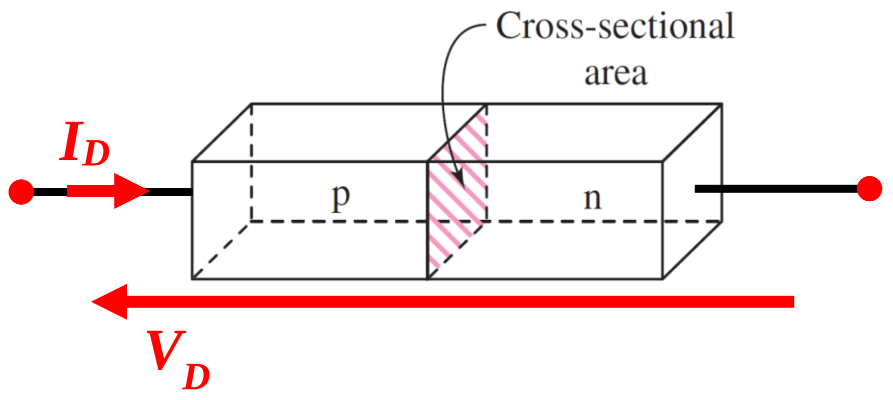
Chapter 03: Diodes

3.1. Introduction

The real power of **semiconductor** electronics occurs when p- and n-regions are directly adjacent to each other, forming a **pn junction.**



The theoretical relationship between the voltage V_D and the current I_D in the pn junction is given by

$$i_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right]$$

I_S is the **reverse-bias saturation current**.

V_T is the **thermal voltage**: $V_T = kT/q$,

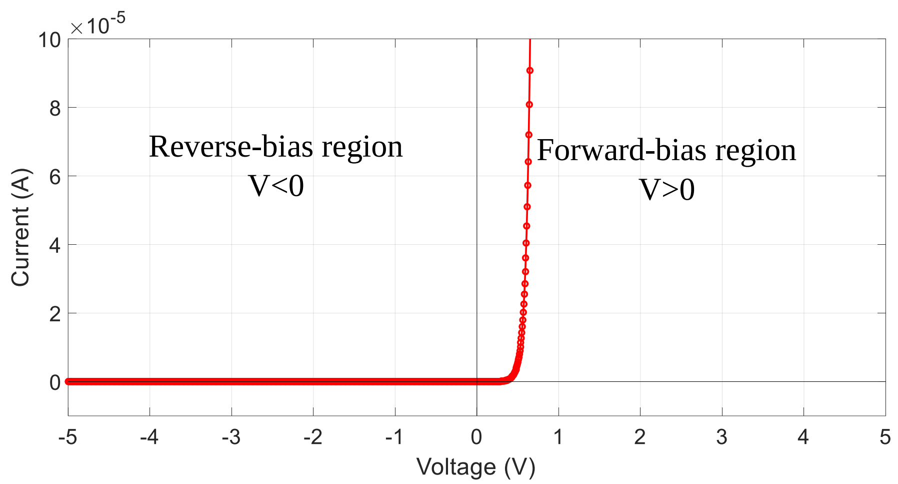
k = Boltzmann's constant ($\approx 1.380649\times10^{-23}$ J/K),

T = absolute temperature in Kelvin,

q = the elementary charge ($\approx 1.602176634 \times 10^{-19}$ C).

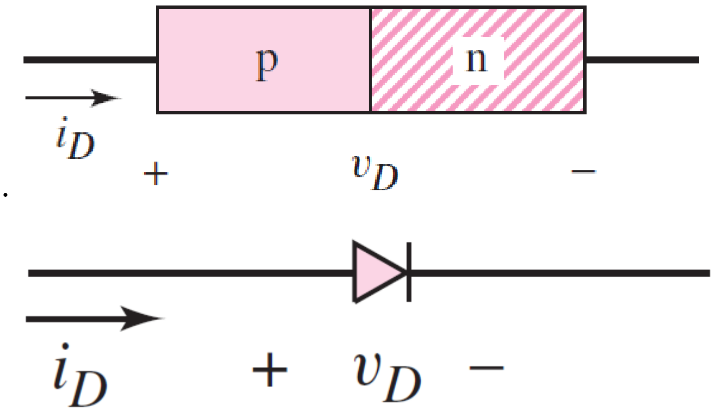
$V_T \approx 26$ mV at T=300 K.

n is usually called the **ideality factor**, and its value is in the range $1 \leq n \leq 2$.



