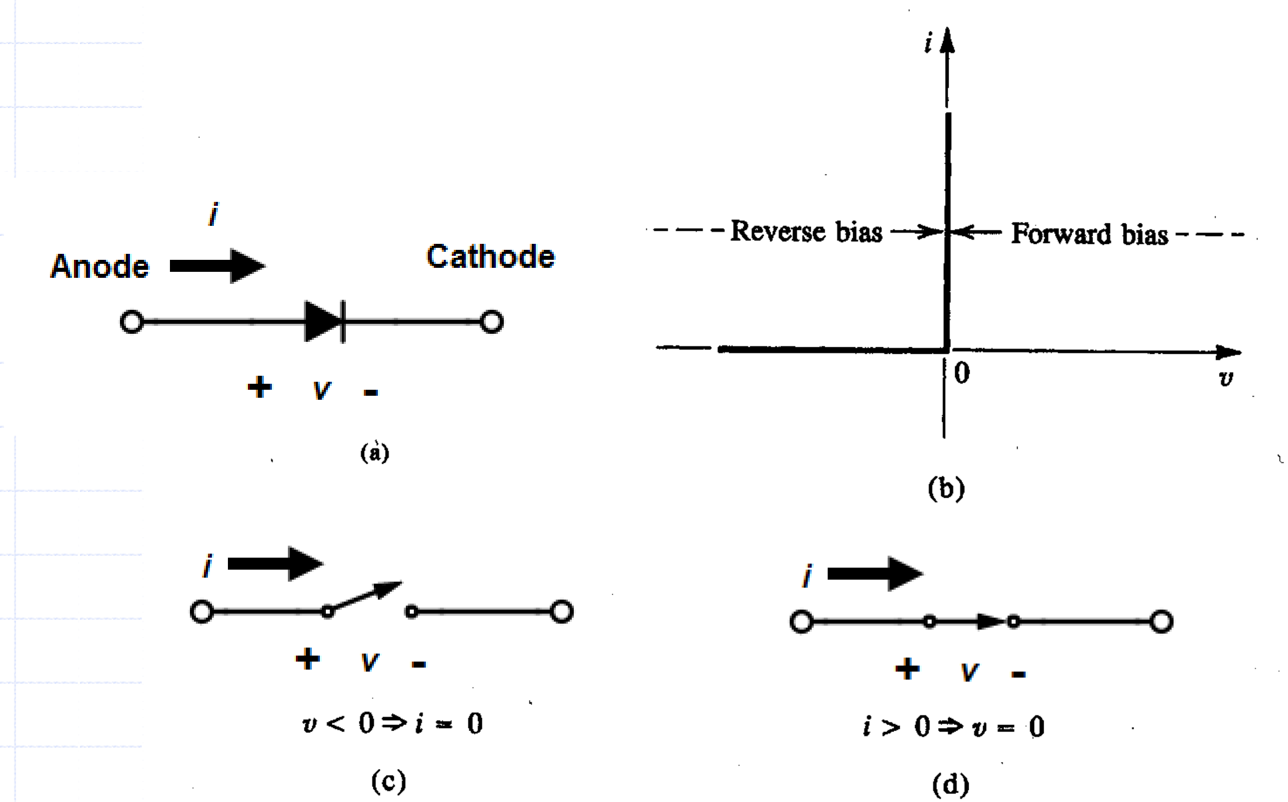
The intersection of the load line and the i-v curve defines the operating or Q (Quiescent) point of the diode.



Q-point = (I_{DQ}, V_{DQ})

Diode Models – The ideal diode model

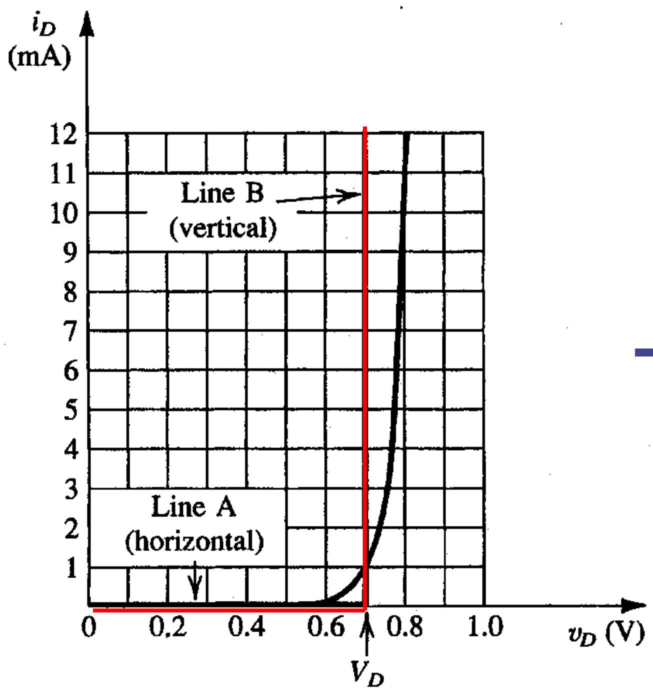
Models the diode as an ideal switch, with the turn-on voltage (V_γ or V_F) =0 when the diode is conducting

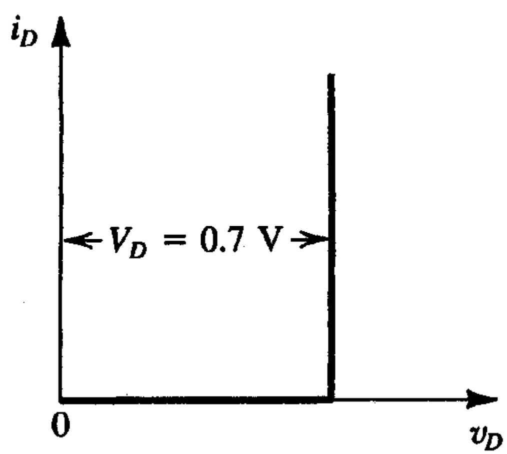


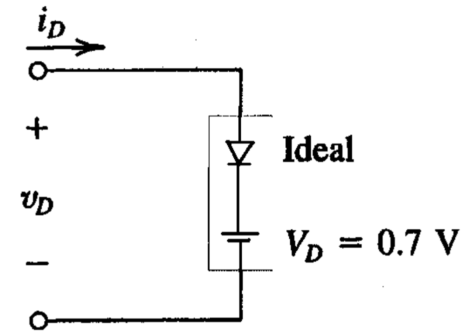
Diode Models – The constant voltage drop model

In the forward-biased region, the forward voltage drop V_γ is assumed to be a constant at 0.7 V.

In the reverse-biased region, the diode current i_D is assumed to be 0.

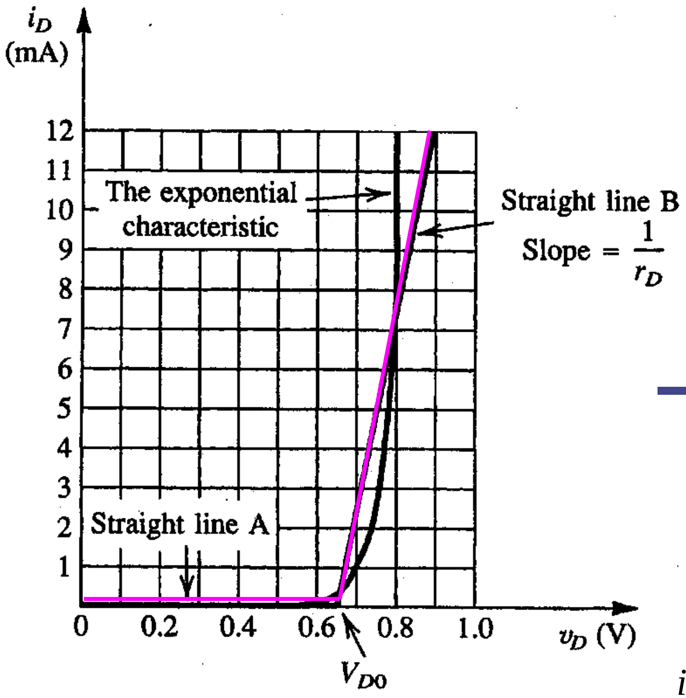


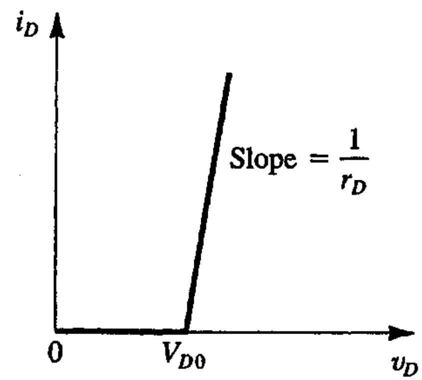


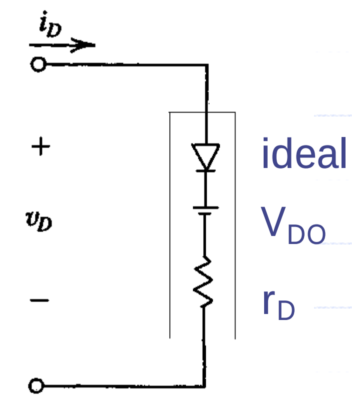


Diode Models – The piecewise linear model

Models the fact that switches are non-ideal, and have resistances when closed. r_D models the forward dynamic resistance when the diode is conducting.







