Chapter 3 : diode circuits

- **3.1 Ideal diodes**
- **3.2 PN junction, just like a diode**
- **3.3 Diode applications**

The three modes of operation for a diode

pn junction equilibrium

- **Depletion region**
- **Potential barrier**

⇨

PN junction reverse bias

- **Capacity of the junction**

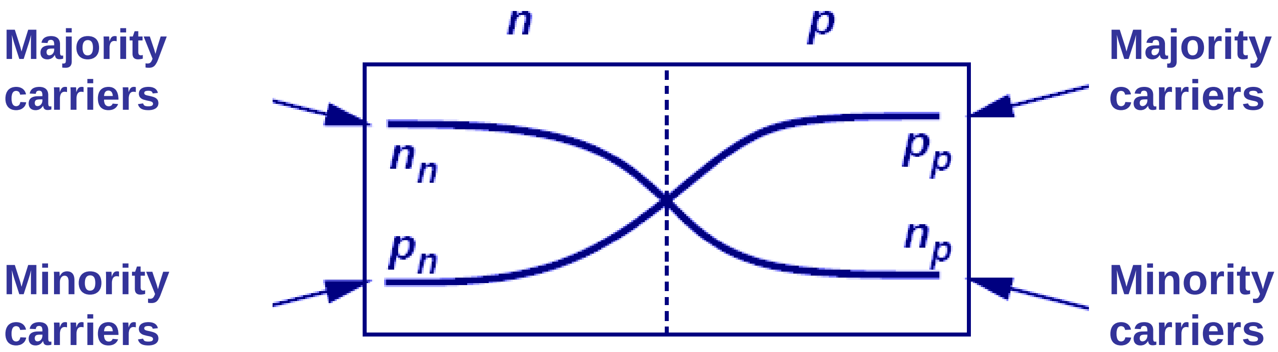
⇨

PN junction forward bias

- **Characteristic I/V**

➢ To understand how a diode works it is necessary to study, the three modes of operation: equilibrium, forward bias, and reverse bias.

Current through the junction: diffusion



n_n : Concentration of electrons at the N side

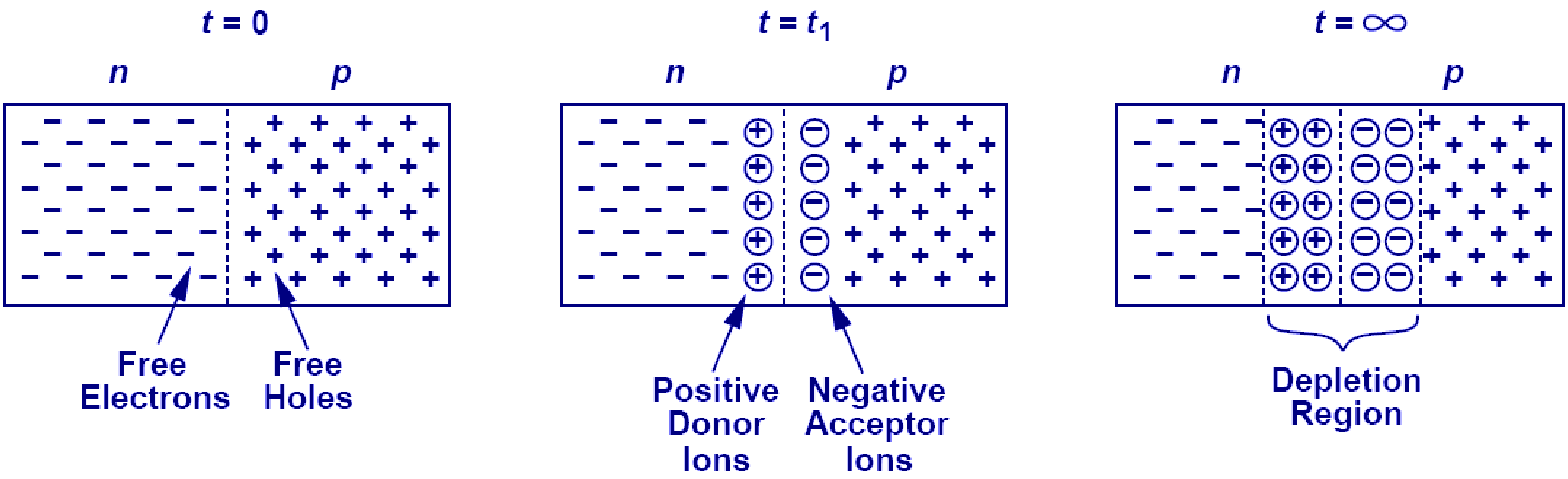
p_n : Concentration of holes at the N side

p_p : Concentration of holes at the P side

n_p : Concentration of electronsat the P side

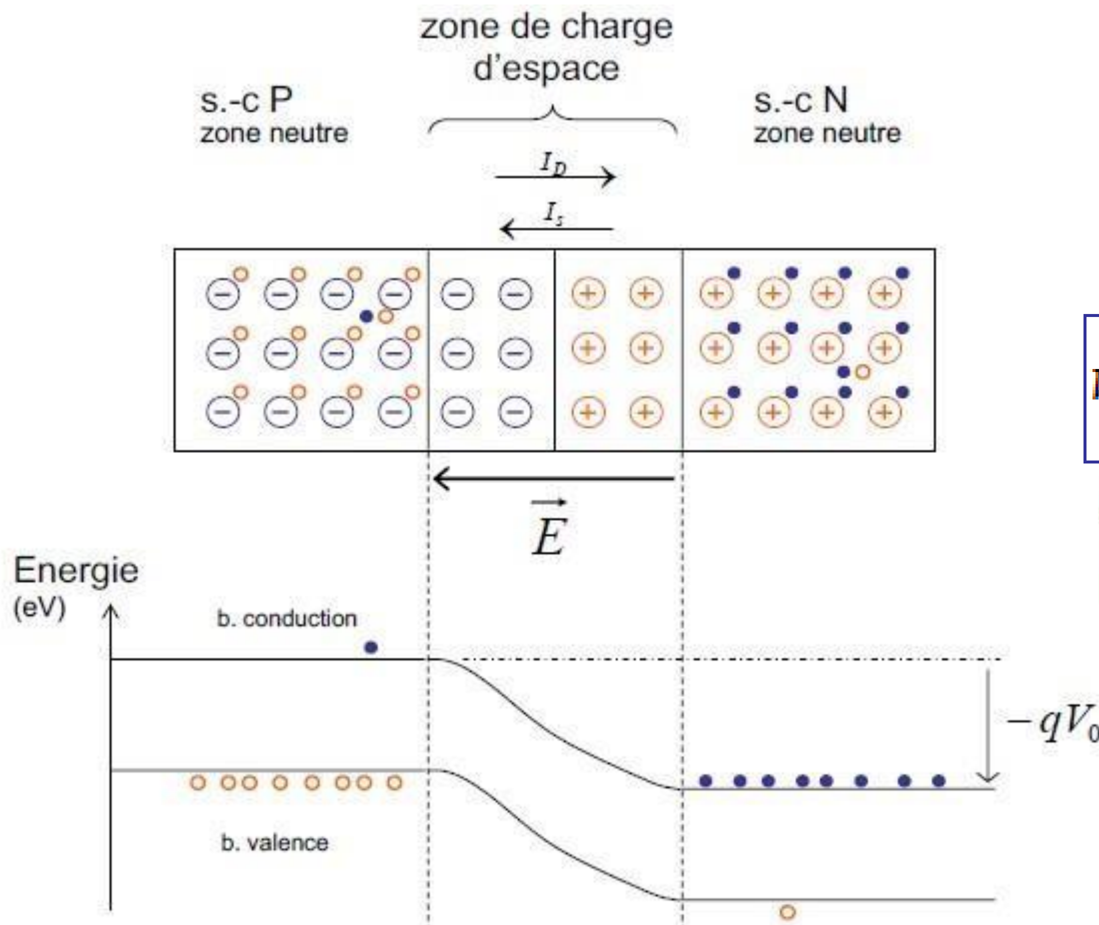
- Each side of the junction contains an excess amount of electrons and holes relative to the other. Thus a gradient in the charge distribution is in place. Therefore a diffusion current passes through the junction.

Region of depletion



- Free électrons and holes diffuse through the junction, and a region with static ions is left behind. This region is known as the « region of depletion ».

Current through the junction: diffusion



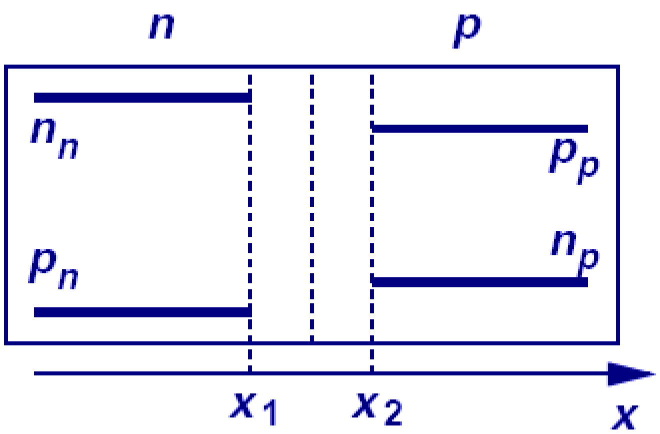
$$V_0 = \frac{kT}{q} . \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

k = 1,38.10^{-23} J/K

T température [K]

- The static ions in the depletion zone create an electric field that results in an electric current.

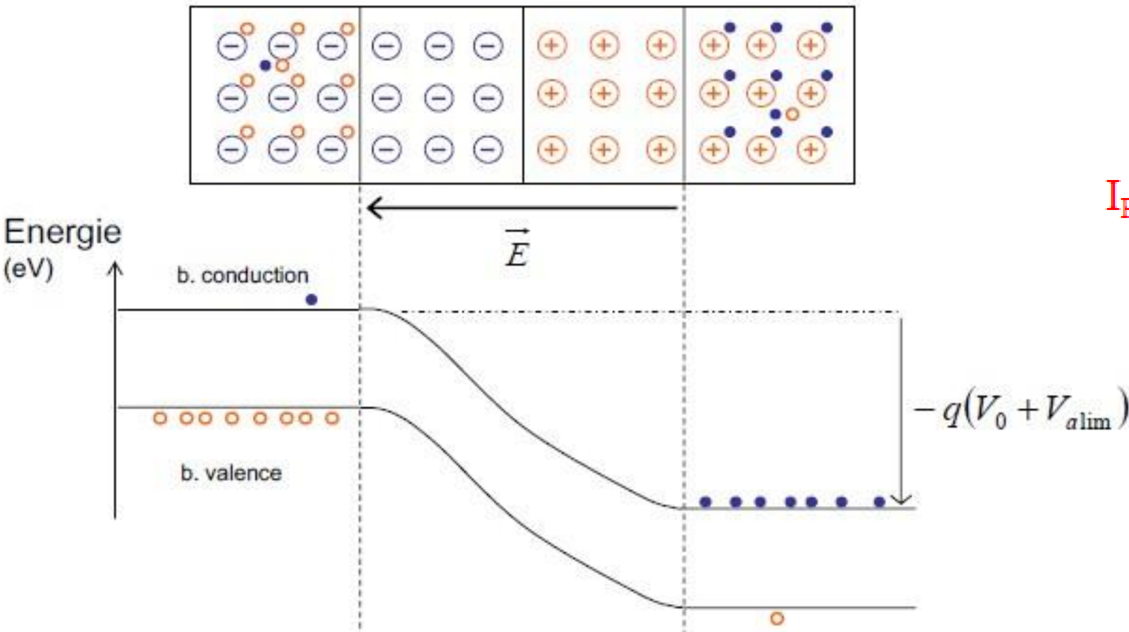
Current through the junction: equilibrium

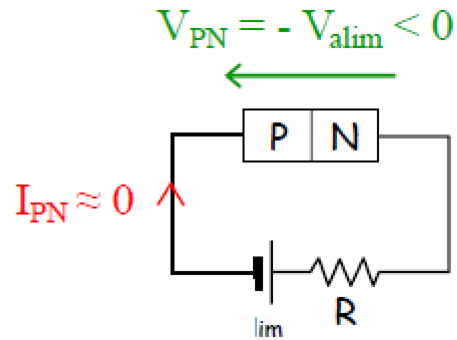


- This figure represents the band diagram of the junction
- The ions in the RD create an electric field opposite to the diffusion current, this field is equivalent to a potential difference called **Potential barrier** (V_0= 0,7V for silicon).
- At equilibrium, only a few majority carriers have enough energy to cross the RD and manage to contribute to the diffusion current **I_D**, it is then compensated by the **bias saturation current**, **I_S**, created by the minority carriers when caught by E in the RD.

Bias saturation current = 10nA

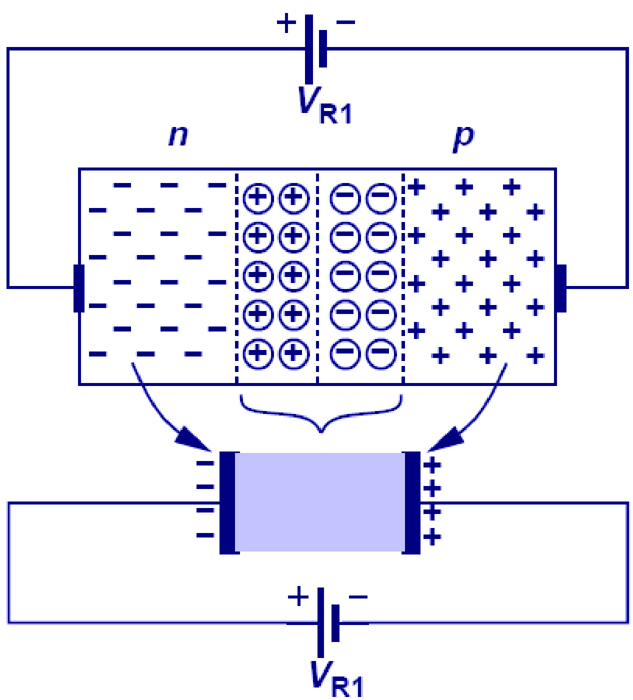
Diode in reverse bias



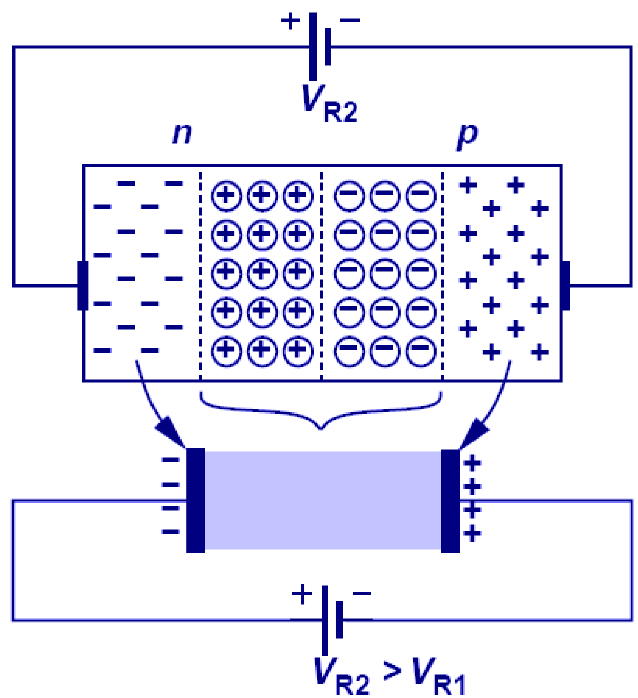


- When a type- N region of the diode is connected to a potential higher than that of type-P the diode is then in reverse bias, this results in a growth of the RD making the electric field more intense at the junction.
- The diffusion current (majority carriers) becomes arpx 0.
- We are left with an extremely weak bias current, $I_{PN}=-I_S$, that of minority carriers.