3.2. pn Junction Diode

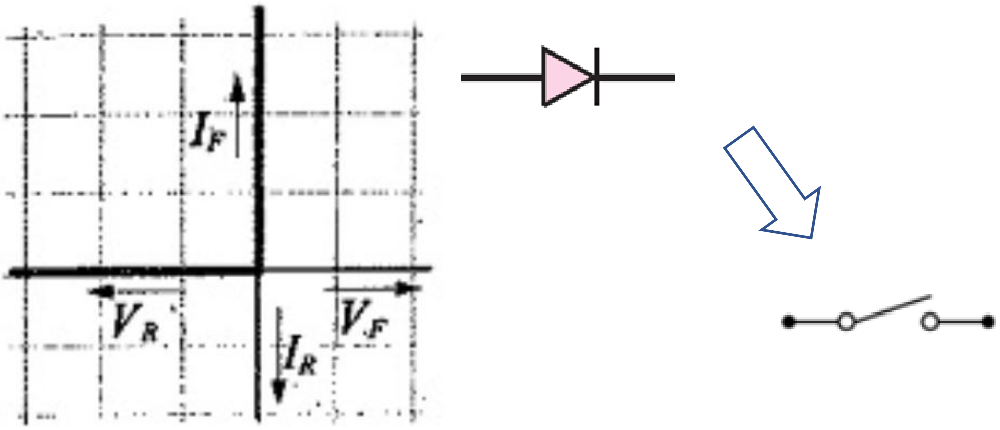
the diode is a two-terminal device with nonlinear *i–v* characteristics. Figure below shows the diode circuit symbol and the conventional current direction and voltage polarity. **The diode** can be thought of and used as a **voltage controlled switch that is "off" for a reverse-bias voltage and "on" for a forward-bias voltage**.



3.3. DC analysis and models

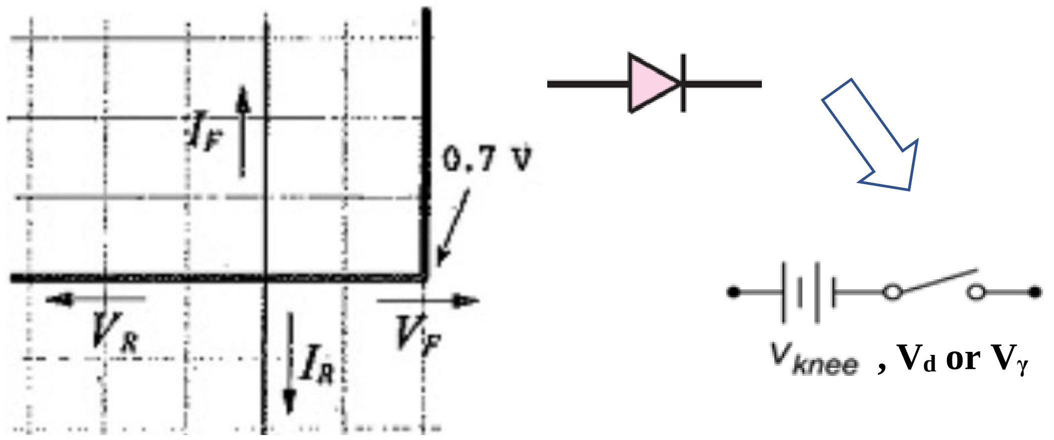
A simpler way to analyze diode circuits is to *approximate* the diode's current–voltage characteristics, using linear relationships or straight lines.

3.3.1. The Ideal Diode Model (First Approximation)
The first approximation is the simplest of the three. It treats the diode as a simple dependent switch: the switch is closed if the diode is forward-biased and open if it is reverse-biased.



3.3.2. Constant Voltage Drop Model (Second Approximation / Simplified Model) Forward Bias: The diode is modeled as an **ideal diode in series with a DC voltage source** (e.g., 0.7 V for silicon or 0.3 V for germanium). Conduction only occurs if the forward voltage exceeds this threshold, and the voltage drop across the diode remains constant at V_d during conduction.