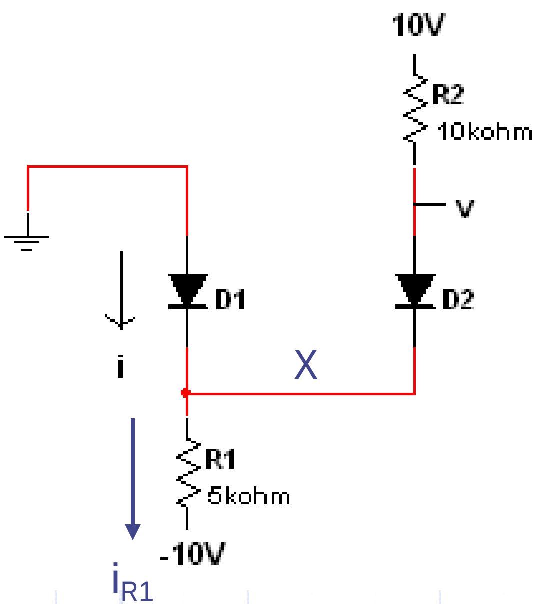
$$i_D = I_S\left(e^{\frac{v_D}{\eta V_T}} - 1\right) \approx I_S e^{\frac{v_D}{\eta V_T}}$$

$$\frac{di_D}{dv_D} = \frac{I_S}{\eta V_T} e^{\frac{v_D}{\eta V_T}} = \frac{1}{r_D}$$

$$r_D = \frac{\eta V_T}{I_S e^{\frac{v_D}{\eta V_T}}} = \frac{\eta V_T}{I_{DQ}} \quad \text{where } I_{DQ} \text{ is the diode current at the Q point.}$$

Application of diode models – Example 1

Assuming the diodes to be ideal, find the values of i and v in the circuit below: (i = 1 mA, v = 0 V)



assume both diodes are on $(i.e\ i = i_{D1} > 0\ and\ i_{D2} > 0)$

$v = 0.$

$$i_{D2} = \frac{10-0}{R_2} = 1\,mA$$

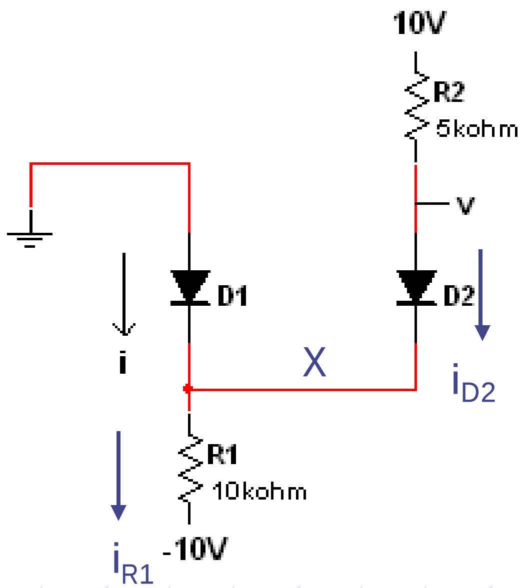
$$i_{R1} = \frac{0-(-10)}{R_1} = 2\,mA$$

KCL at $X \rightarrow i = i_{R1} - i_{D2} = 1\,mA$

Both diode currents are positive, hence assumption is correct.

Application of diode models – Example 2

Assuming the diodes to be ideal, find the values of i and v in the circuit below: (D_1 is off, i = 0 A, v = 3.33V)



$$assume\ both\ diodes\ are\ on\ (i.e\ i = i_{D1} > 0\ and\ i_{D2} > 0)$$

$$v = 0.$$

$$i_{D2} = \frac{10-0}{R_2} = 2\,mA$$

$$i_{R1} = \frac{0-(-10)}{R_1} = 1mA$$

$$KCL\ at\ X \rightarrow i = i_{R1} - i_{D2} = -1mA$$

$$Hence\ diode\ D1\ is\ off.$$

$$assume\ D1\ off,\ and\ D2\ on.$$

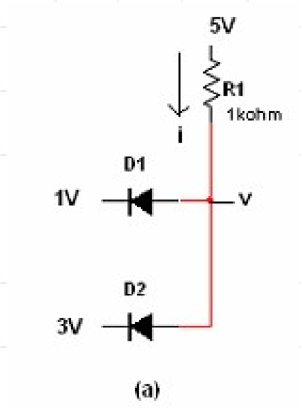
$$i_{D2} = i_{R1} = \frac{10-(-10)}{R_1 + R_2} = 1.33mA$$

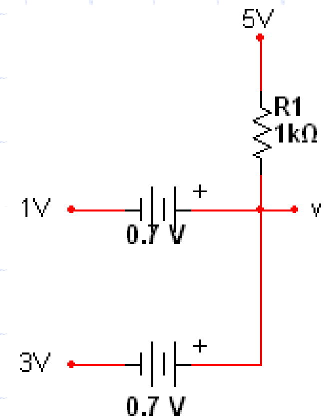
$$v = 10 - i_{D2}R_2 = 3.33V.$$

$$i = 0.$$

Application of diode models – Example 3

Using the constant voltage drop (V_γ=0.7V) model, find i and v in the circuits below: (D_1 on, D_2 off, i = 3.3 mA, v=1.7 V; i = 0.349 mA, v = 6.98 V)

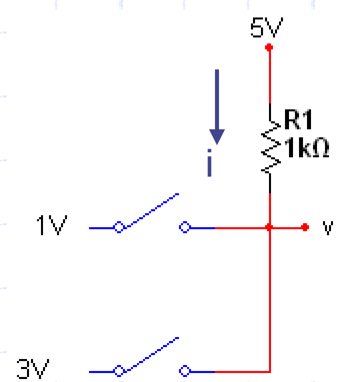




Assume both diodes are on.

v = 1+0.7 = 1.7 and v = 3+0.7 = 3.7 V at the same time.

Therefore, this situation is not possible.

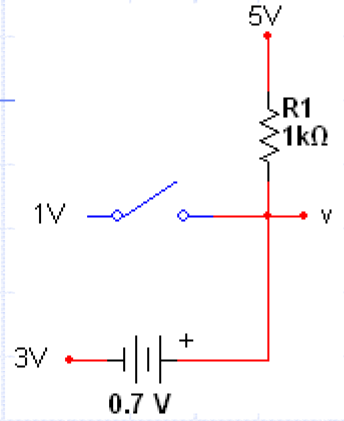


Assume both diodes are off.

i =0, and v = 5 V.

$V_{anode\text{-}cathode}$ of D1 > 0.7 V, and $V_{anode\text{-}cathode}$ of D2 > 0.7 V. At least one of the diodes must be on. Assumption is incorrect.

Application of diode models – Example 3

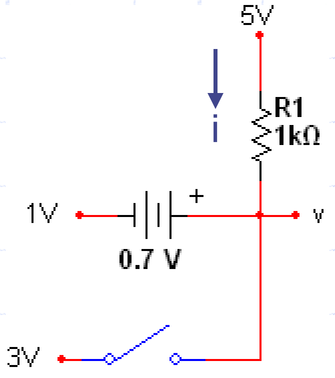


Assume D1 off and D2 on.

v = 3+0.7 = 3.7 V.

However $V_{anode\text{-}cathode}$ of D1 > 0.7 V → D1 must be on.

Assumptions incorrect.



Assume D1 on and D2 off.

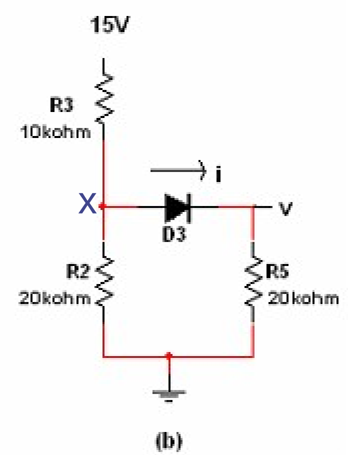
v = 1+0.7 = 1.7 V.

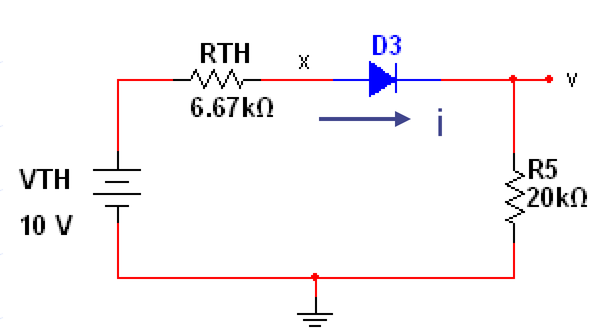
$V_{anode\text{-}cathode}$ of D2 < 0, confirming that D2 is off.

$i = (5 – 1.7)/R_1 = 3.3$ mA.

Assumptions correct, and results stand.

Application of diode models – Example 3

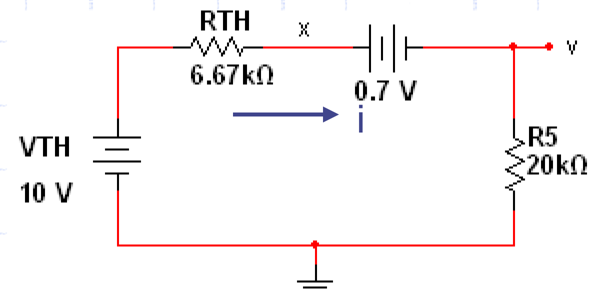




Replace R_2, R_3, and 15 V by Thevenin circuit:

$R_{TH} = R_2//R_3 = 6.67\ k\Omega$

$V_{TH} = R_2X15/(R_2+R_3) = 10\ V.$



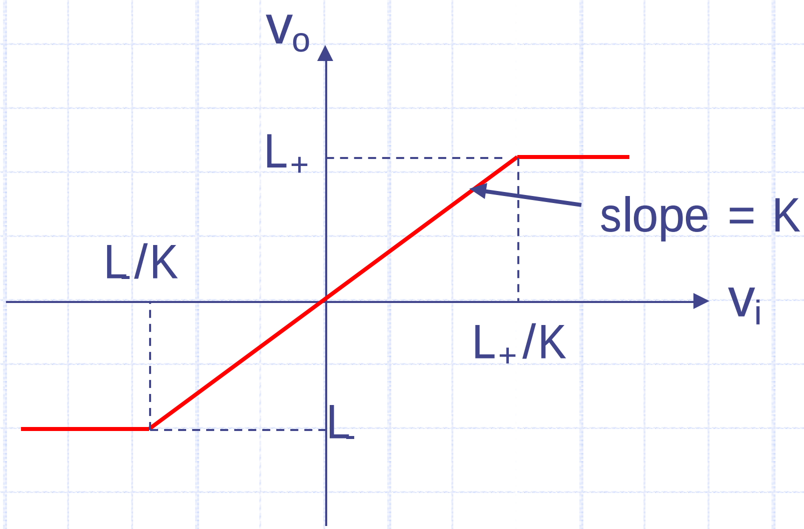
Assume diode is on.