Applications of a diode in reverse bias mode: A voltage dependent capacitor



(a)

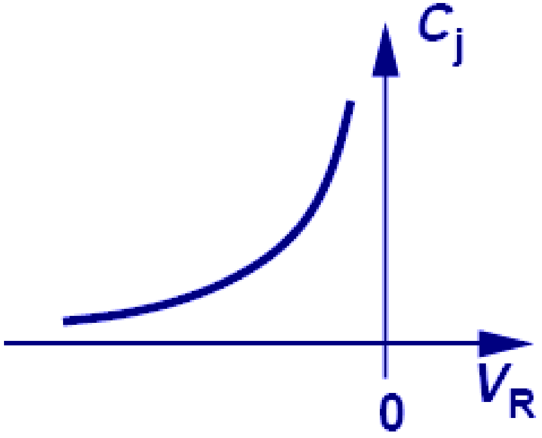


(b)

- A PN junction can be perceived like a capacitor since, by varying V_R, the size of the RD changes, therefore changing the capacitance.

Voltage dependent capacitor

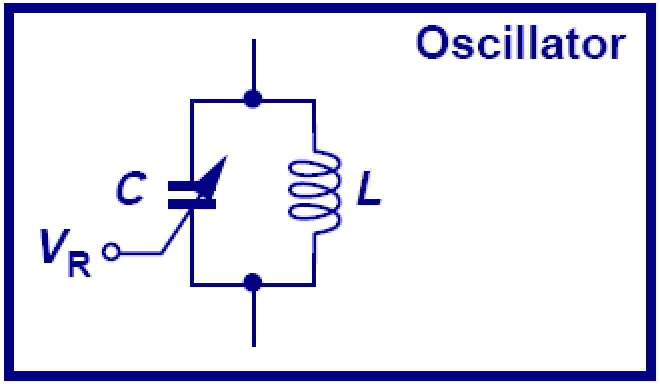
These are the equations describing the capacitance using Voltage.



$$C_j = \frac{C_{j0}}{\sqrt{1+\frac{V_R}{V_0}}}$$

$$C_{j0} = \sqrt{\frac{\varepsilon_{si} q}{2} \frac{N_A N_D}{N_A + N_D} \frac{1}{V_0}}$$

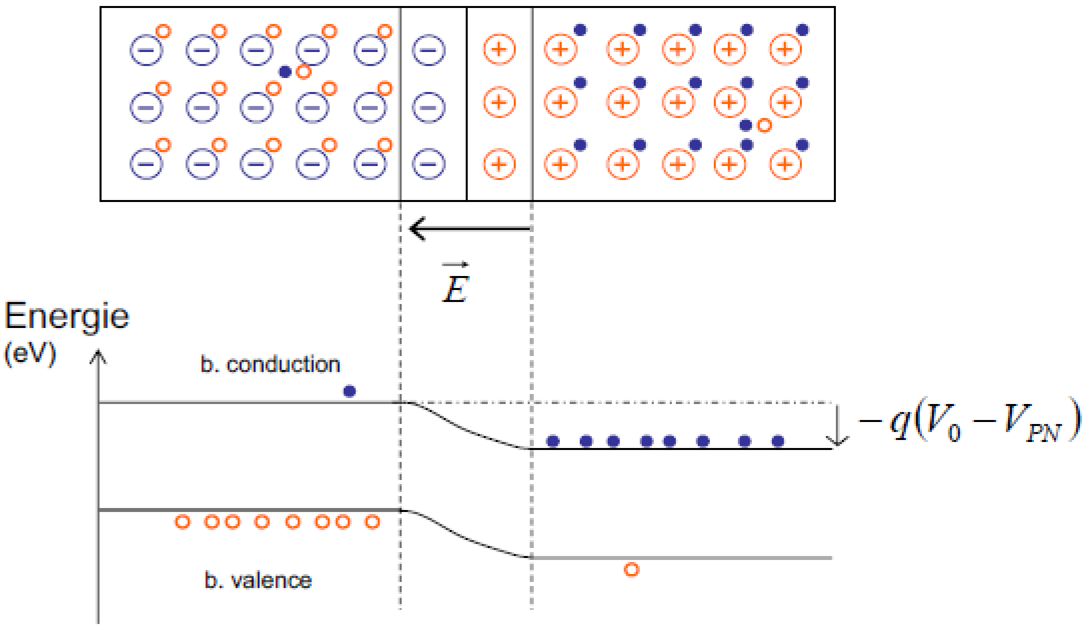
Voltage regulated oscillator

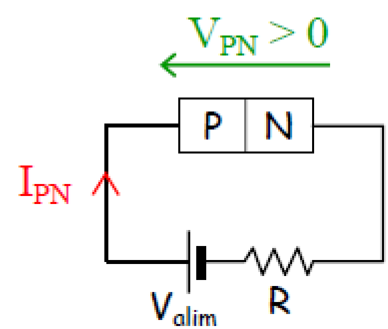


$$f_{res} = \frac{1}{2\pi}\frac{1}{\sqrt{LC}}$$

- One important application for PN junctions in reverse bias is the voltage regulated oscillator. In which an LC circuit is used in an oscillator. By changing the voltage Vr we can change C, changing C would also change the frequency of the oscillator.

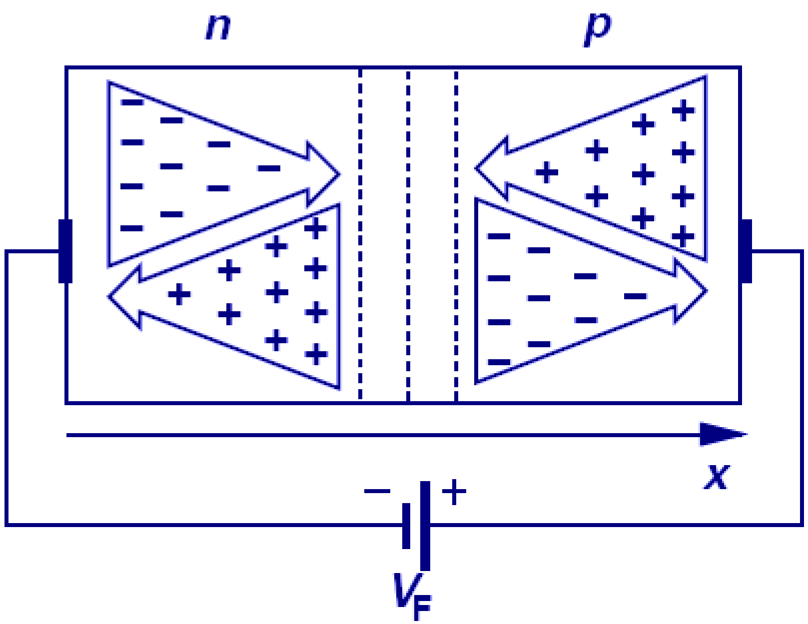
Diode in forward bias





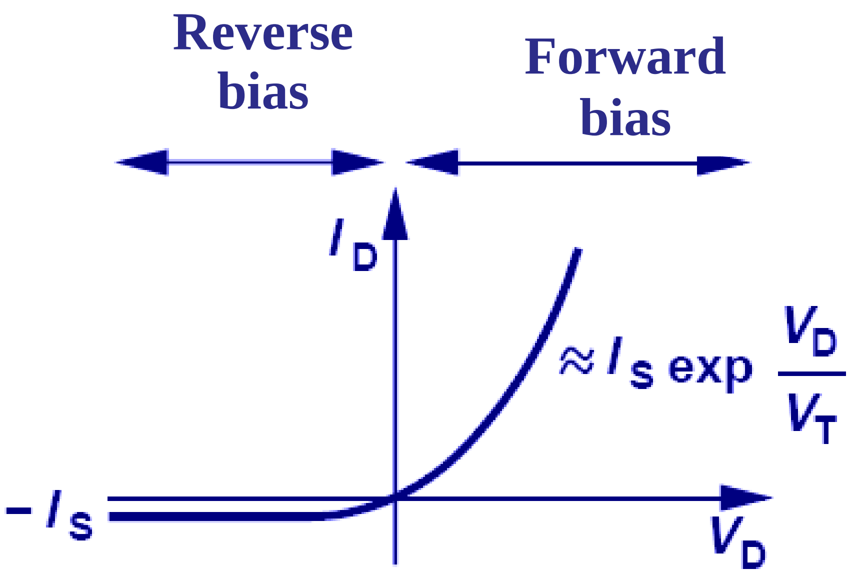
- When the N region of the diode is connected to a potential lower than that of the P region, the diode is in forward bias.
- The region of depletion becomes smaller, lowering the electric field as well as the potential barrier.

Conditions of forward bias



- In forward bias, there are high diffusion currents of minority carriers through the junction. Meanwhile, deeper in the N and P regions, the “reconbinations” of majority carriers become dominant. These two currents are added creating a constant value of I.

I/V characteristic of the PN junction



$$I_D = I_S(\exp\frac{V_D}{V_T} - 1)$$

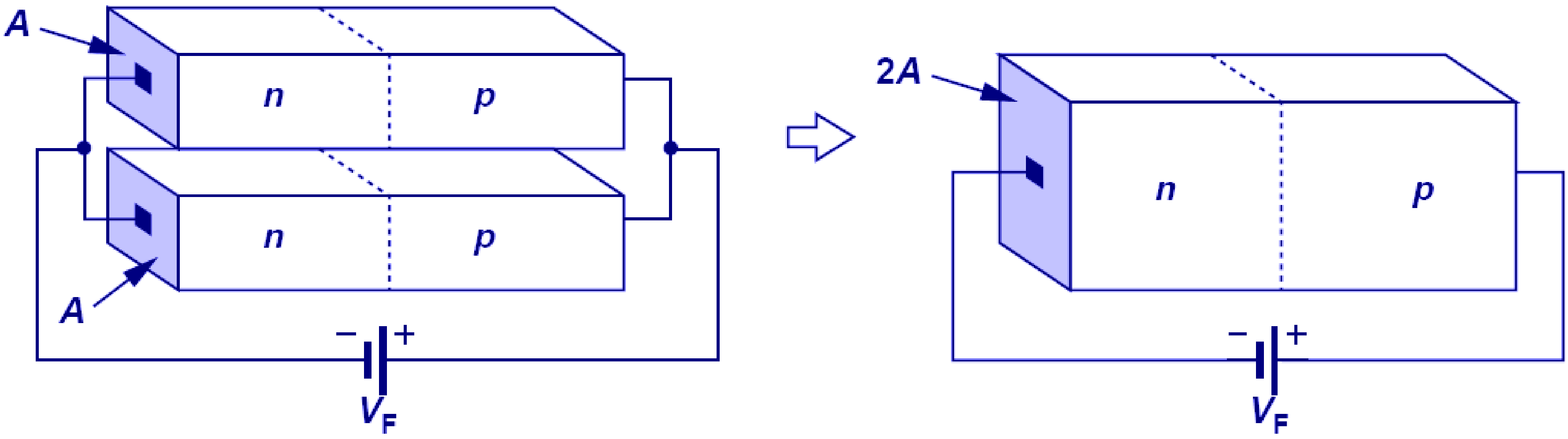
Is: bias saturation current = 10nA

VT: thermal voltage=26mV at T=300K

VD: bias saturation voltage

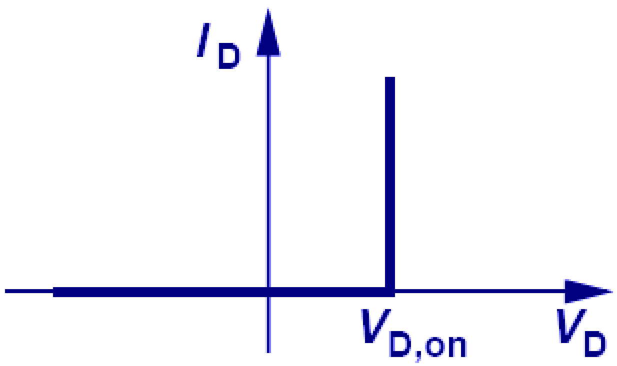
- The relation between current and voltage for a diode is exponential in case of forward bias and relatively constant for reverse bias.

PN junctions in parallel

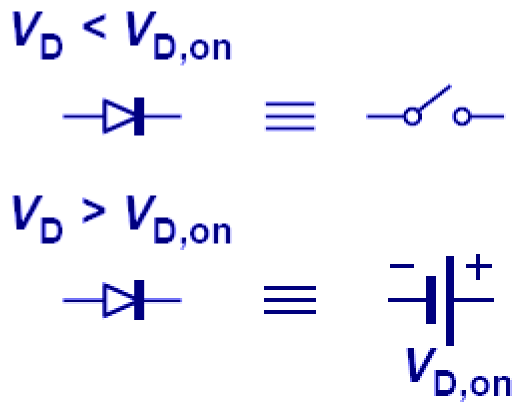


- As long as the currents of the junctions are proportional to the area of their section, therefore the 2 junctions connected in parallel act like 1 junction with an area equivalent to that of the sum of the 2 junctions and crossed by the 2 former currents.