Reverse Bias: The diode still acts as an **open switch** with zero current flow, similar to the ideal model.



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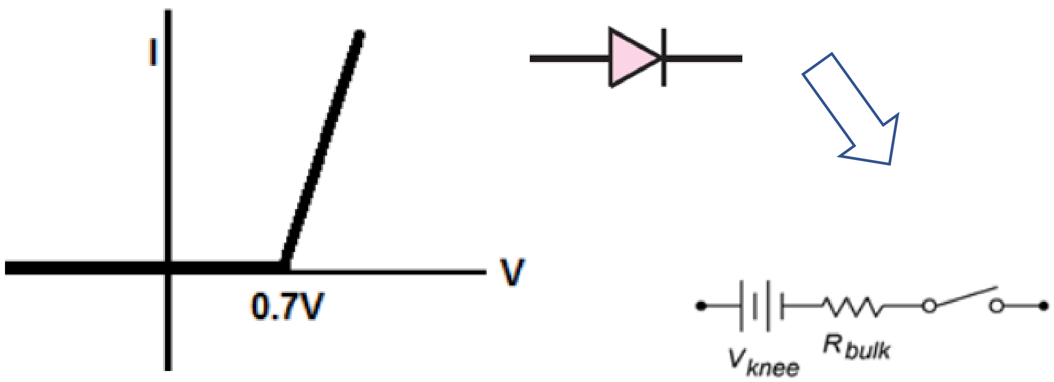
3.3.3. Piecewise Linear Model (Third Approximation / Linear Diode Model)

This is the most accurate of the linear approximations, as it includes the bulk resistance of the diode material in addition to the barrier potential.

Forward Bias: The diode is modeled as an **ideal diode in series with a voltage source and a resistor R_{bulk}, r_d or r_f.**

Reverse Bias: The diode is still typically modeled as an **open switch**.



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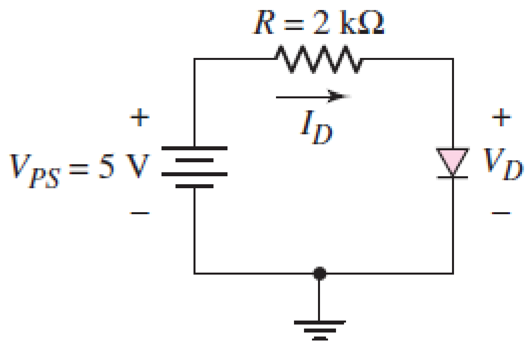
The actual exponential current-voltage (I-V) characteristic curve of the diode is approximated by a straight line (the "best-fit line") in its forward-biased, significant- conduction region (around the Q-point, or quiescent operating point).

The "turn-on" or "cut-in" voltage (V_{on}, V_f or $V\gamma$) is defined as the voltage point where this best-fit line intersects the voltage axis (the line where the forward current, I_D= 0).

Example 3.1

Consider the circuit shown in the figure below.