$i = (V_{TH} – V_\gamma)/(R_{TH} + R_5) = 0.349\ mA$

$v = iR_5 = 6.98\ V.$

Applications of diodes – limiter circuits

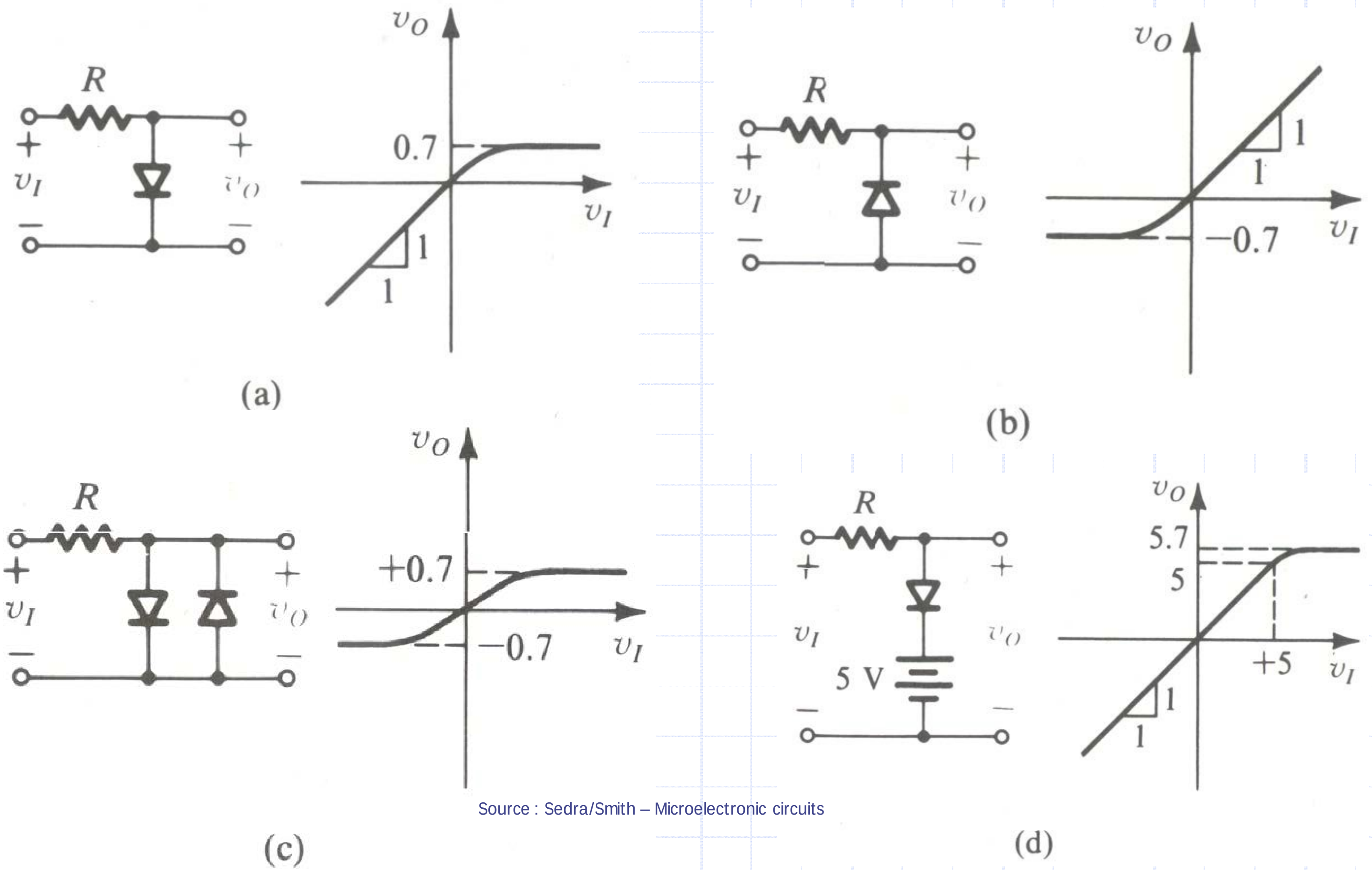
The general transfer characteristic of a limiter circuit is shown below:



When the input voltage v_i exceeds the upper threshold (L_+/K), the output voltage v_o is *limited* to the upper limiting level L_+.

When the input voltage v_i is reduced below the lower threshold (L_-/K), the output voltage v_o is *limited* to the lower limiting level L_-.

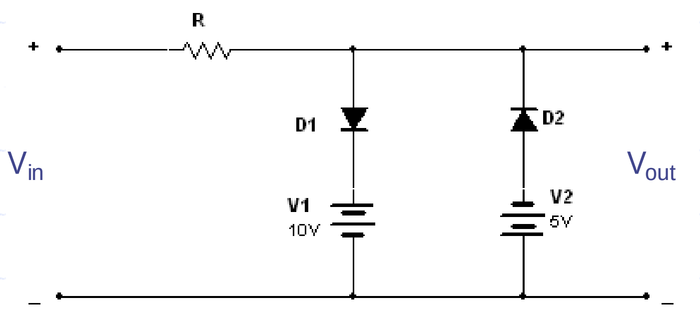
Applications of diodes – diode-based limiter circuits



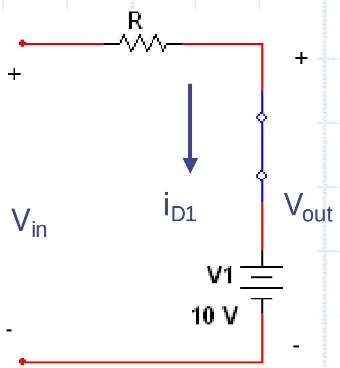
Source : Sedra/Smith – Microelectronic circuits

Diode-based limiter circuits – example 1

Derive and sketch the voltage transfer characteristic (V_{out} versus V_{in}) for the circuit shown. Assume the diodes are ideal. If V_{in} is the waveform shown, superimpose V_{out} on V_{in}.



Both diodes will never be on at the same time.

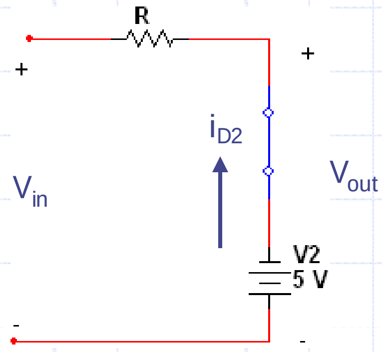


D_1 on.

$V_{out} = V_1 = 10$ V.

$i_{D1} = (V_{in} - V_1)/R$

$i_{D1} > 0 \rightarrow V_{in} > 10$ V.



D_2 on.

$V_{out} = -V_2 = -5$ V.

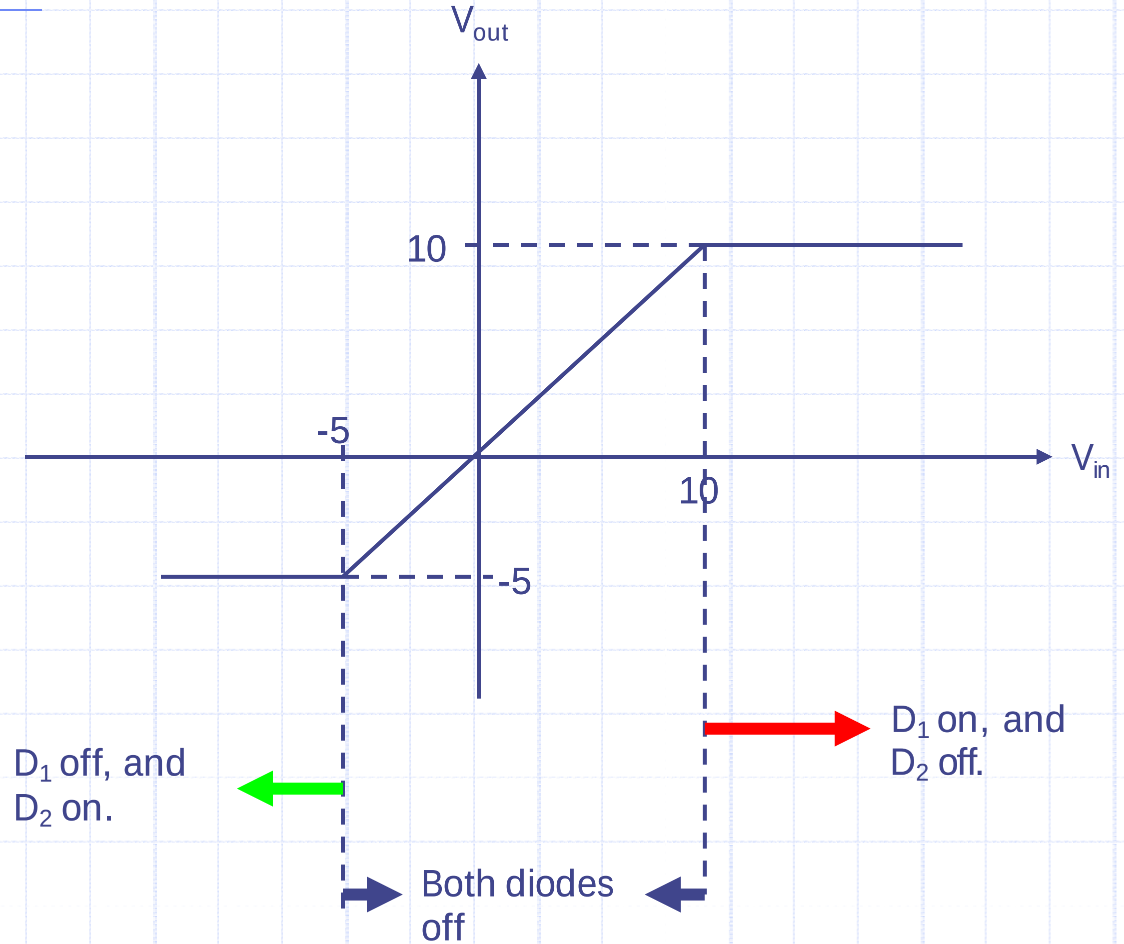
$i_{D2} = (-V_2 - V_{in})/R$

$i_{D2} > 0 \rightarrow V_{in} < -5$ V.