The constant voltage diode model



(a)

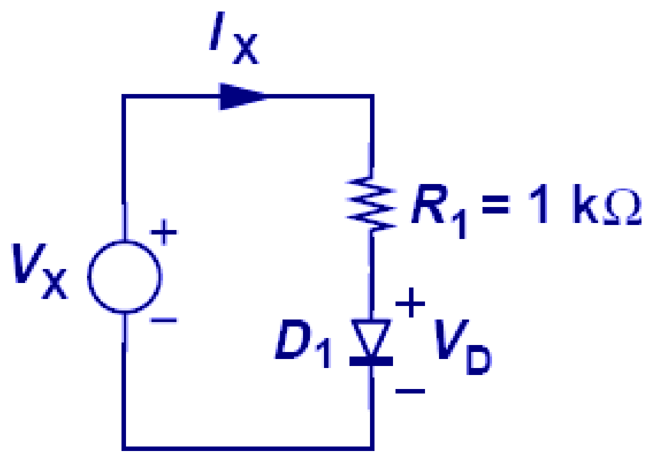


(b)

Ideal diode

- The diode acts as an open circuit if $V_D < V_{D,on}$ and as a source of voltage $V_{D,on}$ if $V_D > V_{D,on}$.

Example:



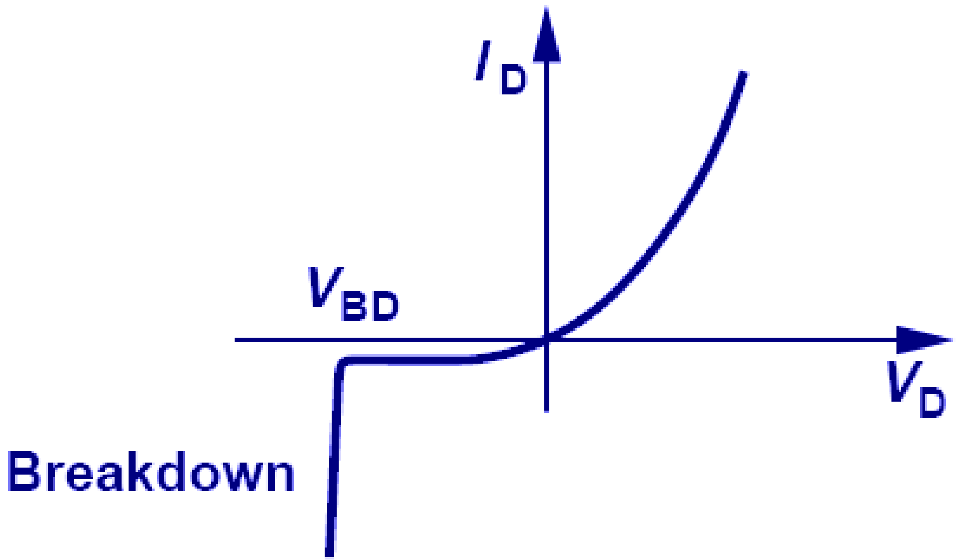
$$V_X = I_X R_1 + V_D = I_X R_1 + V_T \ln\frac{I_X}{I_S}$$

$$I_X = 2.2mA \quad for \quad V_X = 3V$$

$$I_X = 0.2mA \quad for \quad V_X = 1V$$

- This example demonstrates the simplicity offered by a diode with constant voltage over that of an exponential model.

Diode in reverse bias : Breakdown



When a diode is connected in reverse bias, the majority carriers (holes in the P region and electrons in the N region) push away from the junction. The depletion region gets larger, and the forward current finds it harder if not impossible to cross. Meanwhile, the minority carriers allow a very weak current partially constant until the **Breakdown voltage** is reached.

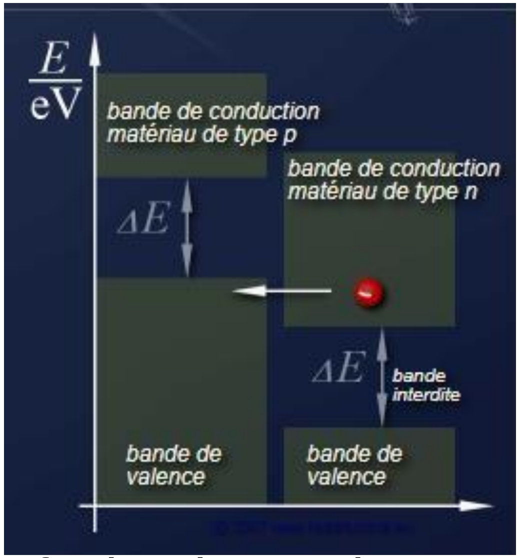
At this stage, the bias current rises fast even with a small rise in reverse bias.

Zener effect and avalanche effect

During the breakdown, 2 possible scenarios could happen: **The Zener effect**, or **the avalanche effect**, even though the two are totally different, and the avalanche effect is much more frequent, the name given to these diodes is **the Zener diode**.

The Zener effect is a case of the « quantum tunneling effect » where it is allowed for the carriers to cross the potential barrier even if their energy is less than the one required to cross the potential step.

The reverse bias (or reverse polarization) of the Valence band in the P material allows a refund of Energy with the conduction band on the N side of the Junction, without added energy, through the very thin Common energy band: **This is called the tunneling** effect**.**



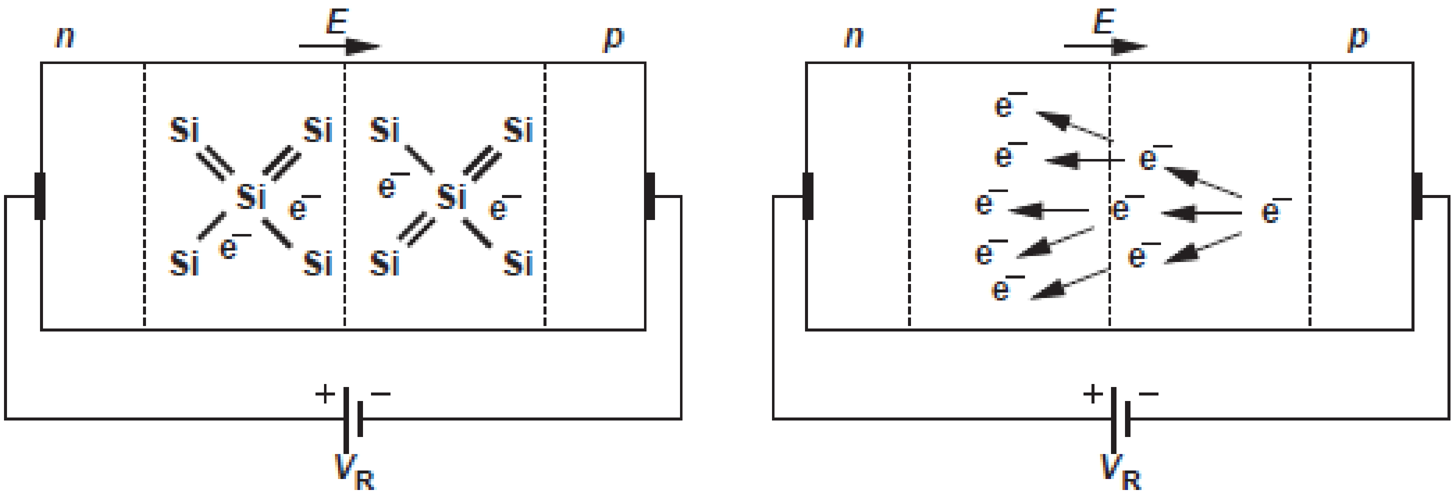
When the point of breakdown is reached, a large number of minority carriers cross Through the “tunnel”. This phenomenon is only possible for highly doped diodes and breakdown voltages of less than 5 Volts.

Zener effect and avalanche effect

The avalanche effect commonly occurs for an inverse potential higher than 5 volts. Types of diode that operate at this threshold have a depletion zone that is deliberately thinner than normal pn junctions and yet larger than Zener diodes, thickness is made larger by lowering the dopage of the material, thus making the breakdown voltage larger. By controlling dopage, it is possible to create diodes with avalanche effects with thresholds from 2 to 200V.

In this type of diodes, all thermodynamic processes at the junctions level create electron-hole pairs. The escaping current is due to electrons, the minority carriers, accelerating due to the electric potential at the barrier.By increasing this biased polarization, the potential reaches a critical limit after which a breakdown occurs.

Zener effect and avalanche effect



The kinetic energy gained by the minority carriers (électrons) is then high enough to break the covalent bonds in the crystalline lattice it encouters. The ejected électrons are then accelerated by the electric field, colliding with other atoms while releasing new waves of electrons. This cascade phenomenon (just like dominos) is whence called the “avalanche effect”.

Diodes in circuits

Diodes as Circuit Elements

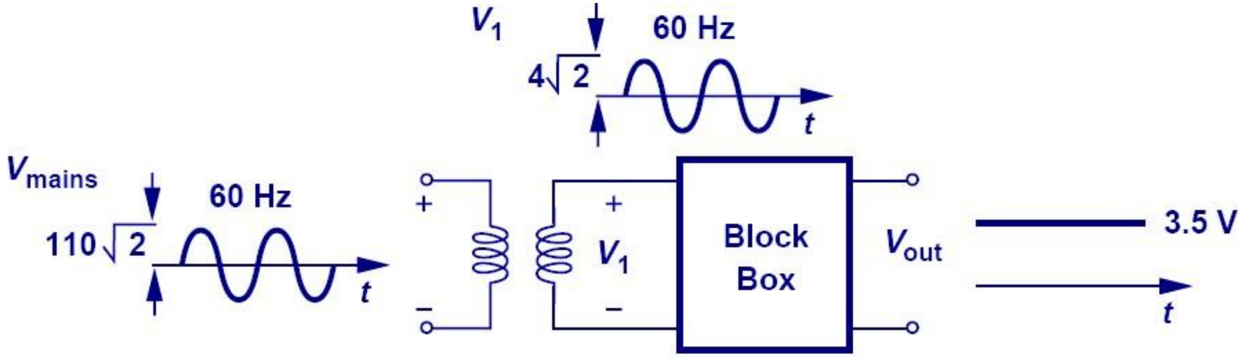
- Ideal Diode
- Circuit Characteristics
- Actual Diode

Applications

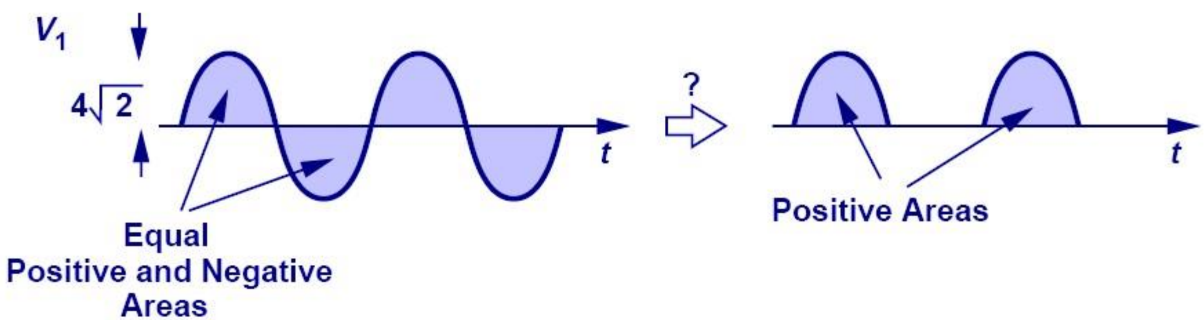
- Regulators
- Rectifiers
- Limiting and Clamping Circuits

➢ After studying the physics behing the diode it is now time to study it as an element in an electric circuit and its variety of applications.

Application of the diode : the cellphone



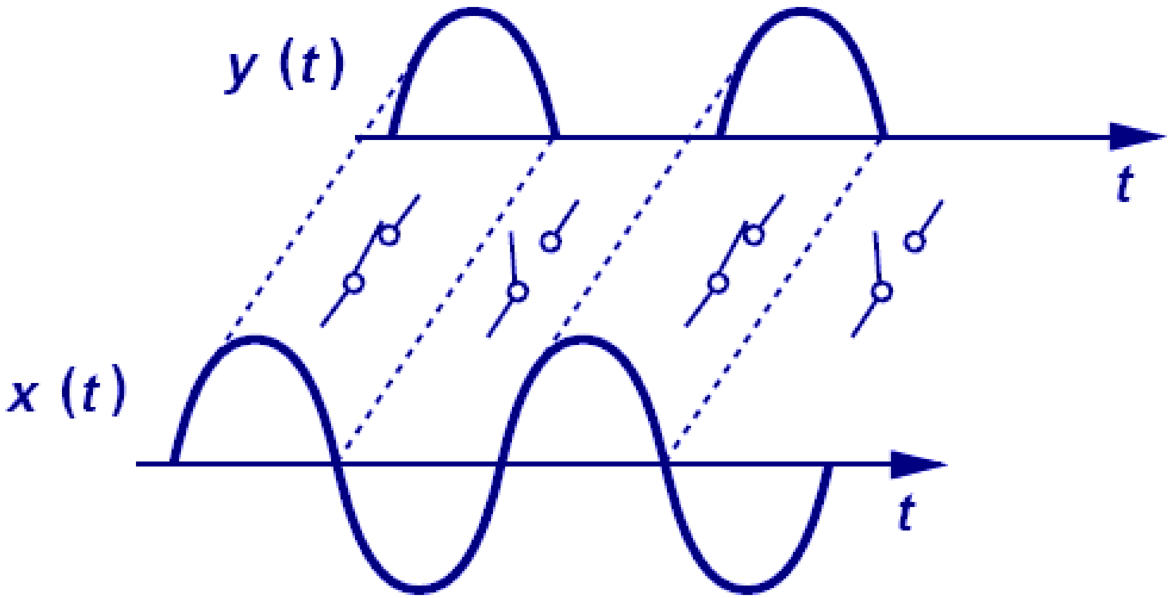
(a)



(b)