$$V_{PS} = I_D R + V_D \quad (1)$$

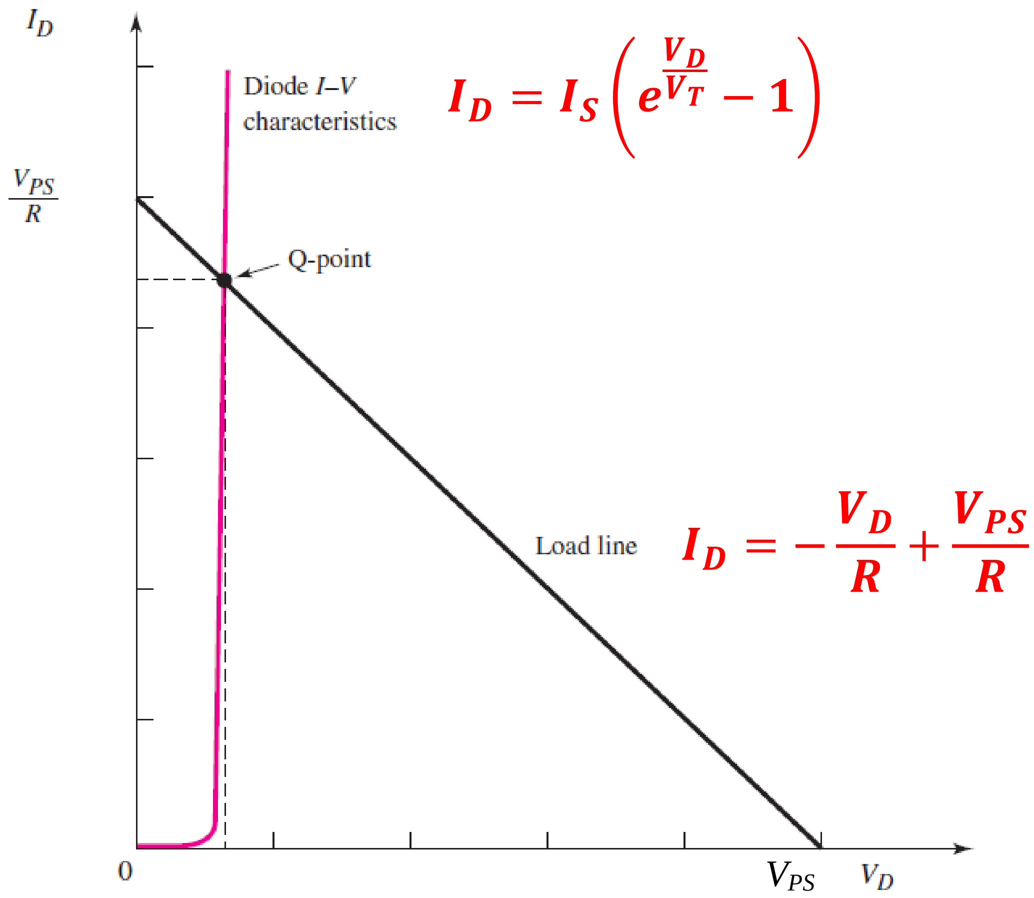
$$I_D = I_S\left[e^{\left(\frac{V_D}{V_T}\right)} - 1\right] \quad (2)$$

Combining equations (1) and (2), we obtain:

$$V_{PS} = I_S R\left[e^{\left(\frac{V_D}{V_T}\right)} - 1\right] + V_D$$

The equation above is a transcendental (nonlinear) equation and cannot be solved directly. We can use graphical or numerical methods to find a solution to this equation.

The intersection of the load line (from equation (1)) and the device characteristics curve (from equation (2)) provides the dc current I_D through the diode and the dc voltage V_D across the diode. This point is referred to as the **quiescent point,** or the ***Q*-point.**



3.4. Diode circuits

3.4.1. Rectifier circuits

A diode rectifier is the first stage in a switched-mode DC power supply (SMPS) while it is the second stage in a DC linear power supply, following the transformer. A DC voltage is required to power essentially every electronic device.

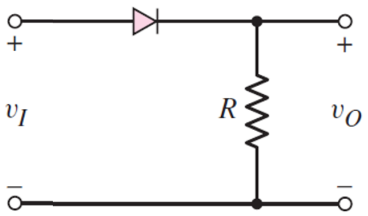
a. Half-Wave Rectification

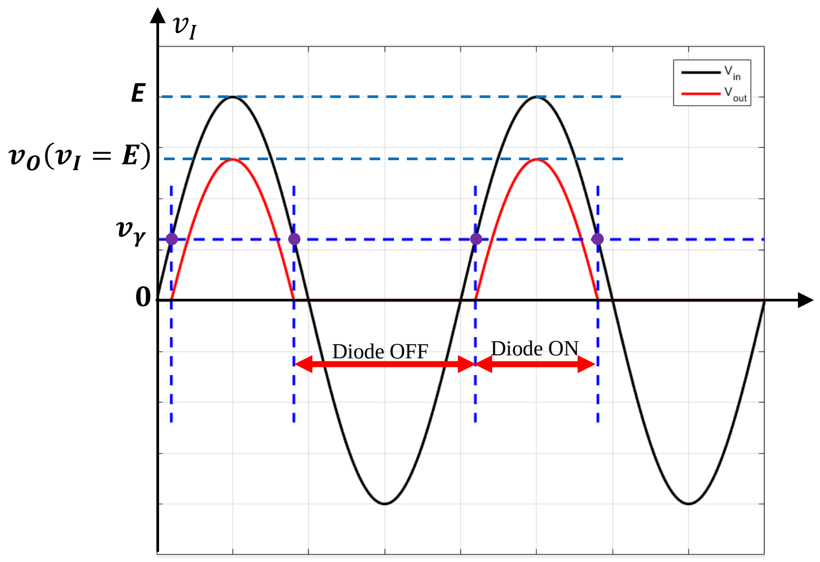
To analyze diode circuits, we can use the following procedure:

- **Assume the Diode State:** we assume the diode is off, removed or open circuit then we calculate the Thevenin's voltage or the open-circuit voltage V_{AK} across diode terminals (anode and cathode).
- **Compare to Turn-On Voltage**:
  - If $V_{AK}<V_\gamma$ ($V_\gamma \approx 0.6$ V for silicon diode), the diode is off and the diode is replaced with open circuit to calculate the output voltage.
  - If $V_{AK}\geq V_\gamma$, the diode is on and the diode is replaced with its linear model (V_γ in series with r_d) to calculate the output voltage.

Example 3.2

- Sketch the output waveform v_O versus time assuming piecewise linear model for the diode.
- Plot the voltage transfer characteristics v_O versus v_I over the range $-E \leq v_I \leq +E$ assuming $v_I = E\ sin(\omega t)$.

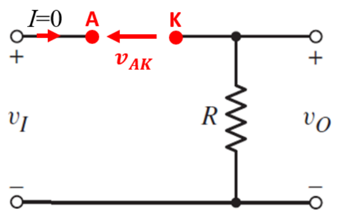




First step: Let's remove the diode or assume it is off and find Thevenin's voltage v_{AK} across diode's terminals.

$v_I - v_{AK} - R\,I = 0$

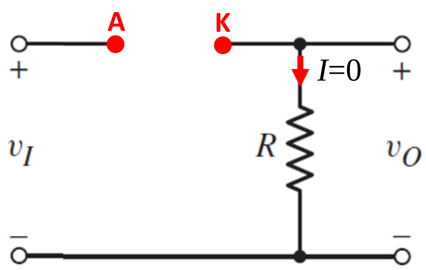
⇨ $\boldsymbol{v_{AK} = v_I}$



Second step: Compare v_{AK} to V_γ and determine v_O.

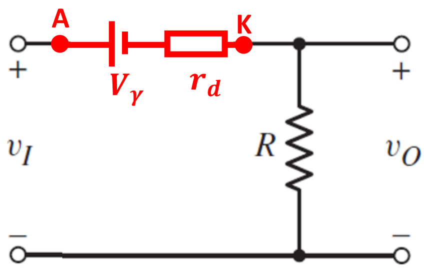
- $v_{AK} < V_\gamma$: The diode is off and it is replaced with open circuit.

$\boldsymbol{v_O = R\,I = 0}$

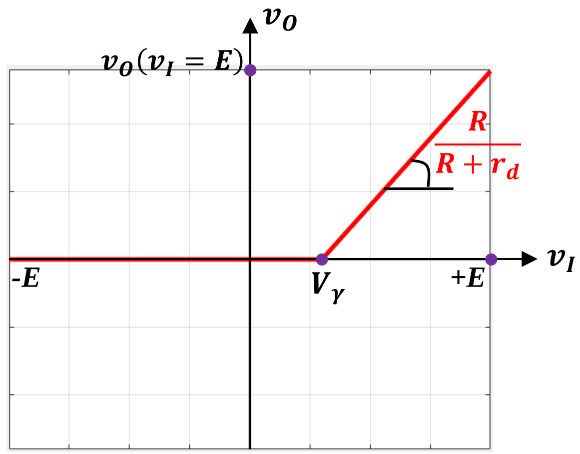


- $v_{AK} \geq V_\gamma$: The diode is on and it is replaced with V_γ in series with r_d.

$$v_O = \frac{R}{R+r_d}(v_I - v_\gamma) \approx \begin{cases} v_I - v_\gamma & \text{if } r_d \ll R \\ v_I & \text{if } r_d \ll R \text{ and } v_\gamma \ll E \end{cases}$$