For $-5 < V_{in} < 10$ V, both diodes are off, and $V_{out} = V_{in}$.

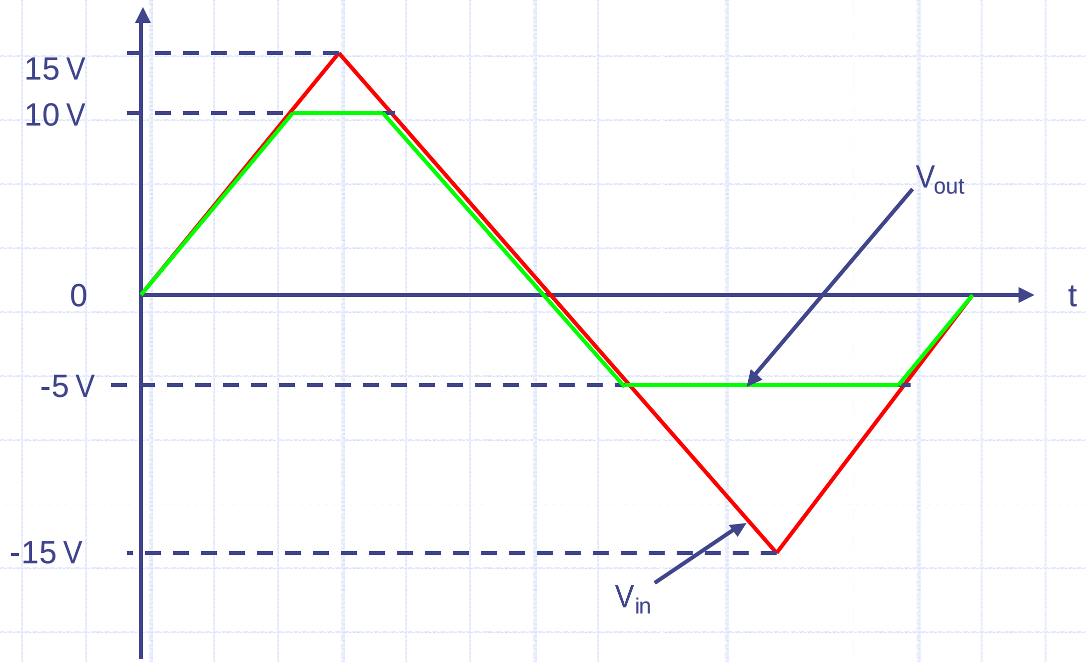
Diode-based limiter circuits – example 1

Voltage transfer characteristics:

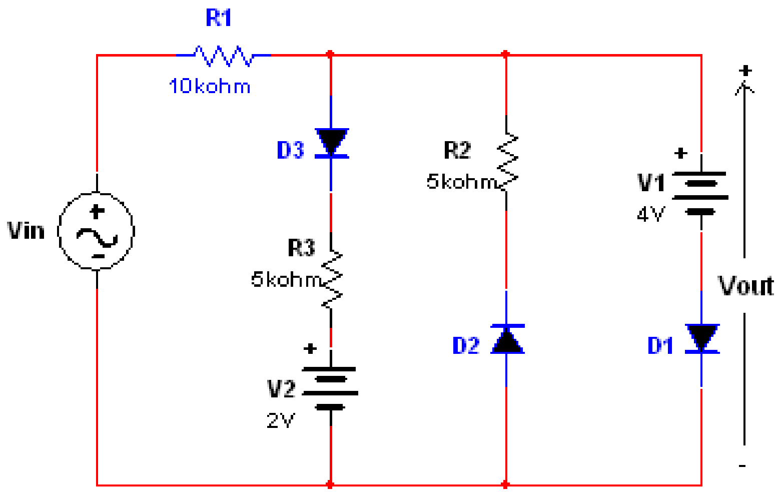


Diode-based limiter circuits – example 1

Plot of V_{in} and V_{out} against time:



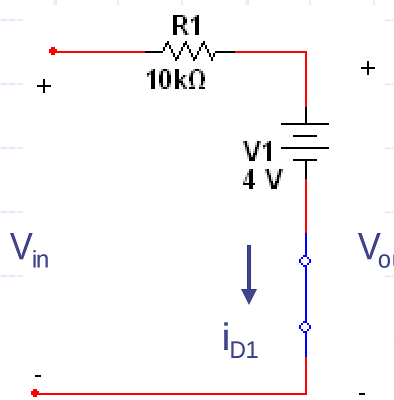
Diode-based limiter circuits – example 2



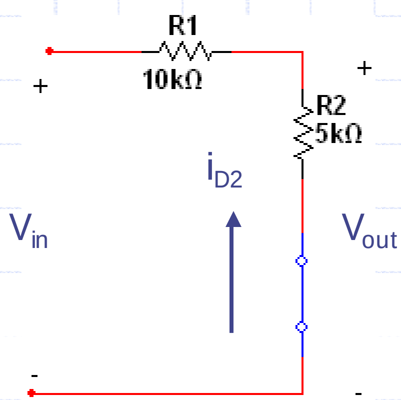
Draw the voltage transfer characteristic (V_{out} versus V_{in}) for the circuit shown. Assume the diodes are ideal.

To get an approximate idea, consider each diode on by itself, and revise analysis later.

D_1 on only



D_2 on only



$V_{out} = R_2 V_{out} / (R_1 + R_2) = V_{in}/3$

$i_{D2} = -V_{in}/(R_1 + R_2)$

$i_{D2} > 0 \rightarrow -V_{in} > 0$ or $V_{in} < 0.$

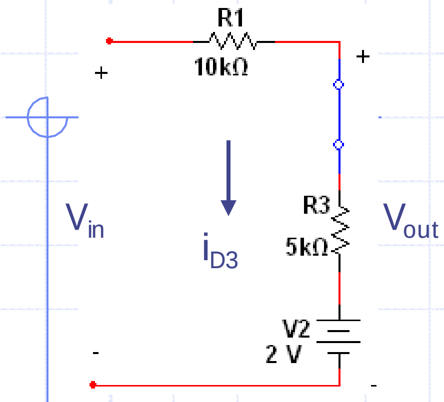
$V_{out} = V_1 = 4V$

$i_{D1} = (V_{in} - V_1)/R_1$

$i_{D1} > 0 \rightarrow V_{in} > V_1 = 4$ V.

Diode-based limiter circuits – example 2

D_3 on only



For $0 < V_{in} < 2$ V, all diodes are off.

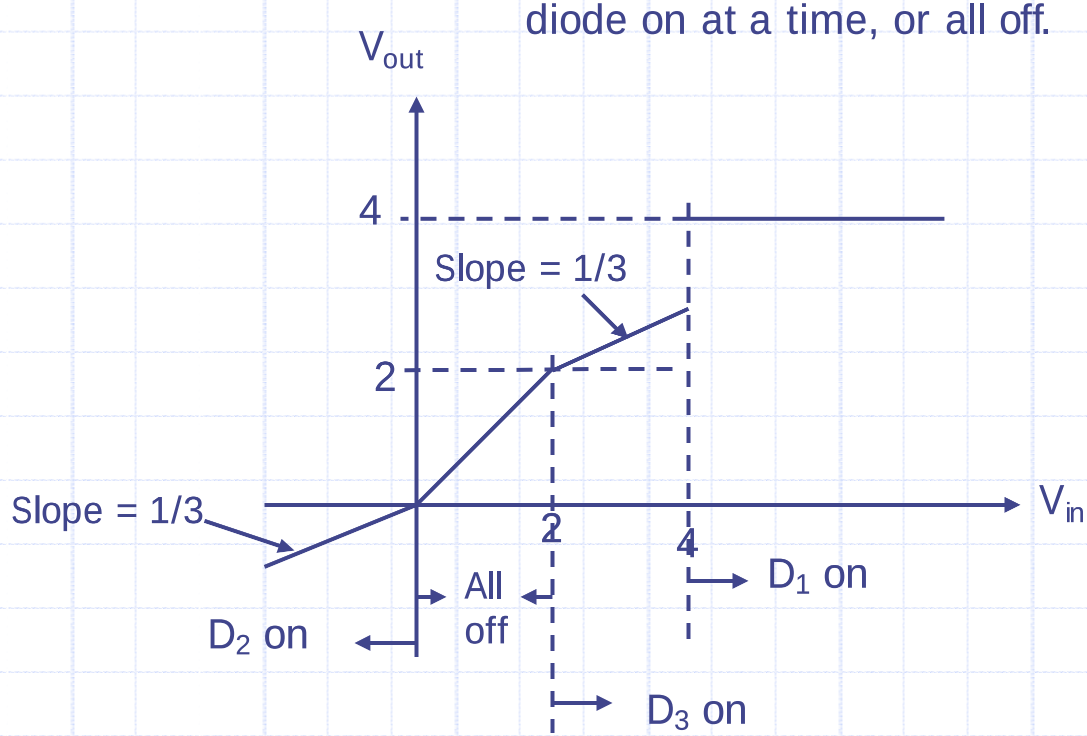
$V_{out} = V_{in}$.

$i_{D3} = (V_{in} - V_2)/(R_1 + R_3)$

$i_{D3} > 0 \rightarrow V_{in} > V_2$ (= 2 V).

$V_{out} = V_2 + i_{D3} X R_3 = 4/3 + V_{in}/3$

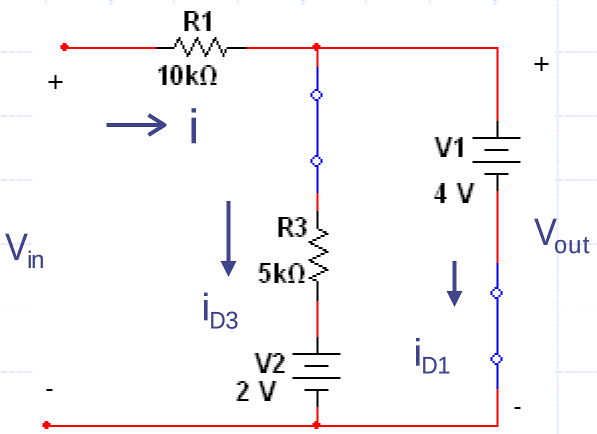
Transfer curve based on one diode on at a time, or all off.