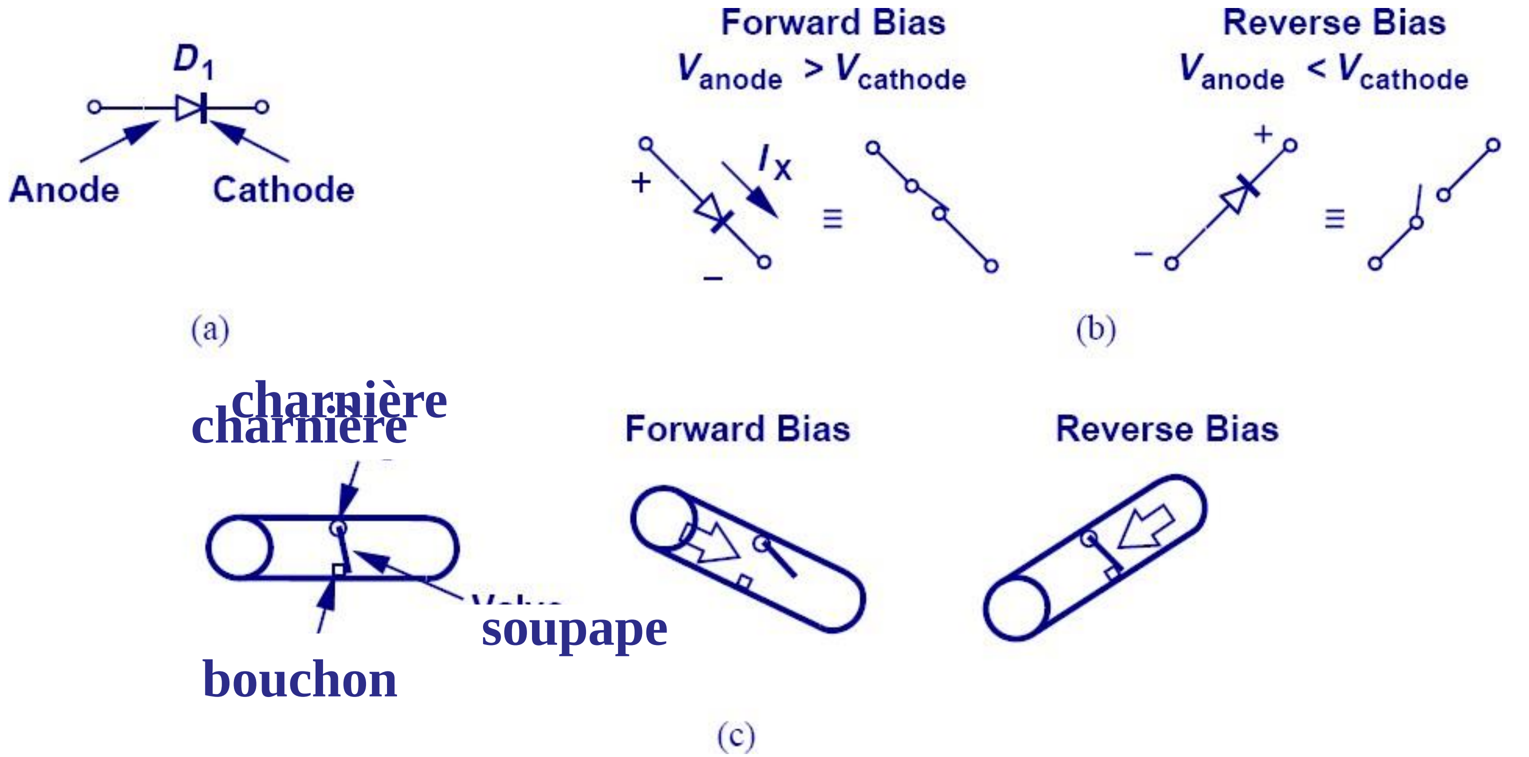
- An important application of diodes in cell phones.
- The diode acts like a black box filtering the positive half of the signal

Action of the diode in a black box (ideal diode)



- The diode acts like a short circuit during the positive half-cycle and as an open circuit during the negative half-cycle.

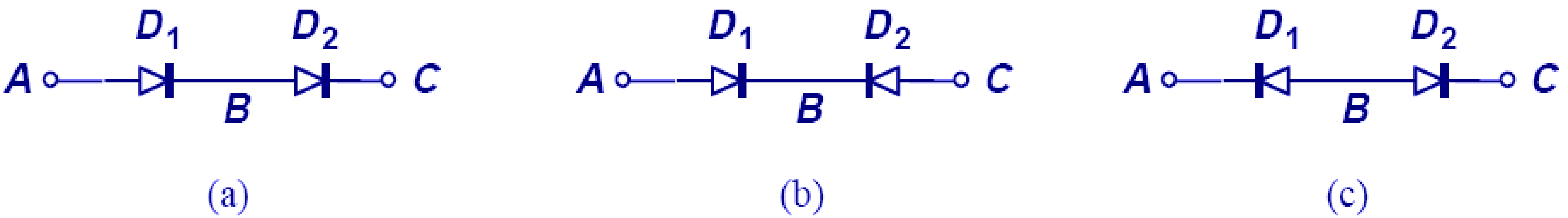
Ideal diode



In an ideal diode if the voltage has a tendancy to get higher than 0 V the current flows.

- It is similar to a water faucet that allows the liquid to flow in one direction only.

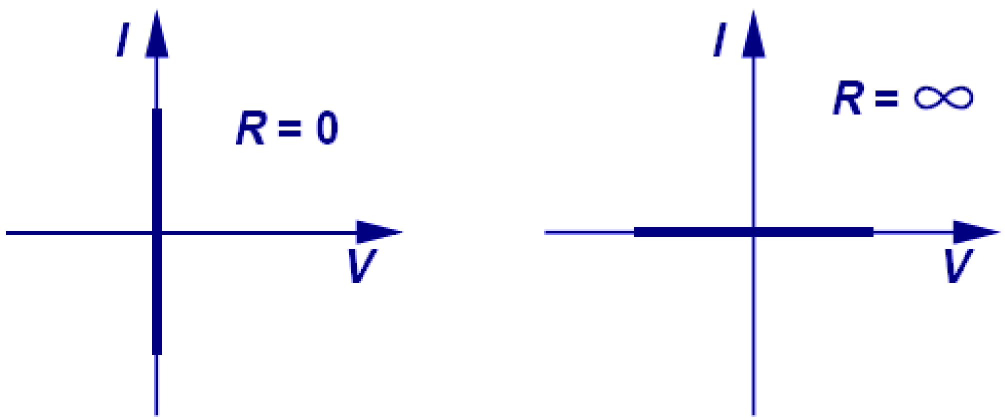
Diodes in Series



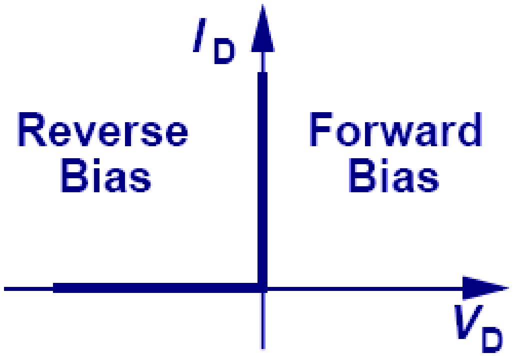
- Diodes cannot be connected in series by random. For the previous circuits only the case a) can allow current to pass from A to C.

I-V characteristic of an ideal diode

$$R = 0 \Rightarrow I = \frac{V}{R} = \infty \qquad R = \infty \Rightarrow I = \frac{V}{R} = 0$$



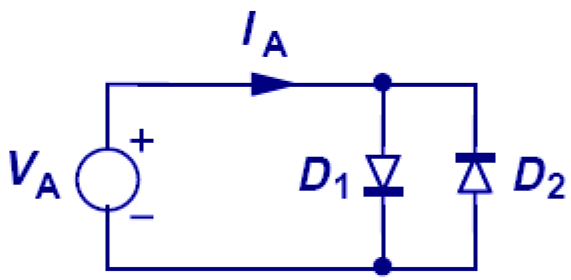
(a)



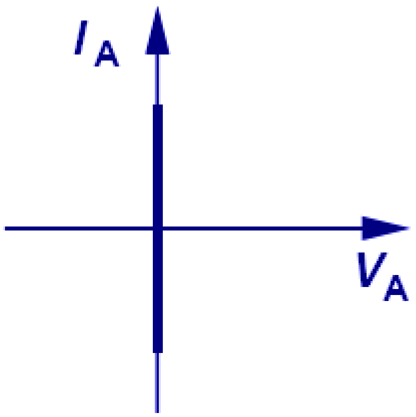
(b)

- If the potential at the ends of the cathode and anode ($V_D = V_{anode} - V_{cathode}$) is greater than 0, its resistance becomes also 0 thus making the current infinite. Meanwhile, if the potential is less than 0 the resistance becomes infinite while the current drops to 0.

Ideal diodes in opposite parallel



(a)

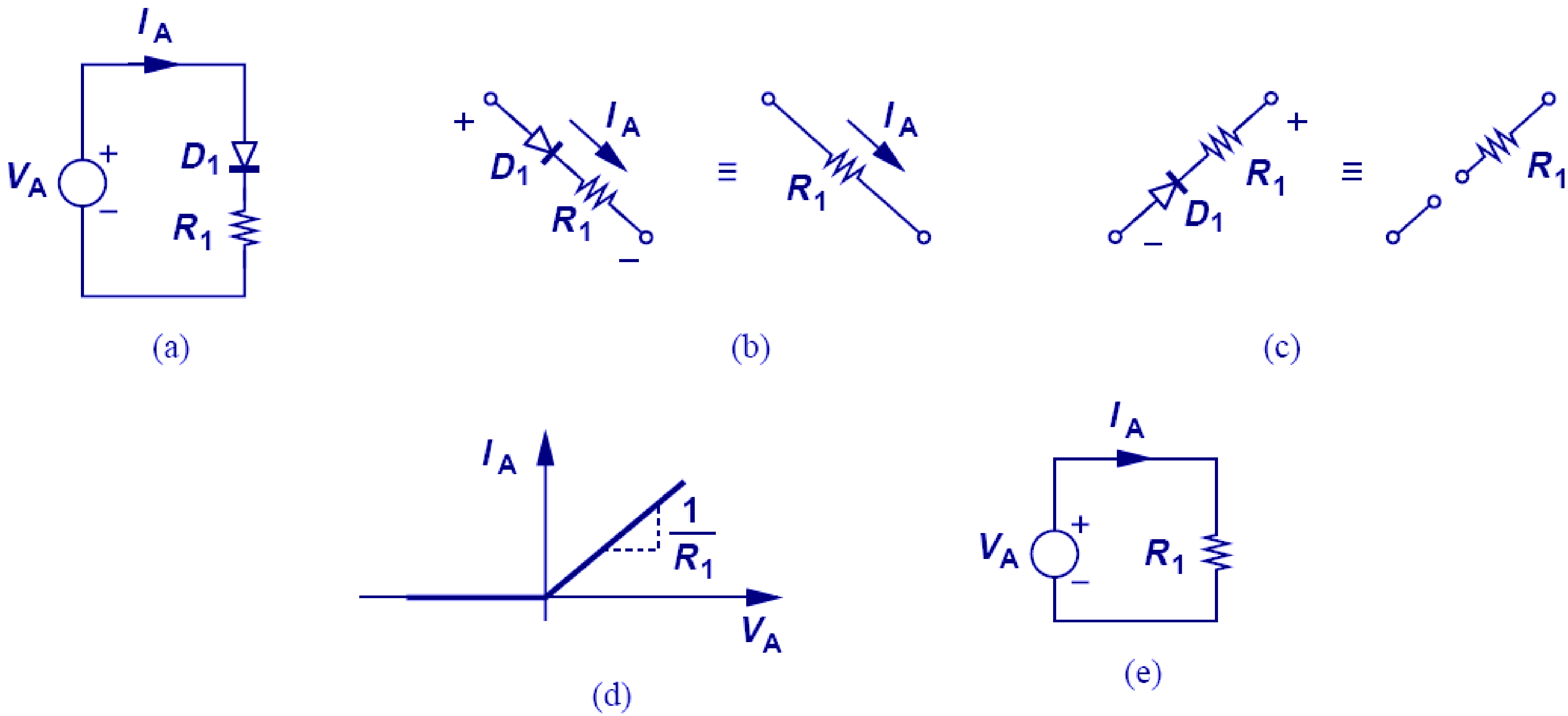


(b)

If $V_A > 0$, D_1 is on and D_2 is off, yielding $I_A = \infty$. If $V_A < 0$, D_1 is off, but D_2 is on, again leading to $I_A = \infty$.

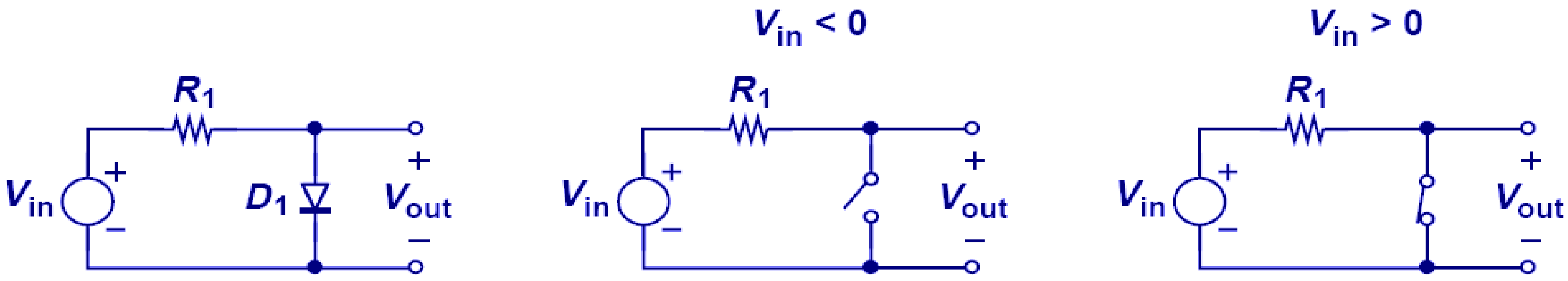
- If 2 diodes are connected in opposite parallel, they will act like short circuit for all potentials (positive or negative).

Diode-resistor combinations

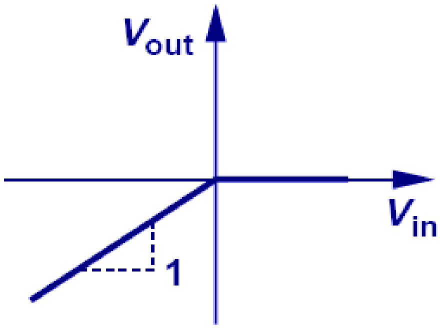


- I-V characteristic for a resistor-diode combination is always 0 for a negative potential and respects ohm’s law for positive ones.