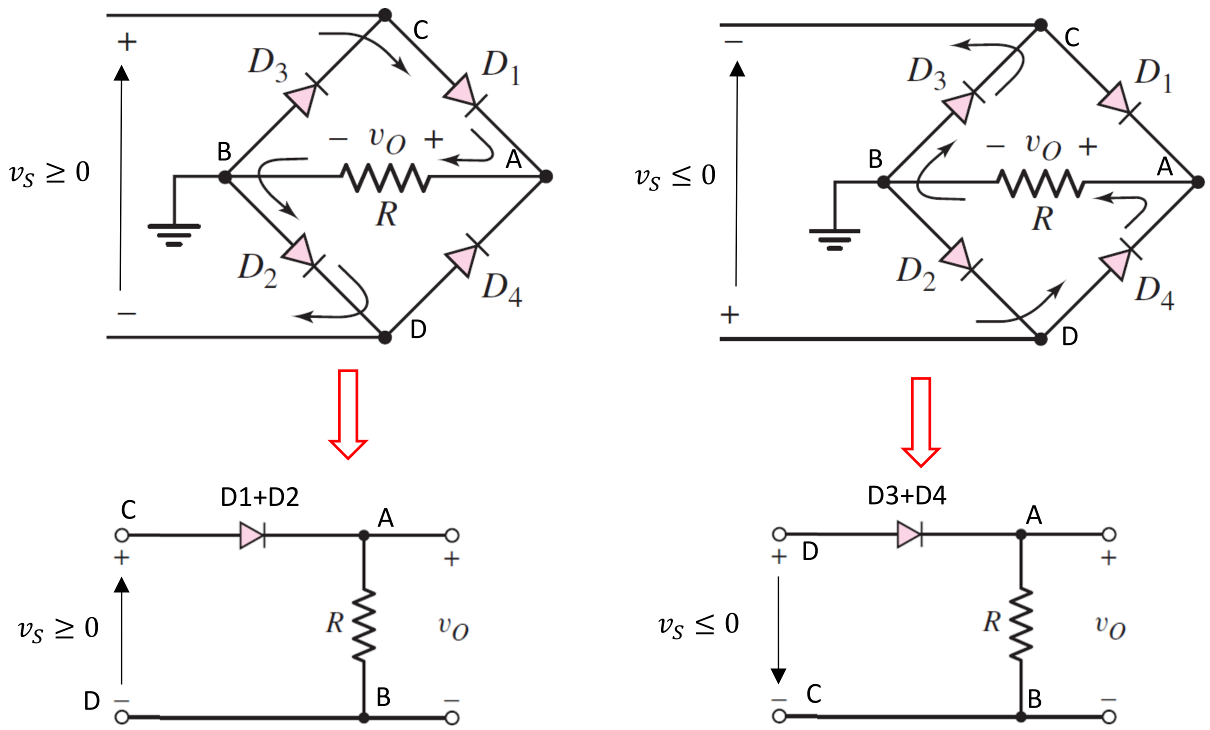


Voltage transfer characteristics $v_O = f(v_I)$

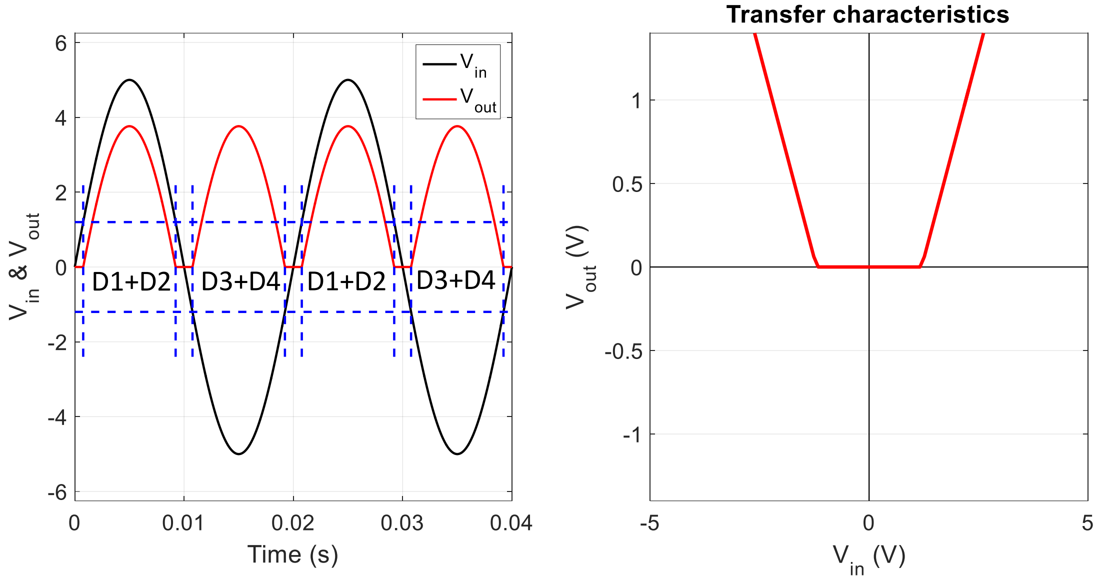


b. **Full-Wave Bridge Rectifier**

The full-wave rectifier circuit works by converting negative half-cycle of the input waveform into positive pulse. An ideal full-wave rectifier produces an output voltage that is the **absolute value** of its input AC voltage.



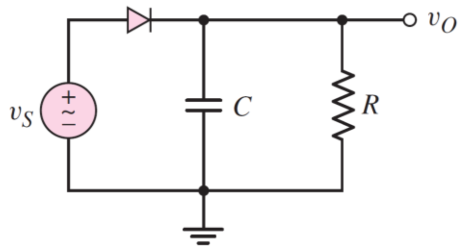
A diode allows current to pass through it in the forward direction (from anode to cathode) but blocks it in the reverse direction, acting like a one-way valve for electricity.

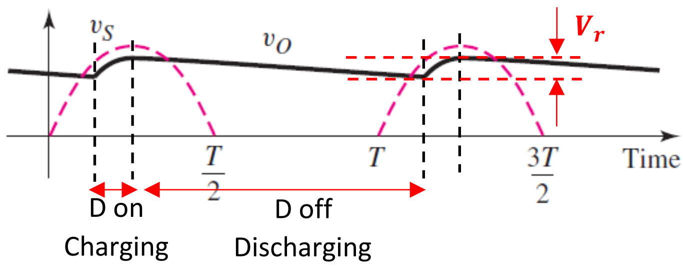


Filters, Ripple Voltage

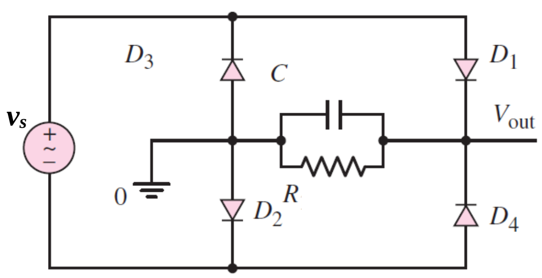