Diode-based limiter circuits – example 2

- Need to adjust analysis since at some stage, both D_1 and D_3 will be on at the same time.

- Both D_1 and D_3 on.



$$V_{out} = V_1 = 4V.$$

$$i_{D3} = \frac{V_1 - V_2}{R_3} = 0.4\,mA.$$

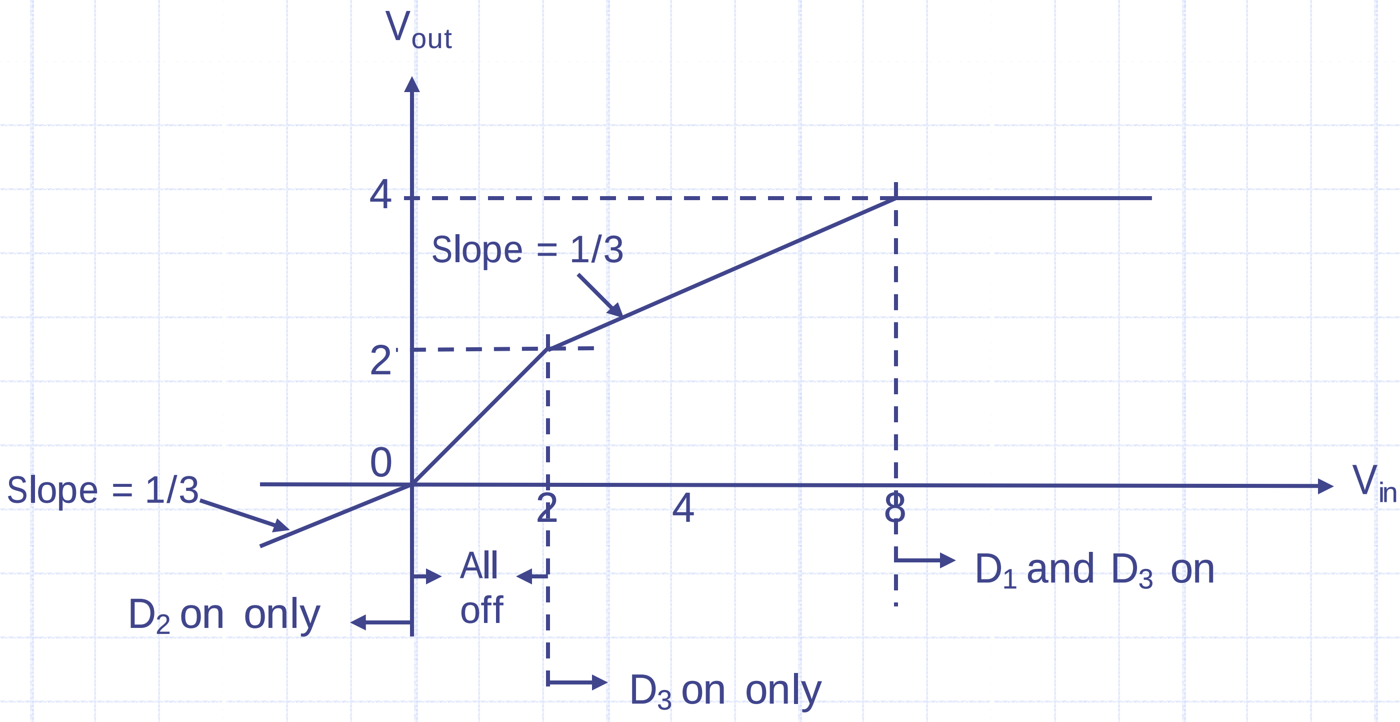
$$i = \frac{V_{in} - V_{out}}{R_1} = \frac{V_{in} - 4}{R_1}$$

$$i_{D1} = i - i_{D3} = \frac{V_{in}}{10} - 0.8$$

$$i_{D1} > 0 \Rightarrow V_{in} > 8V.$$

$$i.e \ when \ V_{in} > 8V, \ D_1 \ and \ D_3 \ are \ both \ on.$$

Diode-based limiter circuits – example 2

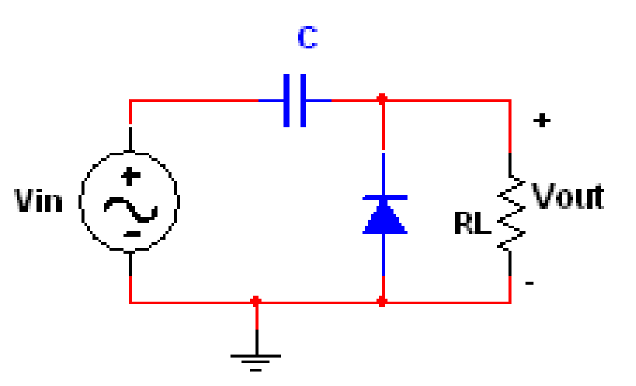


Final transfer curve – note the smooth transition from one region to another.

Applications of diodes – diode-based clamping circuits

Clamping shifts the entire signal voltage by a DC level. In the steady state, the output waveform is an exact replica of the input waveform, except for the DC shift.

Clampers are also known as DC restorers.



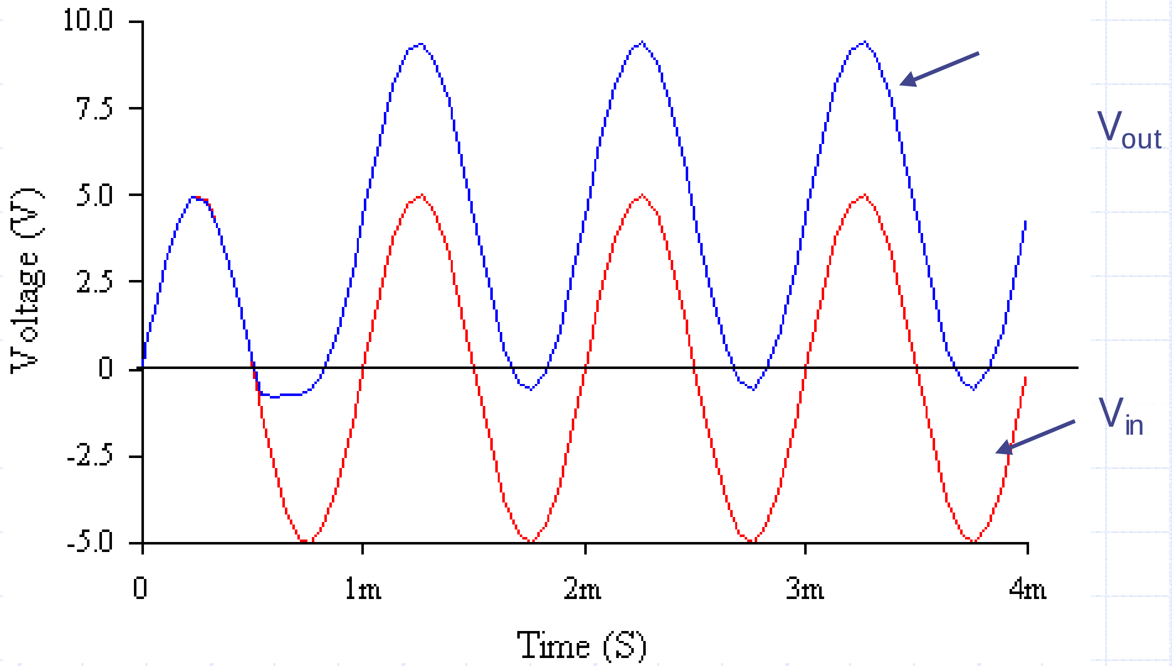
The diode clamper shown inserts a positive DC level to the output waveform.

When V_{in} initially goes negative, the diode is forward biased, and the capacitor charges to V_{in}(peak)-0.7 V.

Just after the negative peak of V_{in}, the diode is reverse biased because its cathode is held at V_{in}(peak)-0.7 V by the charge on the capacitor.

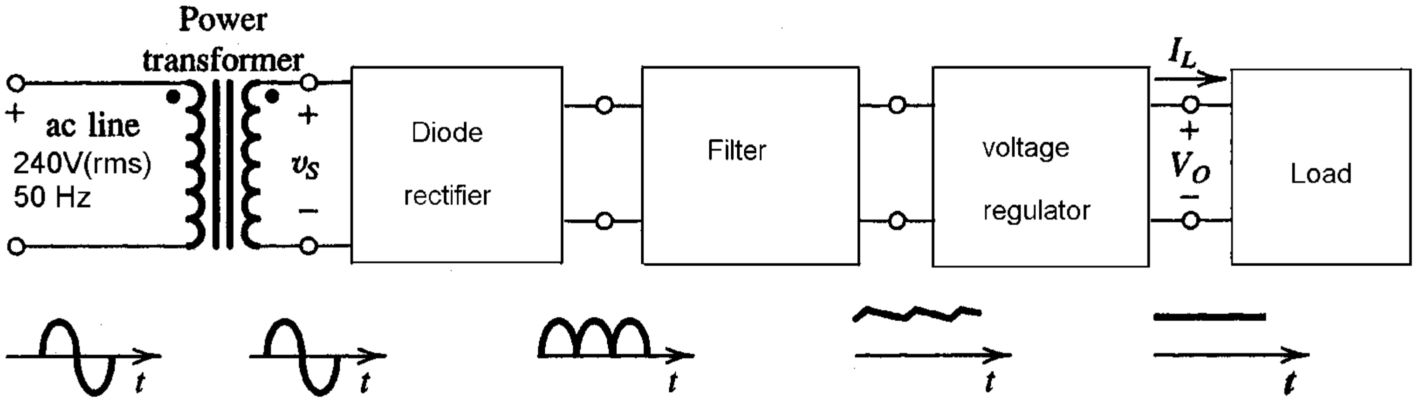
Applications of diodes – diode-based clamping circuits

- The capacitor can only discharge through R_L(high resistance).
- Thus, from the peak of one negative half cycle to the next, the capacitor discharges very little.
- The capacitor voltage acts basically as a battery in series with the input voltage.
- The result is that the output is shifted vertically by a DC offset.