Input/Output characteristic



(a) (b) (c)

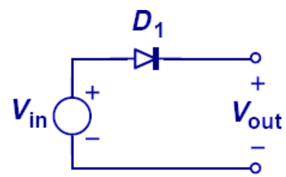


(d)

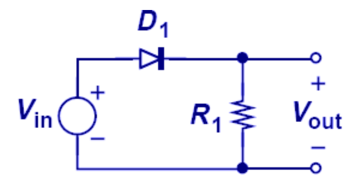
V_{in} is a periodic signal:

- if $V_{in} < 0$, the diode is in reverse bias, then $V_{out} = V_{in}$.
- if $V_{in} > 0$, the diode is in forward bias, it is in short-circuit, then $V_{out} = 0$

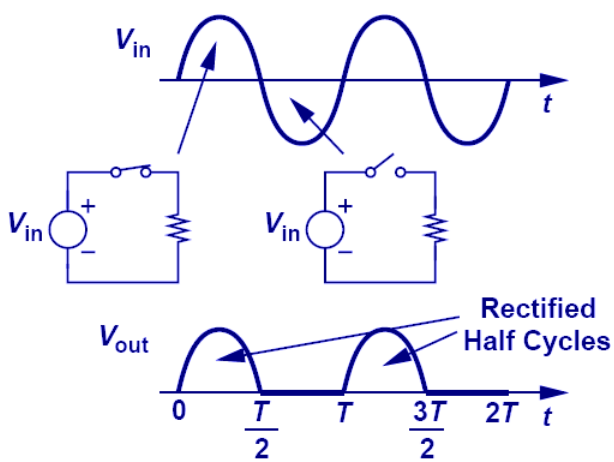
Application of diode: Rectifier



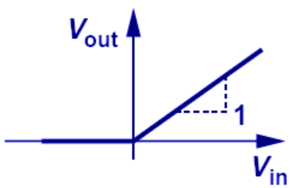
(a)



(b)



(c)



(d)

- A diode rectifier lets the positive half-cycle of the signal pass while blocking the negative half-cycle and vice versa.
- If $V_{in} > 0$, the diode is in short circuit, then $V_{out} = V_{in}$; meanwhile if $V_{in} < 0$, the diode is in off mode, no current is passing R_1, $V_{out} = I_{R_1} R_1 = 0$.

Indicateur de force du signal

$$V_{out} = V_p \sin \omega t = 0 \quad pour \quad 0 \le t \le \frac{T}{2}$$

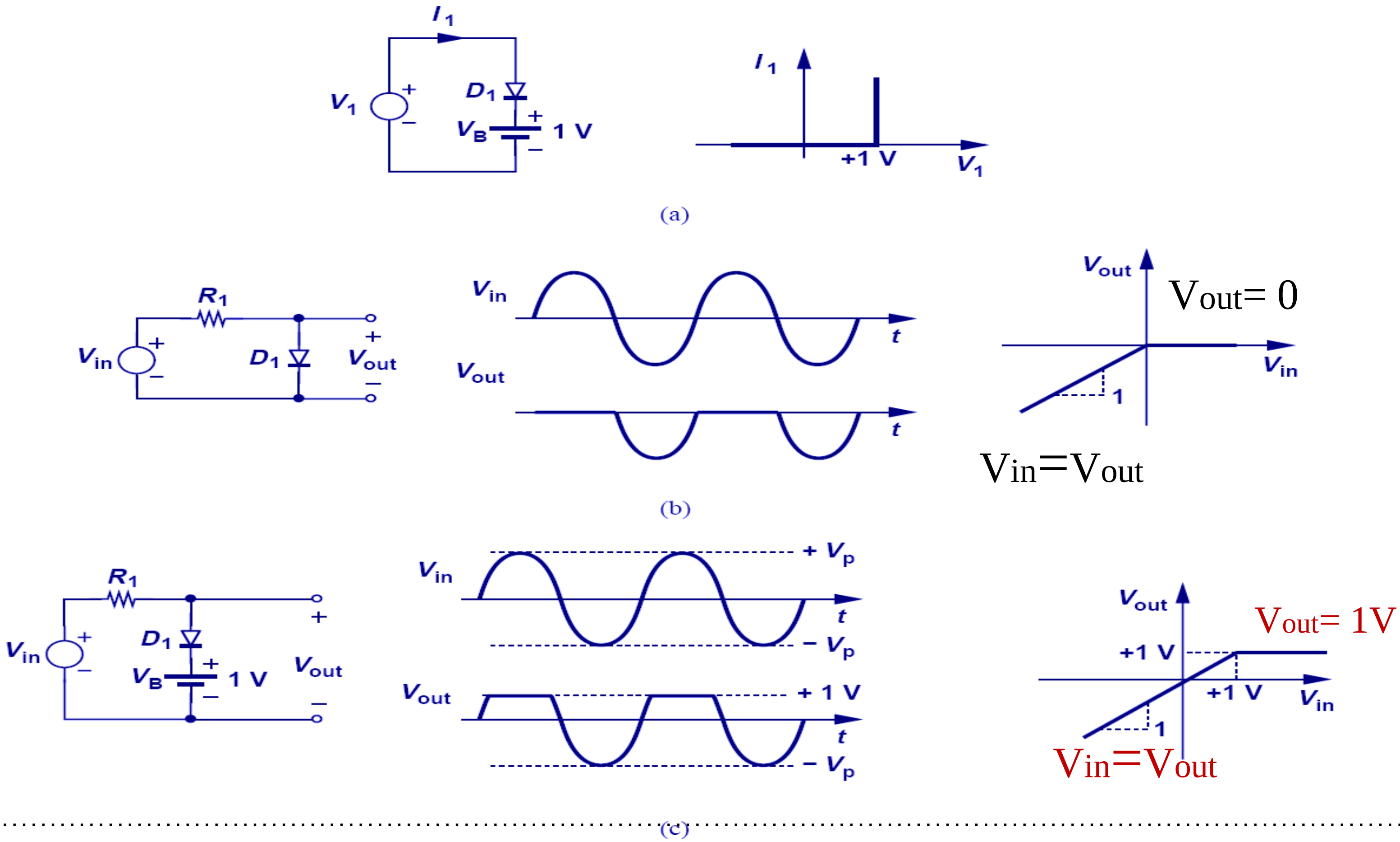
$$\mathrm{V_{out}} = 0 \quad pour \quad \frac{T}{2} \le t \le T$$

$$V_{out,avg} = \frac{1}{T}\int_0^T V_{out}(t)dt = \frac{1}{T}\int_0^{T/2} V_p \sin \omega t dt$$

$$= \frac{1}{T}\frac{V_p}{\omega}\left[-\cos\omega t\right]_0^{T/2} = \frac{V_p}{\pi}$$

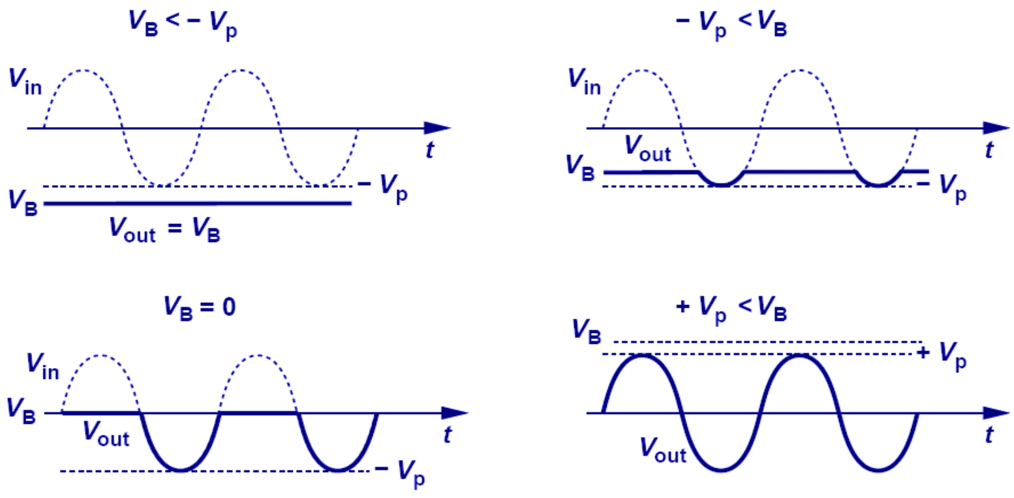
- The average output value of a rectifier can be useful to indicate the voltage of the input, since $V_{out,avg}$ is proportional to V_p, the amplitude of the input signal.

Application of diode : Limiter

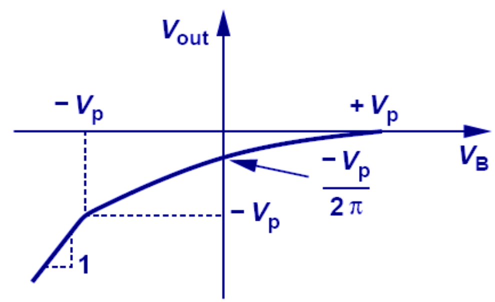


- The goal of a limiter is to keep the output under a certain level.
- The addition of a 1 V battery forces the diode to turn on after V_1 becomes greater than 1 V.

Limiter: When the battery is variable



(a)

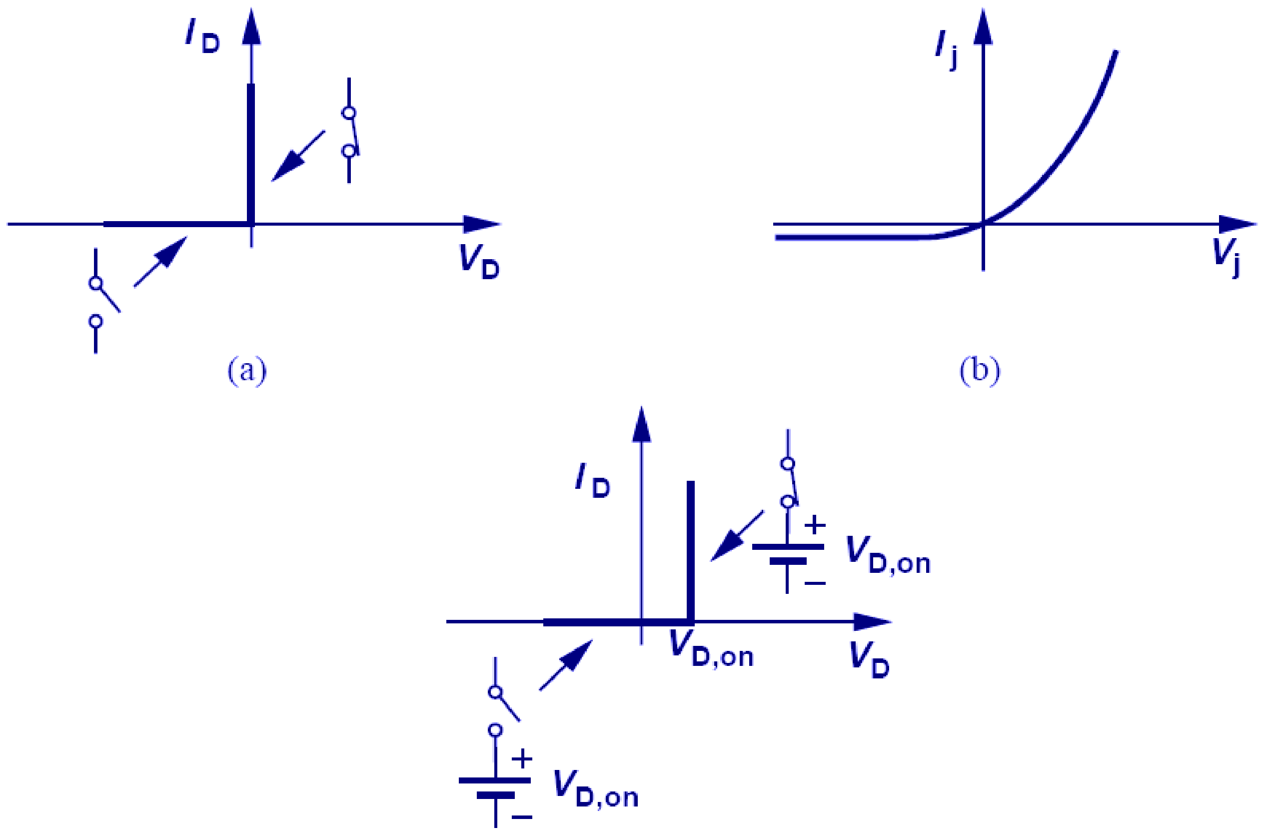


(b)

An important case is in question when Vb of the battery varies.

- rectification’ does not occur if V_B is larger than the input voltage or equal to 0

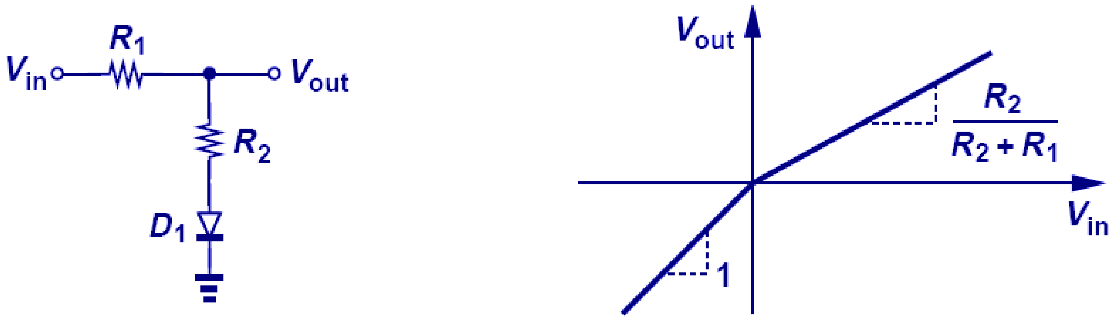
Diffrent models of diode



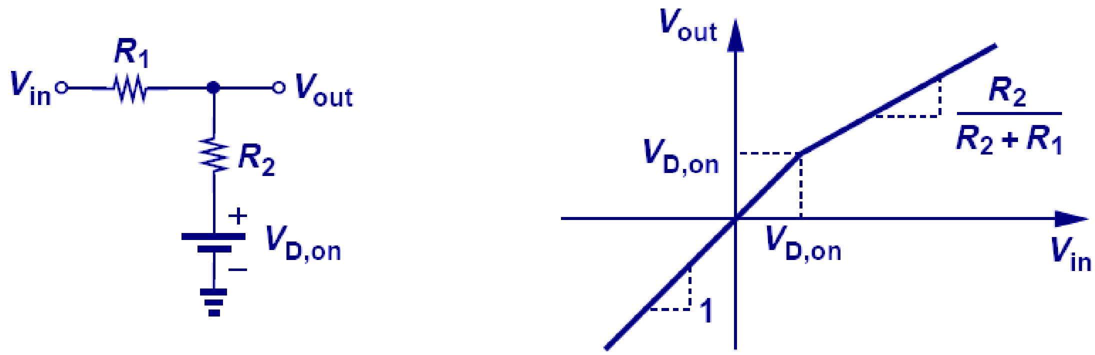
(c)

- Further, we study the ideal model of a diode.
- The figures above represent a) the ideal diode b) the pn junction with exponential variation c) the Diode with constant voltage.