Adding a capacitor in parallel with the load in a half-wave rectifier filters and smooths the output voltage by **reducing AC ripple**.

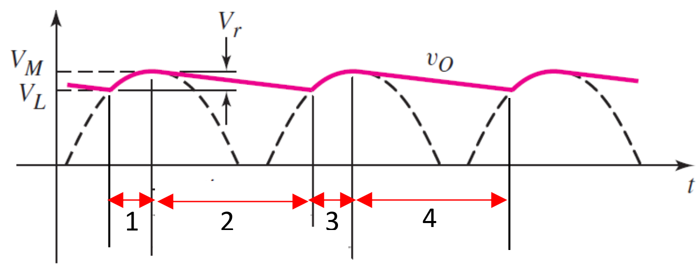
In a half-wave rectifier with a capacitor filter, the capacitor charges through the diode when the diode is on (forward-biased) and discharges through the load resistor when the diode is off (reverse-biased).





A full-wave rectifier has lower ripple voltage (***V_r***) than a half-wave rectifier because it converts both halves of the AC cycle into a pulsating DC output.





1: D1 and D2 on, D3 and D4 off → C charges through $2r_d$ of D1 and D2.
2: D1, D2, D3 and D4 off → C discharges through R.
3: D1 and D2 off, D3 and D4 on → C charges through $2r_d$ of D3 and D4.
4: D1, D2, D3 and D4 off → C discharges through R.