Applications of diodes – Basic DC power supply

The block diagram of a DC power supply and the intermediate waveforms are shown below:



Source : Sedra/Smith – Microelectronic circuits

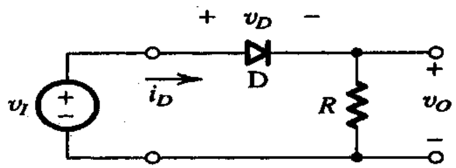
The *power transformer* (usually a step-down type) provides an appropriate sinusoidal amplitude for the DC power supply. In addition, it provides electrical isolation between the electronic equipment and the power-line circuit, hence minimising the risk of electric shock.

The *diode rectifier* converts the sinusoid to a unipolar output, with non-zero average or DC value.

The *filter* smoothes out the pulsating nature of the output waveform from the rectifier.

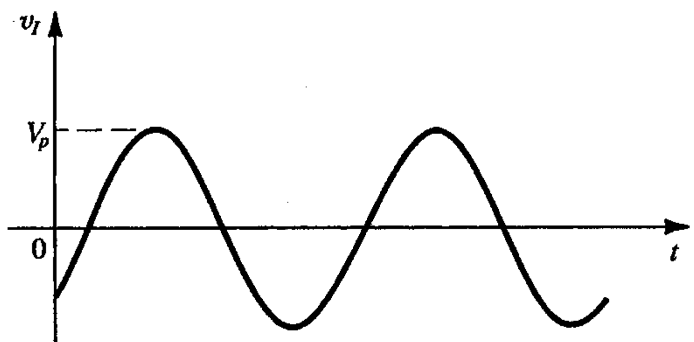
Applications of diodes – The half-wave rectifier

Figures below show a half-wave rectifier and its associated waveforms.



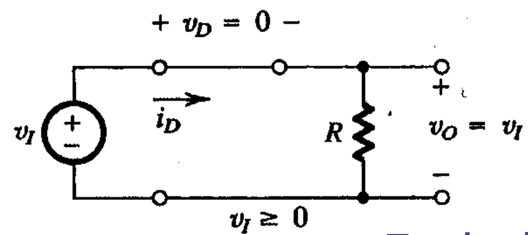
(a)

Half-wave rectifier circuit



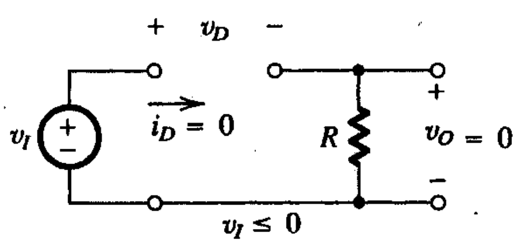
(b)

Sinusoid input to rectifier



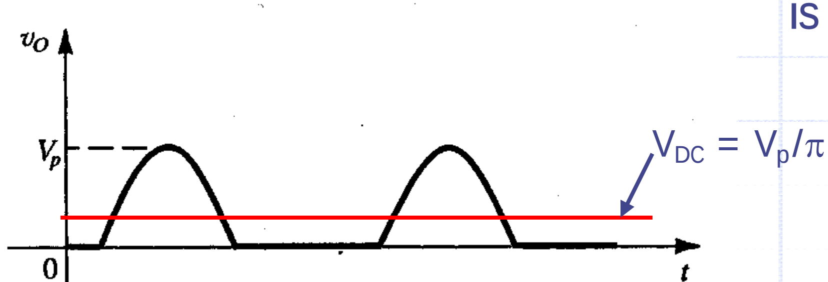
(c)

Equivalent cct. when diode is ON



(d)

Equivalent cct. when diode is OFF



(e)

output waveform

Applications of diodes – The half-wave rectifier

- When V_I is positive, the diode is forward biased, and conducts current. For an ideal diode, $V_O = V_I$
- When V_I is negative, the diode is reverse biased, i = 0, and $V_O = 0$.
- The average value of V_O(= the DC value) is given by:

$$V_O = \frac{1}{T}\int_0^T V_O(t)\,dt$$

- If $V_I = V_P \sin(\omega t)$,where $\omega = 2\pi f$
- Then $V_O(t) = V_P \sin(\omega t)$ for $0 \le t \le 0.5T$
- and $V_O(t) = 0$ for $0.5T \le t \le T$

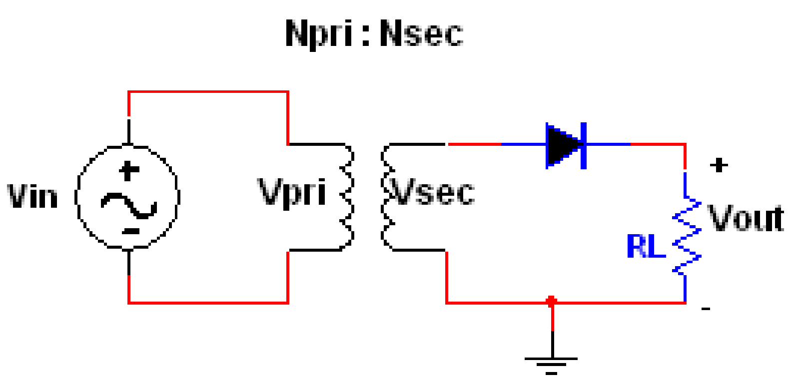
$$V_O(DC) = \frac{1}{T}\int_0^{0.5T} V_P \sin(\omega t)\,dt + \frac{1}{T}\int_{0.5T}^{T} 0\,dt = \frac{V_P}{\pi}$$

- Thus, an input AC signal with zero average or DC value, is converted to an output with a DC value of V_P/π

Half wave rectifier with transformer coupled input voltage

Figure below shows a half wave rectifier using a transformer.

The transformer allows the input voltage to be stepped up or down, according to the turns ratio, n where $n = N_{pri}/N_{sec} = V_{pri}/V_{sec}$.



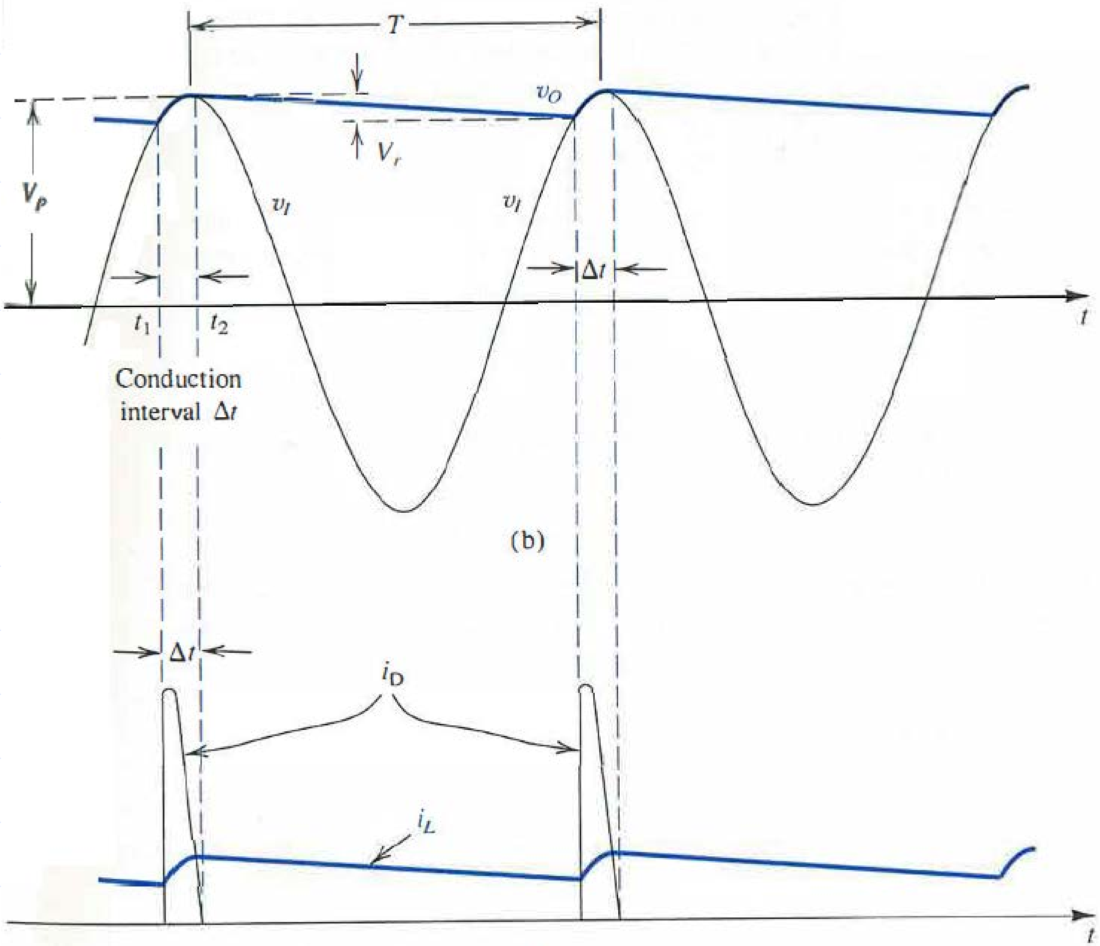
If $n = 2$, $V_{in}(peak)=156V$, and $V_\gamma=0.7V$, then

$V_{sec}(peak)=V_{in}(peak)/n=78V$, and

$Vout(peak)=V_{sec}(peak)-V_\gamma=77.3V$

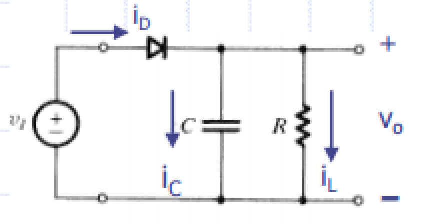
PIV_{min} of diode $= V_{sec}(peak)=78V$

Half-wave rectifier with a filter capacitor



(b)

(c)



(a)

Diode is assumed to be ideal, and

RC >> T.