Input/Output characteristics with the two models



(a) (b)



(c) (d)

- The circuit up above represents the difference between the 2 diode models (ideal and constant voltage V_D); with 2 different points of shifting slope (0 and $V_{D,on}$).

ADDITIONAL EXAMPLES

Example 3.13 In the circuit of Fig. 3.15, D_1 and D_2 have different cross section areas but are otherwise identical. Determine the current flowing through each diode.

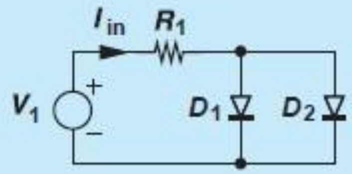


Figure 3.15 Diode circuit.

Solution

$$I_{in} = I_{D1} + I_{D2}.$$

We also equate the voltages across D_1 and D_2:

$$V_T \ln \frac{I_{D1}}{I_{S1}} = V_T \ln \frac{I_{D2}}{I_{S2}}$$

that is,

$$\frac{I_{D1}}{I_{S1}} = \frac{I_{D2}}{I_{S2}}.$$

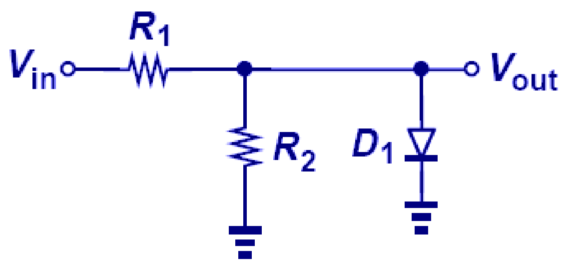
Solving together yields

$$I_{D1} = \frac{I_{in}}{1 + \frac{I_{S2}}{I_{S1}}}$$

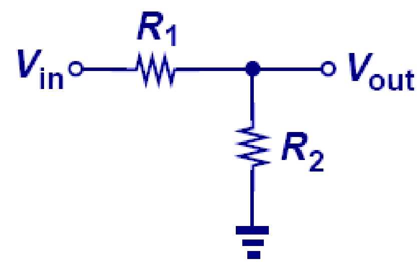
$$I_{D2} = \frac{I_{in}}{1 + \frac{I_{S1}}{I_{S2}}}.$$

, $I_{D1} = I_{D2} = I_{in}/2$ if $I_{S1} = I_{S2}$.

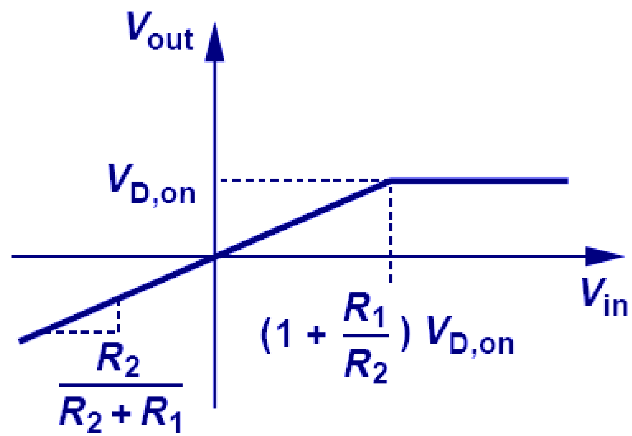
In/Out characteristics with the constant voltage model



(a)



(b)

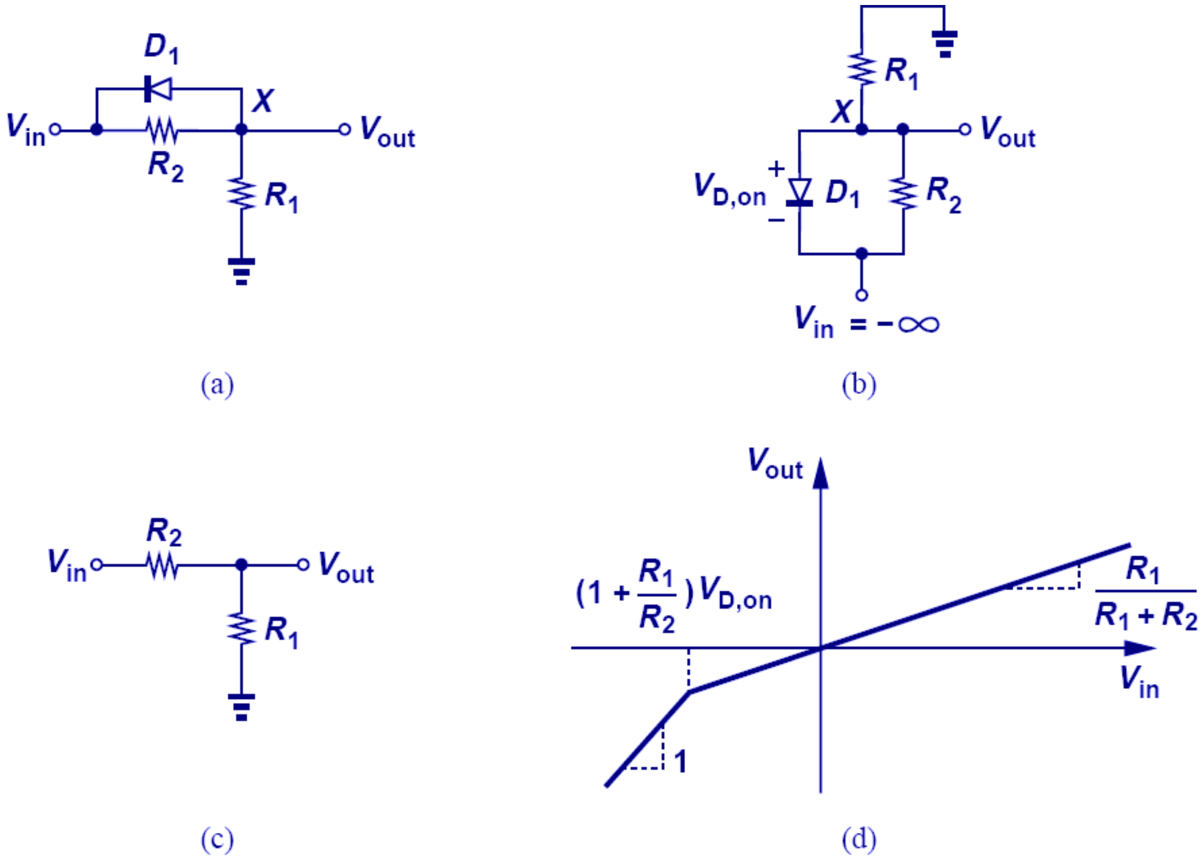


(c)

- In the constant voltage model, the voltage drop is not 0, but is equal to $V_{D,on}$ when it conducts.

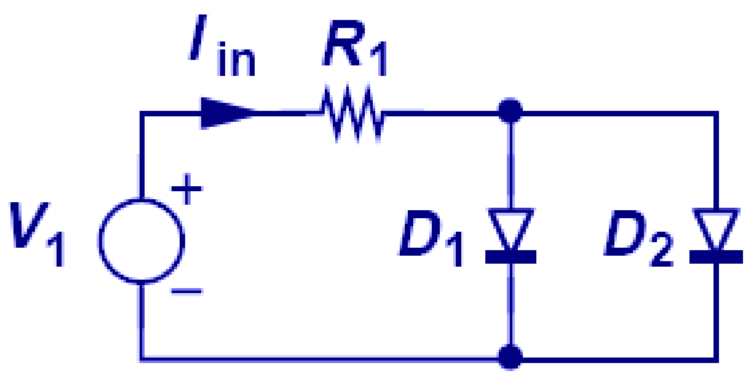
Other examples of diodes with constant voltage

Ex 3.15



- ➢ In this example, as long as Vin is connected to the cathode, the diode cunducts when Vin is negative ($<V_{D,on}$)
- ➢ The point of change of the slope changes when the current crossing R_1 is equal to that crossing R_2.

Exponential model



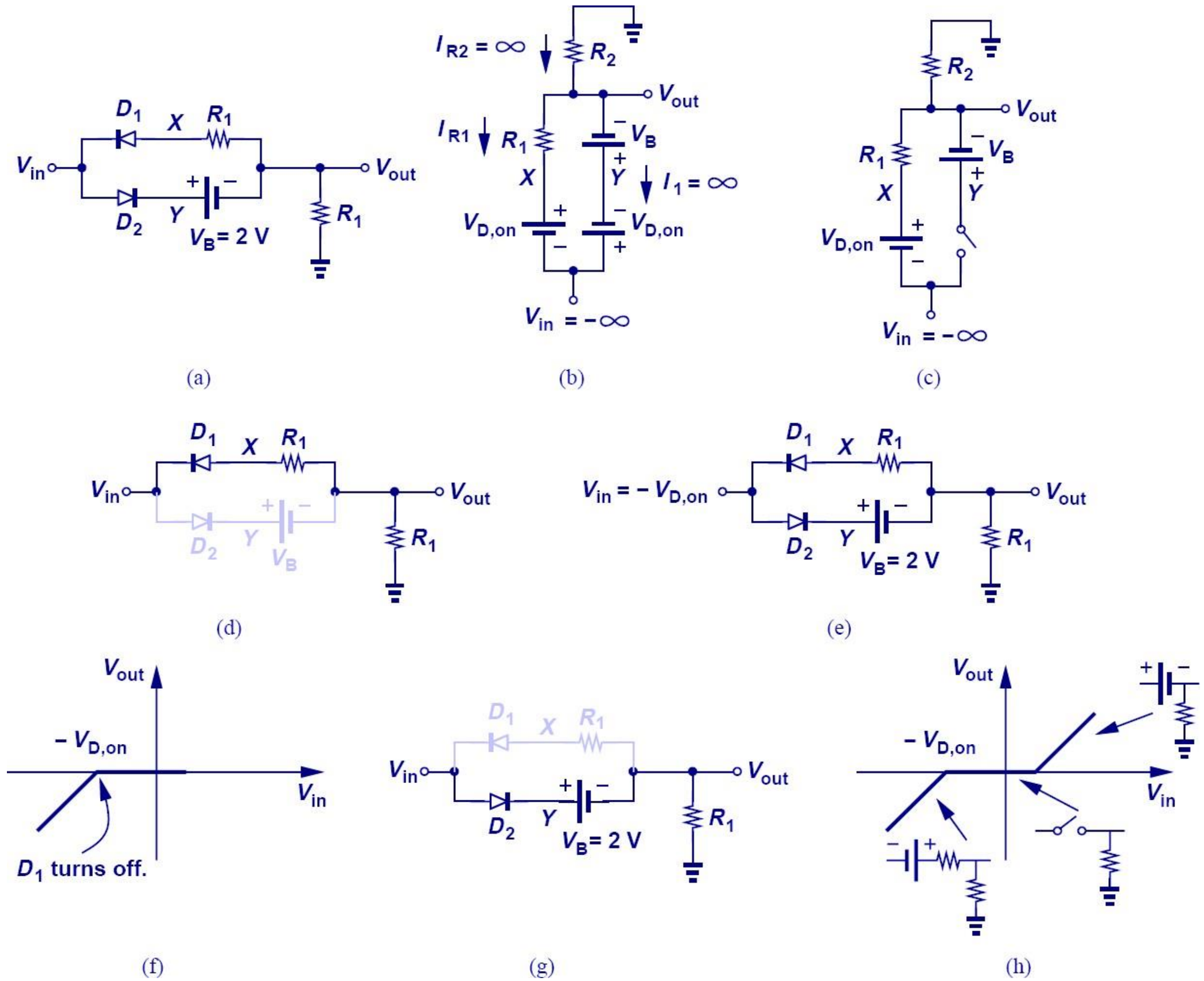
$$I_{D1} = \frac{I_{in}}{1 + \frac{I_{s2}}{I_{s1}}}$$

$$I_{D2} = \frac{I_{in}}{1 + \frac{I_{s1}}{I_{s2}}}$$

- In this example, as long as the diodes have different areas of crossection, only the exponential model can be used (already proved on P.36).

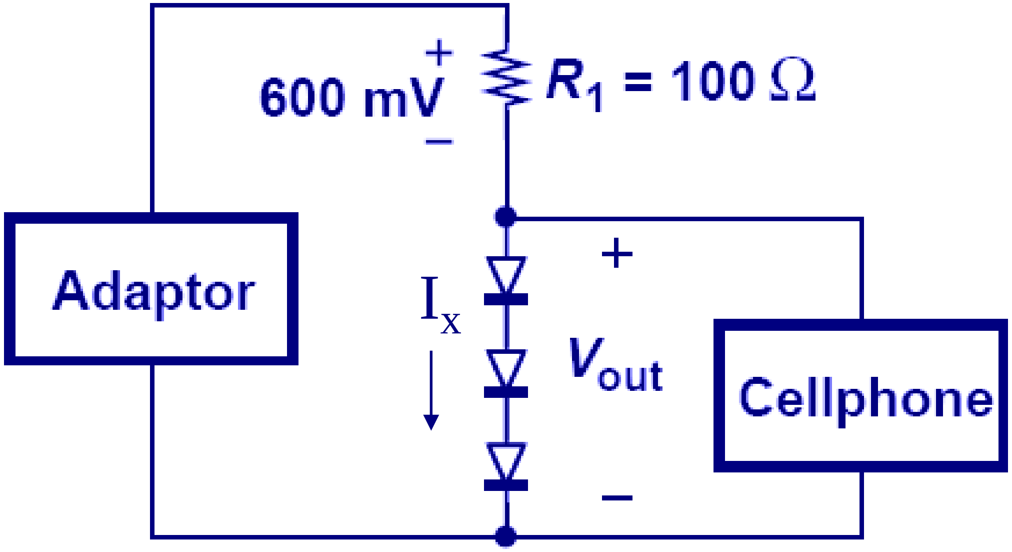
Other examples of constant voltage diodes

Ex 3.16



- ➢ This example shows the importance of high quality estimation and good confirmation.