Source : Sedra/Smith – Microelectronic circuits

Half-wave rectifier with a filter capacitor

- $I_L = \frac{V_o}{R}$ $\quad i_D = i_C + i_L = C\frac{dv_I}{dt} + i_L$
- Assuming V_r is small, $v_o \approx V_P$ and $I_L = \frac{V_P}{R}$
- During the diode-off interval, $v_o = V_P e^{-t/RC}$
- At the end of the discharge interval, $V_P - V_r \approx V_P e^{-T/RC}$
- For $RC \gg T$, $e^{-T/RC} \approx 1 - T/RC$
- Hence $V_r \approx V_P \frac{T}{RC} = \frac{V_P}{fRC}$
- Also $V_r = \frac{I_L}{fC}$ illustrating that the capacitor discharges with a constant current $I_L = \frac{V_P}{R}$
- Conduction interval Δt: $V_P \cos(\omega \Delta t) = V_P - V_r$
- If $\omega \Delta t$ is small then $\cos(\omega \Delta t) \approx 1 - \frac{1}{2}(\omega \Delta t)^2$
- Hence $\omega \Delta t \approx \sqrt{\frac{2V_r}{V_P}}$. For $V_r \ll V_P$, the conduction angle $\omega \Delta t$ will be small as assumed.
- $i_{Daverage} = I_L\left(1 + \pi\sqrt{\frac{2V_P}{V_r}}\right)$ and $i_{Dmax} = I_L\left(1 + 2\pi\sqrt{\frac{2V_P}{V_r}}\right)$

Half-wave rectifier with a filter capacitor

A peak rectifier is fed by a 60-Hz sinusoid with a peak voltage V_p = 100 V. The load resistance R = 10 kΩ. Find the value of the capacitance C that will result in a peak-to-peak ripple of 2 V. Also, calculate the fraction of the cycle during which the diode is conducting and the average and peak values of the diode current.

$$V_r = 2V.$$

$$V_r = \frac{V_p}{fRC} \Rightarrow C = \frac{V_p}{V_r fR} = 83.3\,\mu F \quad assu\min g \;\; V_p = 100V \; or \;\; V_\gamma = 0.$$

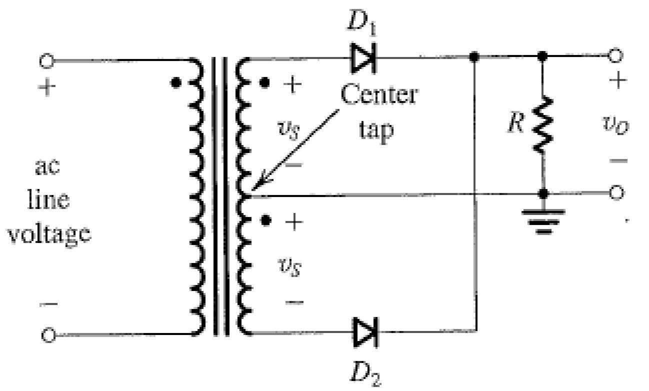
$$\theta = \omega\Delta t \approx \sqrt{\frac{2V_r}{V_p}} = 0.2\; rad.\; or \;\; 3.18\,\%$$

$$I_L = \frac{V_p}{R_L} = 10\,mA.$$

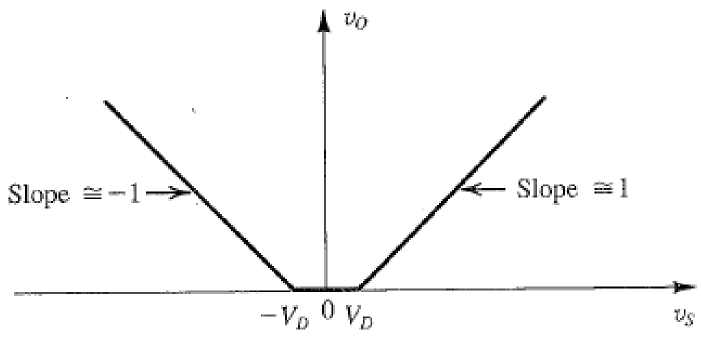
$$I_D(average) = I_L\,(1+\pi\sqrt{\frac{2V_p}{V_r}}) = 324\; mA.$$

$$I_D(\max) = I_L\,(1+2\pi\sqrt{\frac{2V_p}{V_r}}) = 638\; mA.$$

Full wave rectifiers

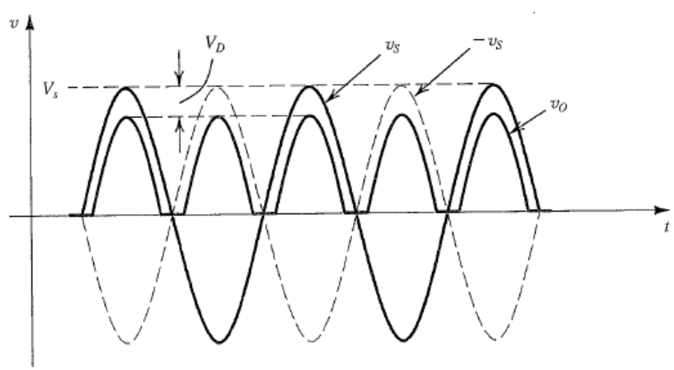


Full-wave rectifier utilising a transformer with a centre-tapped secondary winding.



(b)

Transfer characteristic assuming a constant voltage-drop model.



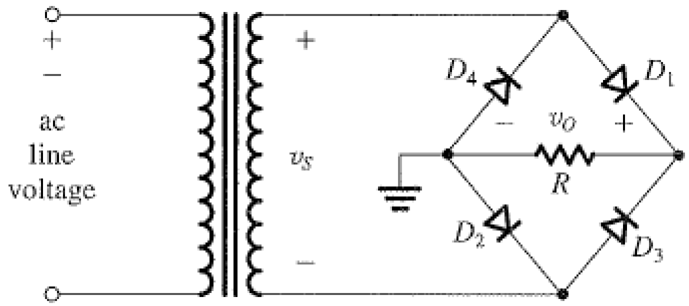
(c)

Input and output waveforms.

Note PIV = $2V_s - V_D$.

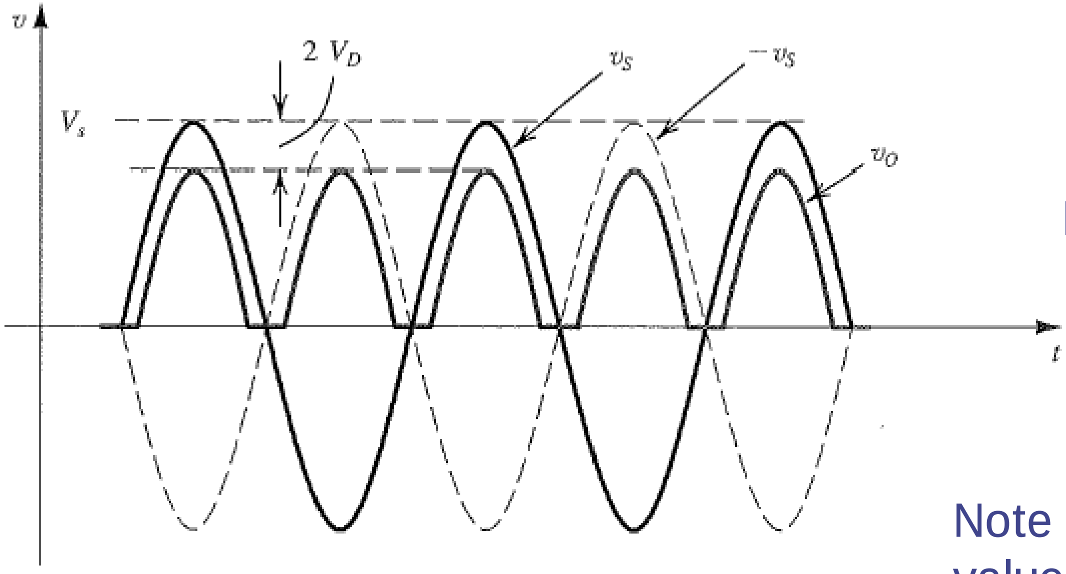
Source : Sedra/Smith – Microelectronic circuits

Full wave rectifiers



(a)

The bridge rectifier



(b)

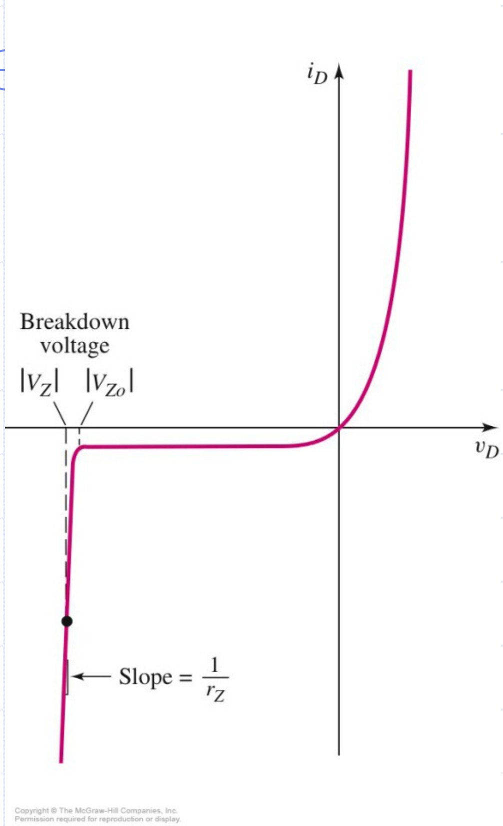
Input and output waveforms.

Note PIV = $V_s - V_D$, about half the value for the full-wave rectifier using a centre-tapped transformer.

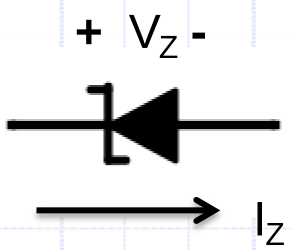
Source : Sedra/Smith – Microelectronic circuits

Zener diodes

Diodes that operate specifically in the breakdown region.



Diode i-v characteristics in the breakdown region



Circuit symbol

https://upload.wikimedia.org/wikipedia/commons/thumb/2/24/Zener_Diode.JPG/1024px-Zener_Diode.JPG

$V_Z = V_{Zo} + r_z I_Z$ for $I_Z > I_{Zo}$, and $V_Z > V_{Zo}$.

V_Z = Zener breakdown voltage,

I_Z = reverse-bias current

r_z = incremental resistance, typically small in values (few ohms to tens of ohms)

Zener diodes – an application example

The 6.8 V zener diode in the circuit below is specified to have V_Z = 6.8 V at I_Z = 5 mA, r_z =20 Ω, and I_{ZK} (≈ I_{Zo}) = 0.2 mA. The supply voltage V^+ is nominally 10 V but can vary by ± 1 V.

(a) Find V_o with no load and with V^+ at its nominal value.

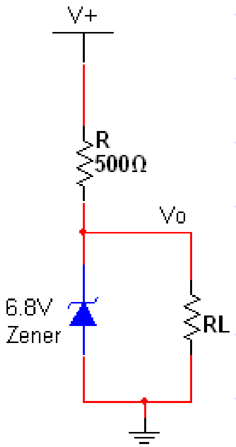
(b) Find the change in V_o resulting from the ±1 V change in V^+. Note that $\Delta V_o/\Delta V^+$, usually expressed in mV/V, is known as line regulation.

(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 the load regulation ($\Delta V_o/\Delta I_L$) in mV/mA. V^+ = V^+(nom).

(d) Find the change in V_o when R_L = 2 kΩ. V^+ = V^+(nom).

(e) Find the change in V_o when R_L = 0.5 kΩ. V^+ = V^+(nom).

(f) What is the minimum value of R_L for which the diode still operates in the breakdown region?



((a) 6.83 V (b) ±38.5 mV, 38.5 mV/V (c) -20 mV, -20mV/mA (d) -68 mV (e) 5 V (f) 1.5 kΩ)

Zener diodes – an application example

(a) with no load, $V_Z = I_Z r_z + V_{ZO} \quad \rightarrow V_{ZO} = V_Z - I_Z r_z = 6.7V$.

$$I_Z = \frac{V^+_{nom} - V_{ZO}}{R + r_z} = 6.346 \ mA \ \ and \ \ V_Z = I_Z r_z + V_{ZO} = 6.83V.$$

(b) With no load, $V_O = V_Z = I_Z r_z + V_{ZO}$.

$$I_Z = \frac{V^+ - V_{ZO}}{R + r_z}$$

$$\therefore \ V_O = V_Z + \frac{r_z}{R + r_z}(V^+ - V_{ZO}) \quad or \quad \frac{\Delta V_O}{\Delta V^+} = \frac{r_z}{R + r_z}$$

For $\Delta V^+ = \pm 1V$, $\Delta V_O = \pm 38.5 \, mV$.

i.e line regulation is $\pm 38.5 \ mV/V$.

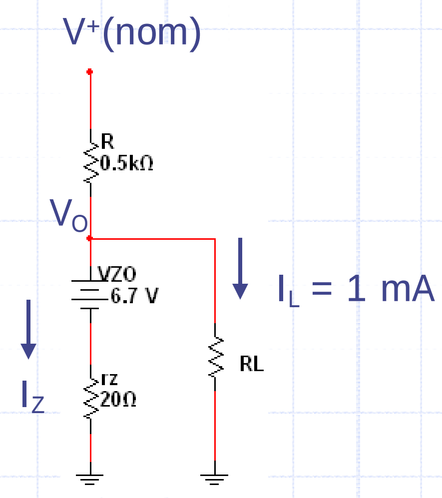
(c) $V_O = 6.83V$ with no load, and $V^+ = nom. = 10V$.

$$\frac{V^+ - V_O}{R} = I_Z + I_L \quad and \ \ V_O = I_Z r_z + V_{ZO} \ \ and \ \ I_L = 1mA \ \Rightarrow I_Z = 5.3846 \ mA.$$

and $V_O = 6.808V$.

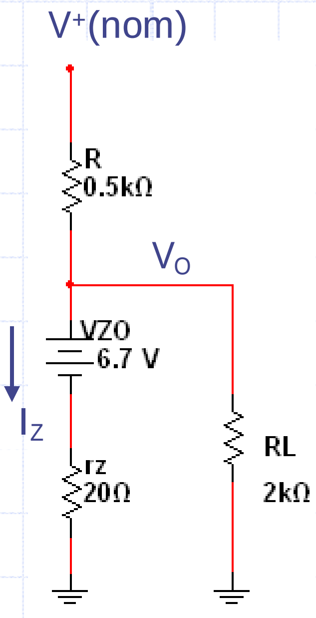
$\Delta V_O = 6.808 - 6.83 = -22 \, mV$

$$load \ \ regulation = \frac{V_{load} - V_{noload}}{I_{load}} = -22 \, mV/mA.$$



(c)

Zener diodes – an application example



(d)

$$(d)\quad \frac{V^+_{nom} - V_O}{R} = I_Z + \frac{V_O}{R_L} \quad and \quad V_O = I_Z r_z + V_{ZO} \quad results \;\; in \;\; V_O = 6.7619V\ .$$

$$\Delta V_O = 6.7619 - 6.83 = -68.1mV$$

$$Note : I_L = \frac{V_O}{R_L} = 3.381mA.$$

$$(e)\; R_L = 0.5\ k\Omega \;\; V^+ = V^+_{nom} = 10V\ .$$

$$I_L \approx \frac{6.8}{0.5} = 13.6\ mA$$

$$I_R \approx \frac{V^+_{nom} - 6.8}{R} = 6.4\,mA \quad \Rightarrow \quad I_Z \;\; is \;\; negative!$$

$$\therefore\ Zener \;\; is \;\; not \;\; in \;\; breakdown \;\; \mathrm{mod}\, e, it \;\; is \;\; off\ .$$

$$V_O = \frac{R_L}{R_L + R} V^+_{nom} = 5V \;\; (which \;\; is \; less \; than \;\; V_{ZK}, \;\; in \;\; \sup port \;\; of \;\; conclusion).$$

$$(f)\;\; I_{ZK} \approx I_{ZO} = 0.2\,mA = I_Z\,(\min).$$

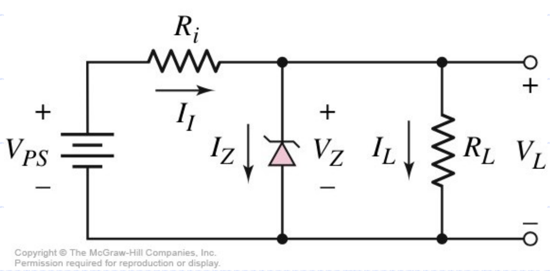
$$V_Z \approx V_{ZO} = V_{ZK} = 6.7V\ .$$

$$I_R(\min) = \frac{V^+_{nom} - V_Z}{R} = 4.6\,mA.$$

$$I_L = I_R\,(\min) - I_Z\,(\min) = 4.4\,mA$$

$$\therefore\ R_L(\min) = \frac{6.7}{4.4} = 1.5\ k\Omega.$$

Formal analysis of Zener diode voltage regulator circuit



$$R_i = \frac{V_{PS} - V_Z}{I_I} = \frac{V_{PS} - V_Z}{I_Z + I_L} \qquad (1)$$

Assuming $r_Z = 0$, $I_Z = \dfrac{V_{PS} - V_Z}{R_i} - I_L \quad (2), \quad$ *where* $I_L = \dfrac{V_Z}{R_L}$

Constraints on the diode:

1. must remain in breakdown region, and

2. power dissipation in diode must not exceed its rated value.

I_Z *minimum when* I_L *is maximum, and source voltage is minimum.*

$$\text{From (1), } R_i = \frac{V_{PS}(\min) - V_Z}{I_Z(\min) + I_L(\max)} \qquad (3a)$$

I_Z *maximum when* I_L *is minimum, and source voltage is maximum.*

$$\text{From (1), } R_i = \frac{V_{PS}(\max) - V_Z}{I_Z(\max) + I_L(\min)} \qquad (3b)$$

Equating (3*a*) *and* (3*b*),

$$[V_{PS}(\min) - V_Z].[I_Z(\max) + I_L(\min)] = [V_{PS}(\max) - V_Z].[I_Z(\min) + I_L(\max)] \qquad (4)$$

Rule of thumb : Choose $I_Z(\min) = 0.1 I_Z(\max)$ *to ensure diode is in breakdown.*

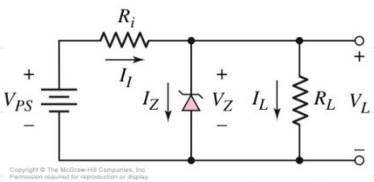
$$\text{Thus from (4), } I_Z(max) = \frac{I_L(max)[V_{PS}(max) - V_Z] - I_L(min)[V_{PS}(min) - V_Z]}{V_{PS}(min) - 0.9V_Z - 0.1V_{PS}(max)} \quad (5)$$

(5) *gives the maximum required power rating of the Zener diode.*

(3*a*) *or* (3*b*) *gives the required value of* R_i.

Design of a Zener regulator circuit

The voltage regulator circuit is to power a car radio at V_L = 9 V from an automobile battery whose voltage may vary between 11 and 13.6 V. The current in the radio will vary between 0 (off) to 100 mA (full volume). Design the circuit, i.e find values of R_i, P_{Ri}(max), P_Z(max), I_Z(min), and I_Z(max).



$$V_{PS} : 11V \rightarrow 13.6V$$

$$I_L : 0 \rightarrow 100mA$$

$$From\ (5)\ of\ previous\ slide, with\ I_L\ (\max) = 100\ mA, V_{PS}\ (\max) = 13.6V,$$

$$I_L(\min) = 0\ and\ V_{PS}(\min) = 11V,\ I_Z\ (\max) = \frac{100(13.6-9)-0}{11-0.9X9-0.1X13.6} \approx 300mA$$

$$I_Z(\min) = \frac{1}{10} I_Z(\max) = 30mA$$

$$P_Z(\max) = I_Z\ (\max)\ X\ V_Z = 2.7W$$

$$From\ (3a), R_i = \frac{V_{PS}(\min) - V_Z}{I_Z\ (\min) + I_L\ (\max)} = \frac{11-9}{30+100} = 15.4\Omega$$

$$V_{R_i}(\max)\ when\ V_{PS}\ is\ \max imum\ or\ V_{R_i}(\max) = V_{PS}(\max) - V_Z = 4.6V.$$

$$P_{R_i}(\max) = \frac{4.6^2}{15.4} = 1.37W.$$