Adaptor of the cellphone



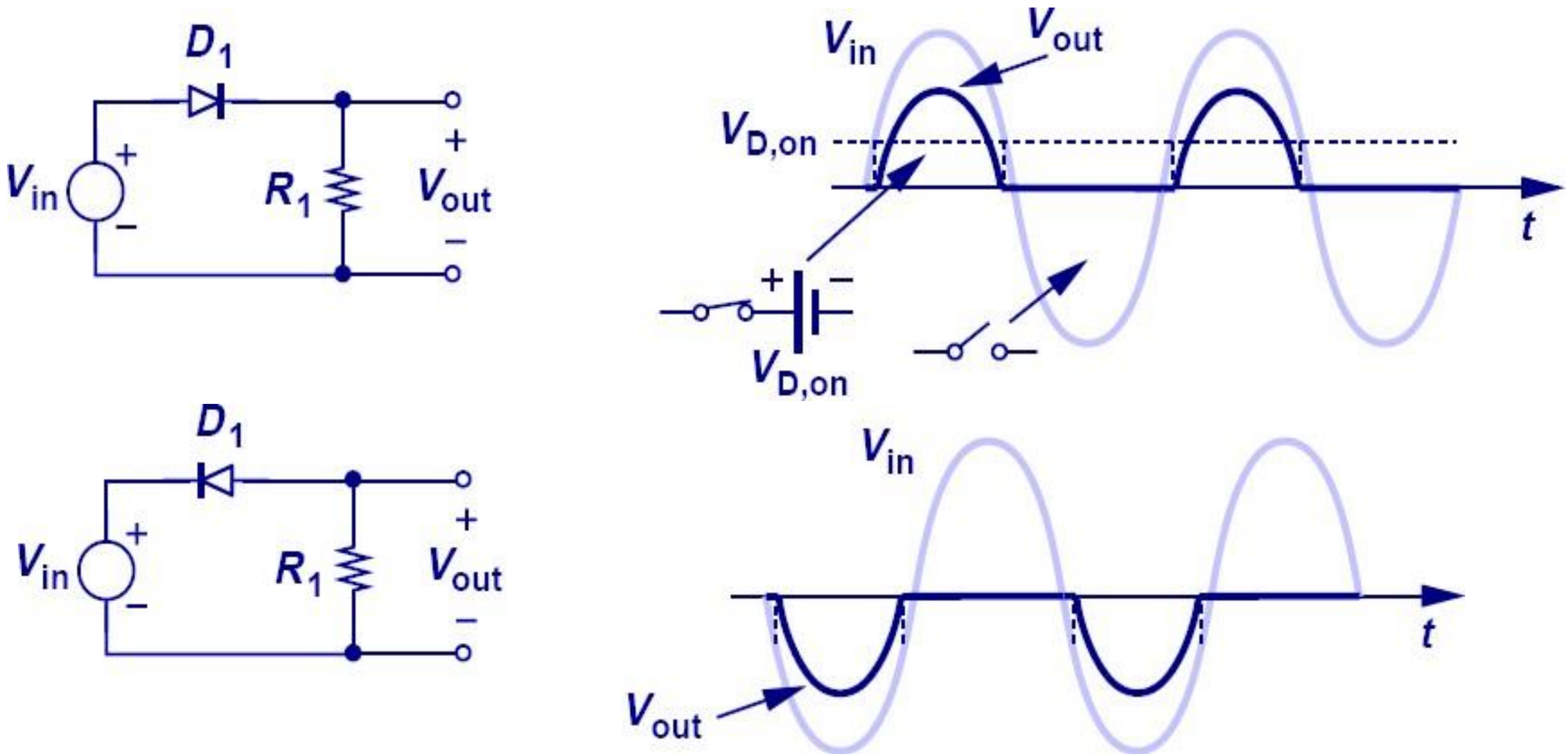
$$V_{out} = 3V_D$$
$$= 3V_T \ln \frac{I_X}{I_s}$$

- $V_{out} = 3\ V_{D,on}$ is used to charge cellphones.
- Meanwhile if I_x changes, the voltage on the ends of the 2 diodes changes slightly since it is represented by 'ln' in function of I_x making this adaptor more stable facing large fluctuations of current.

Applications of a Diode

Half-Wave and Full-Wave rectifiers ⇨ Limiting Circuits ⇨ Clamping Circuits ⇨ Regulators ⇨ Voltage Doublers

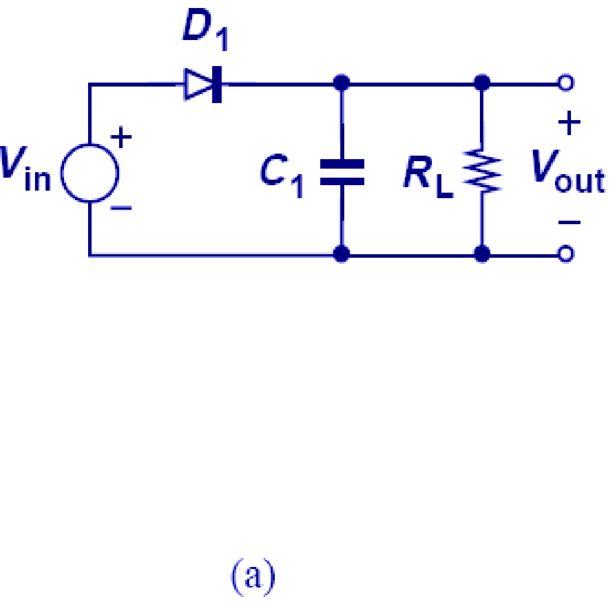
Half-Wave Rectifier

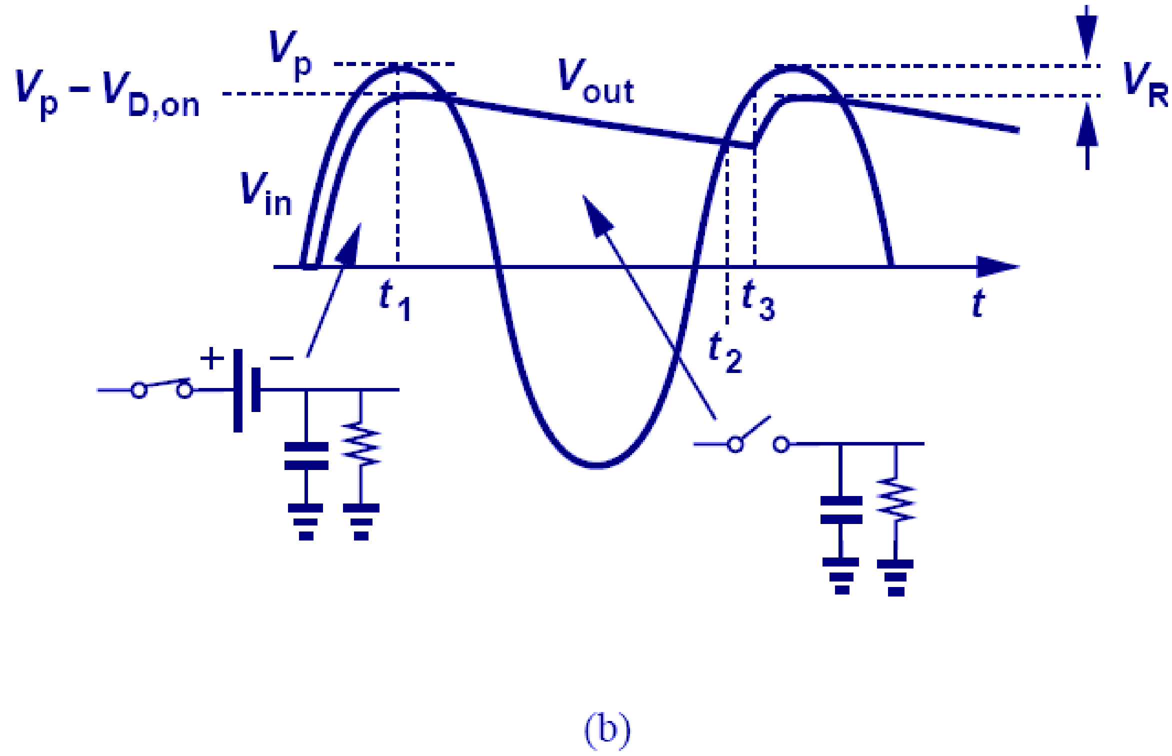


- A common application of diodes is half-wave rectifying, where either the positive or the negative half of the input wave is blocked.
- But how to generate a constant output?

Half-Wave Rectifier

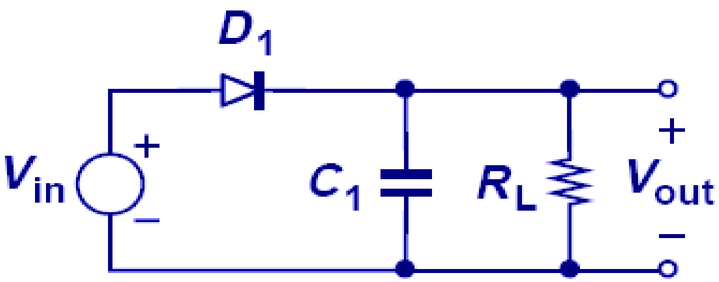
Diode with charge capacitor with load

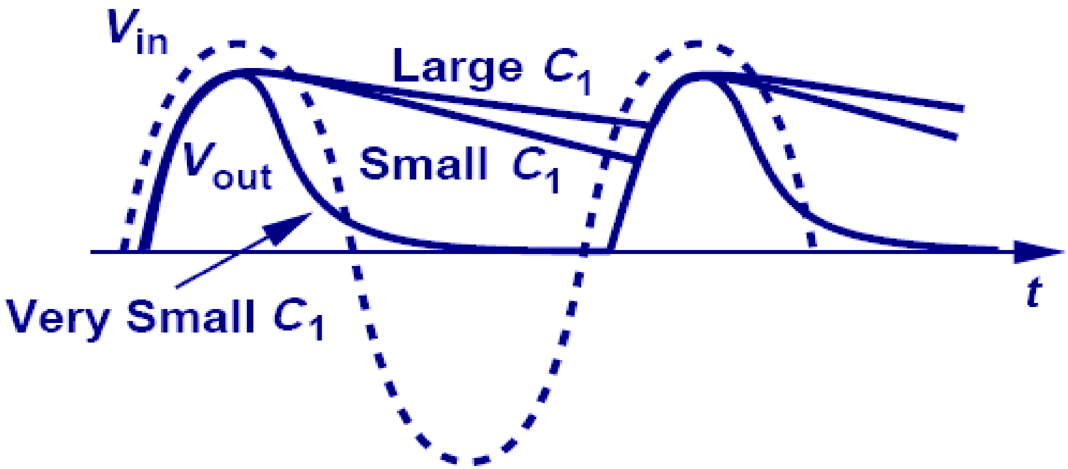




- There exists a path for the capacitor to discharge
  But V_{out} Will not be constant and oscillations will persist.

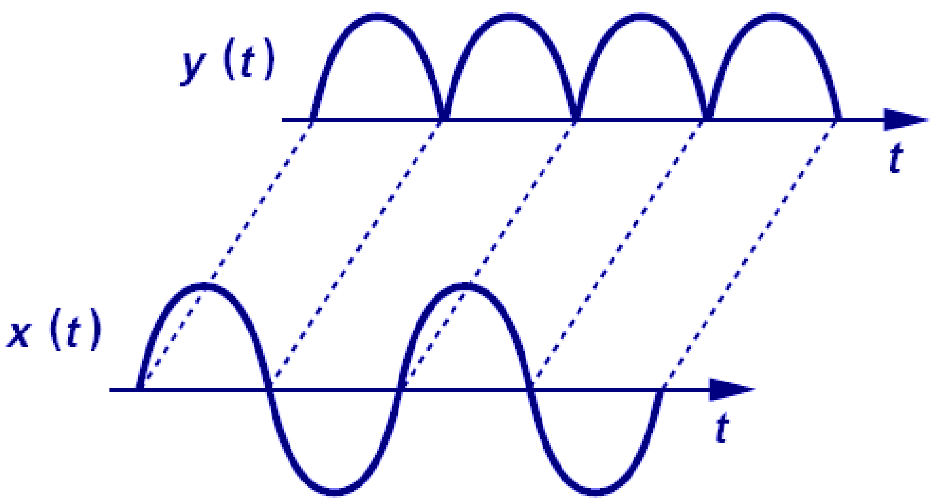
Behavior for different values of capacitance.



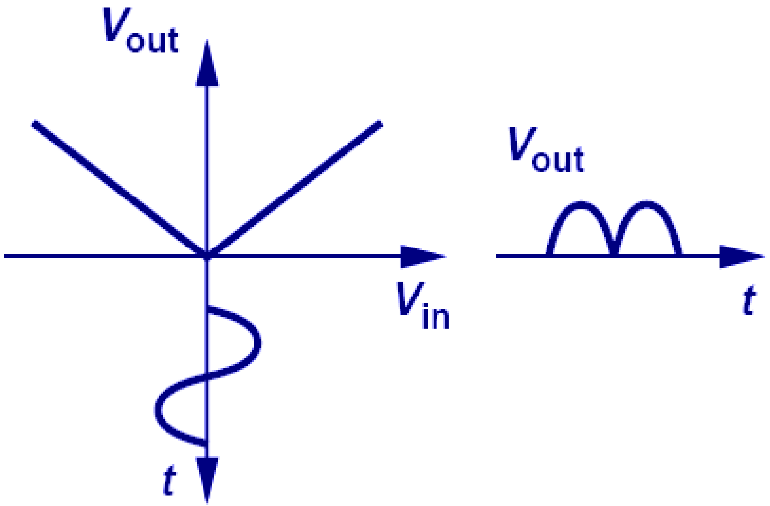


- If C_1 is very large, the current crossing R_L ,when D_1 is open creates only small fluctuations in V_{out}. On the other hand, if C_1 is very small we will therefore have bigger fluctuations in V_{out}.

Full-Wave Rectifier



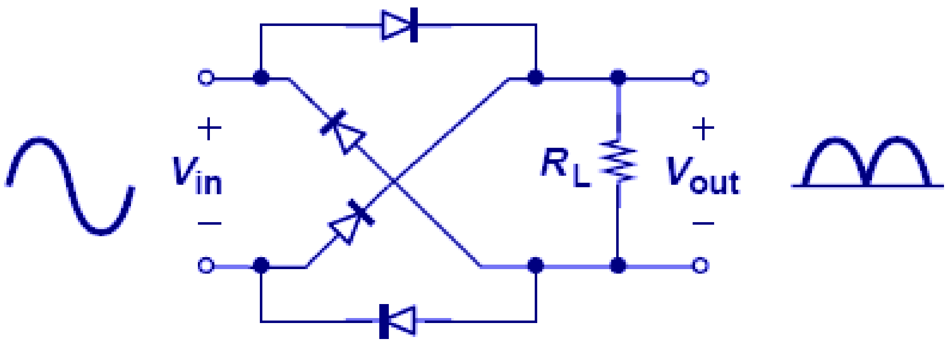
(a)



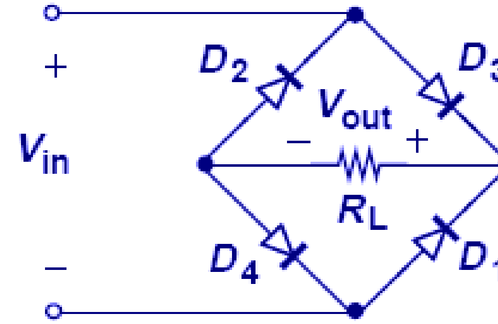
(b)

- The ‘full-wave rectifier’ allows both half-cycles through, all while inverting the negative half-cycle.
  As we previously demonstrated a full-wave rectifier doubles the frequency of the input signal.

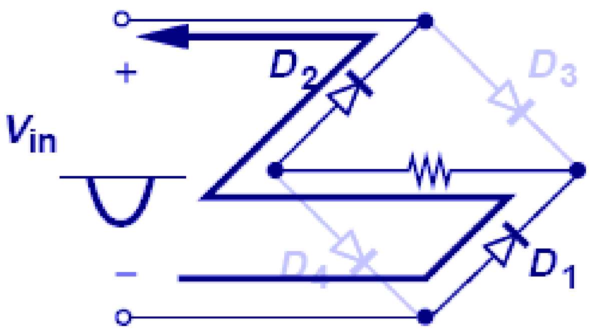
Full-Wave Rectifier: Bridge rectifier



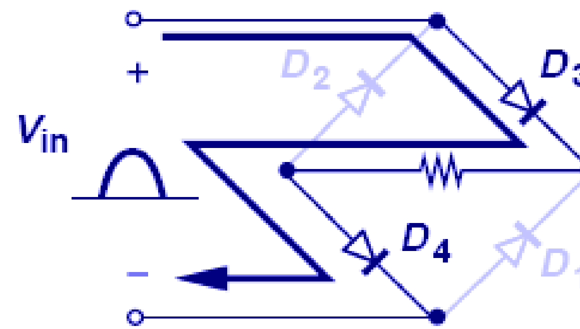
(a)



(b)



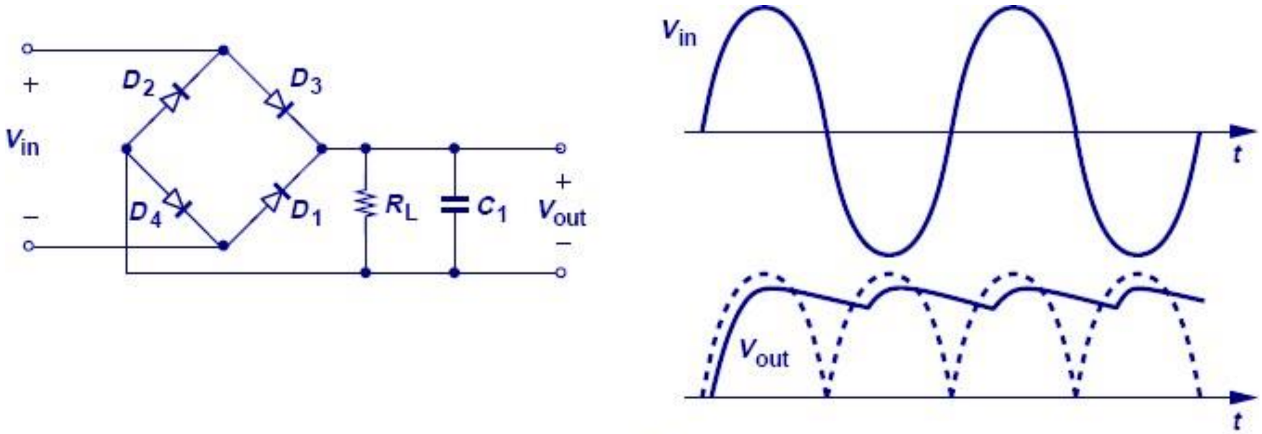
(c)



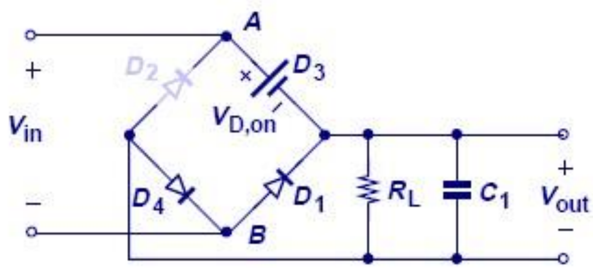
(d)

- The figures above demonstrate a 'full-wave rectifier', such that D_1 and D_2 allows or inverts the input signal for the first half-cycle while D_3 et D_4 do the opposite.

‘Full-Wave Rectifier’



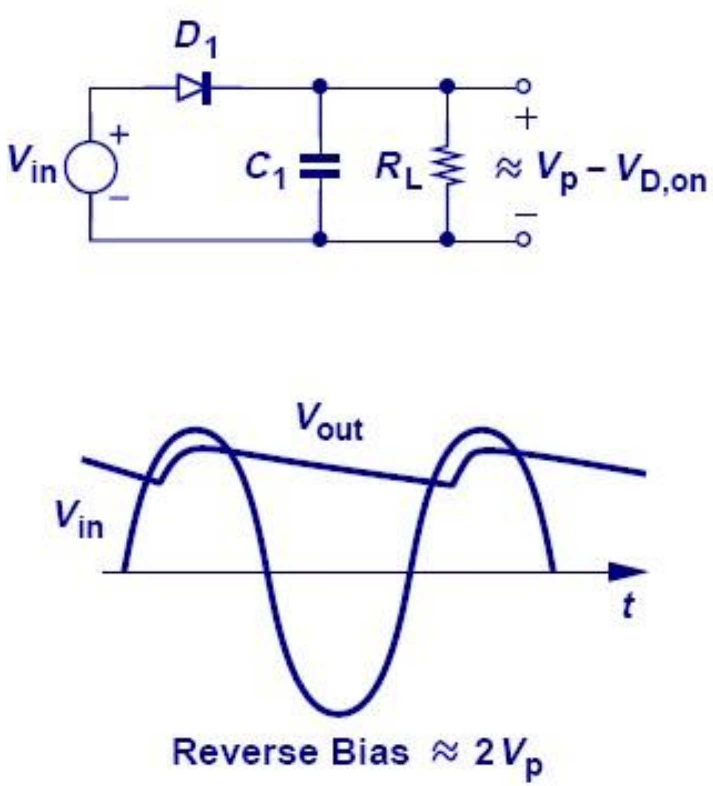
(a)



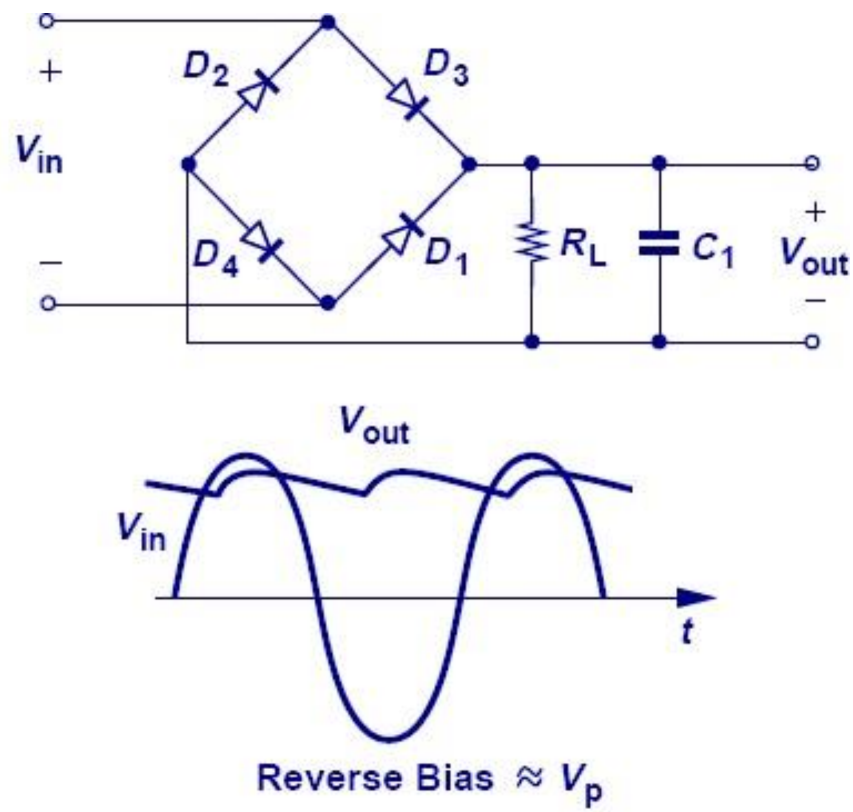
(b)

- All while C_1 Takes half the period to discharge, the ripple Voltage is cut in half. Moreover (b) shows that each diode is subjected to a bias voltage drop of Vp (versus 2 Vp for a ‘half-wave rectifier’)

Summary of ‘Half et Full-Wave Rectifiers’



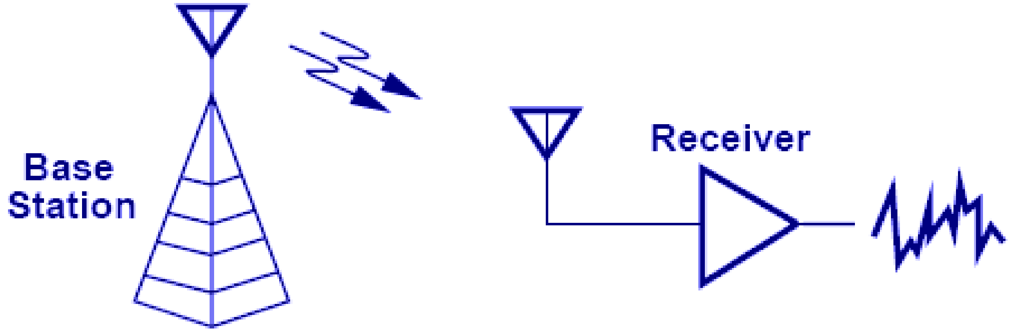
(a)

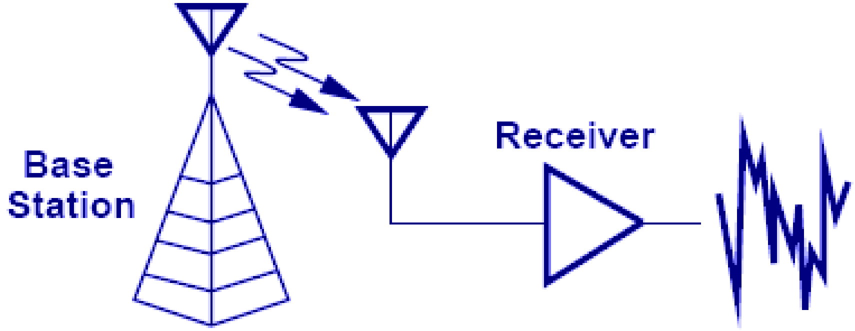


(b)

- ‘Full-wave rectifier’ is More desirable for applications such As adaptors and chargers

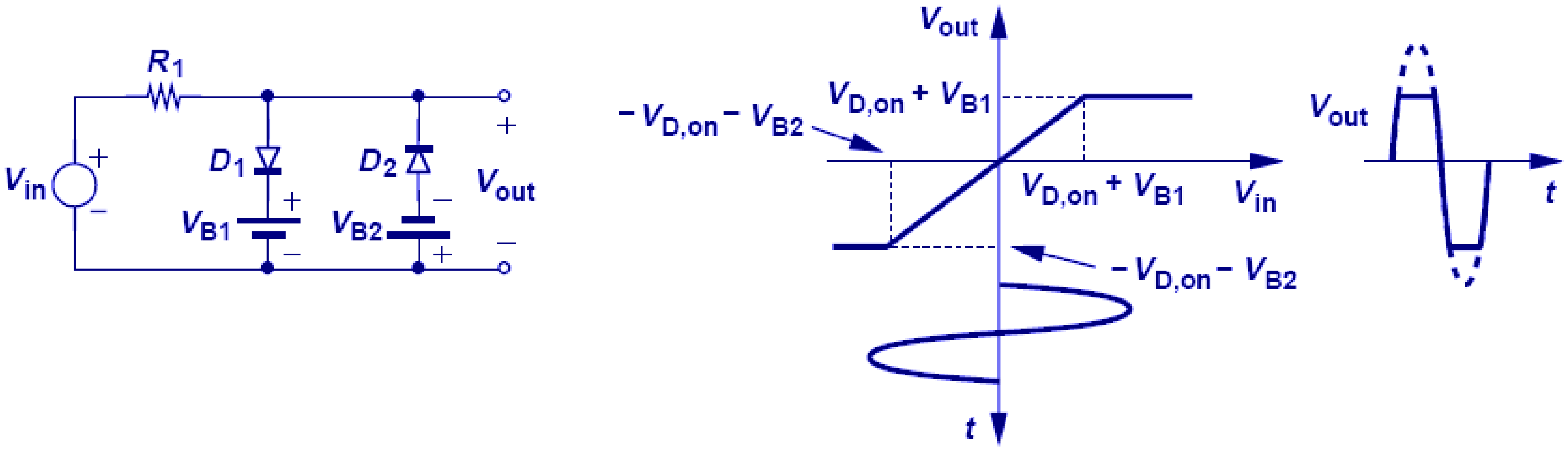
Limiting Circuits





- The motivation for having a limiting circuit is to maintain the signal under a certain threshold so it does not saturate the whole circuit.
- When a receptor is close to an emitting station, the signals are of interest, and limiting circuits are then in order.

General voltage limiting circuit



- 2 batteries connected in parallel with 2 opposite diodes to control the voltage limiting (see the figure above).