Derivation of average and RMS value of half-wave and full-wave rectifier signal

The average voltage of a half-wave rectifier is $V_{avg} = V_m/\pi$, and its RMS voltage is $V_{rms} = V_m/2$. For a full-wave rectifier, the average voltage is $V_{avg} = 2V_m/\pi$ and the RMS voltage is $V_{rms} = V_m/\sqrt{2}$.

Half-wave rectifier

The output of a half-wave rectifier is a sine wave for the first half-cycle ($0 \le \omega t \le \pi$) and zero for the second half-cycle ($\pi \le \omega t \le 2\pi$).

Average voltage (V_{avg})

- **Formula**: The average voltage is found by integrating the voltage over one period ($T = 2\pi$) and dividing by the period.
- $V_{avg} = \frac{1}{2\pi}\int_0^{2\pi} v(t)d(\omega t) = \frac{1}{2\pi}\int_0^{\pi} V_m \sin(\omega t)d(\omega t) + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0\ d(\omega t)$
- $V_{avg} = \frac{V_m}{2\pi}[-\cos(\omega t)]_0^{\pi} = \frac{V_m}{2\pi}(-\cos(\pi) - (-\cos(0))) = \frac{V_m}{2\pi}(1+1) = \frac{2V_m}{2\pi} = \frac{V_m}{\pi}$

RMS voltage (V_{rms})

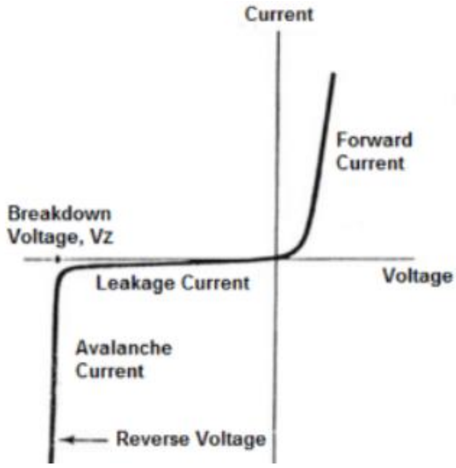
- **Formula**: The RMS voltage is the square root of the mean of the square of the voltage over one period.
- $V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} [v(t)]^2 d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} [V_m \sin(\omega t)]^2 d(\omega t)}$
- $V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_0^{\pi} \sin^2(\omega t)d(\omega t)}$
- Using the identity $\sin^2(\theta) = \frac{1-\cos(2\theta)}{2}$:
- $V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_0^{\pi} \frac{1-\cos(2\omega t)}{2} d(\omega t)} = \frac{V_m}{\sqrt{4\pi}}\int_0^{\pi}(1-\cos(2\omega t))d(\omega t)$
- $V_{rms} = \frac{V_m}{2\sqrt{\pi}}[\omega t - \frac{\sin(2\omega t)}{2}]_0^{\pi} = \frac{V_m}{2\sqrt{\pi}}[(\pi - 0) - (0 - 0)] = \frac{V_m\sqrt{\pi}}{2\sqrt{\pi}} = \frac{V_m}{2}$

3.5. Special diodes

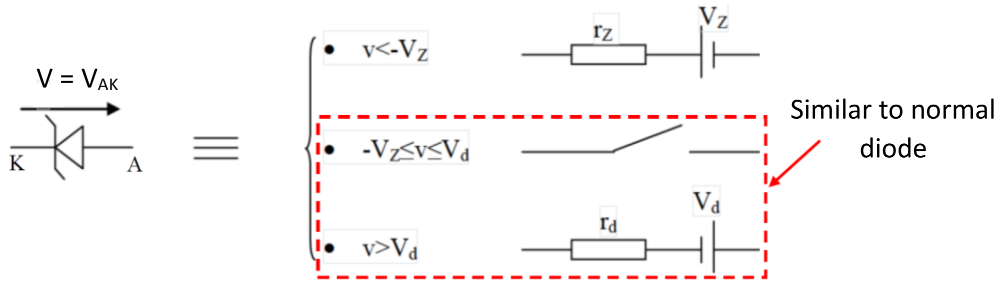
3.5.1 Zener diode

A Zener diode is a special type of silicon diode designed to conduct current in reverse at a specific breakdown voltage called the Zener voltage.

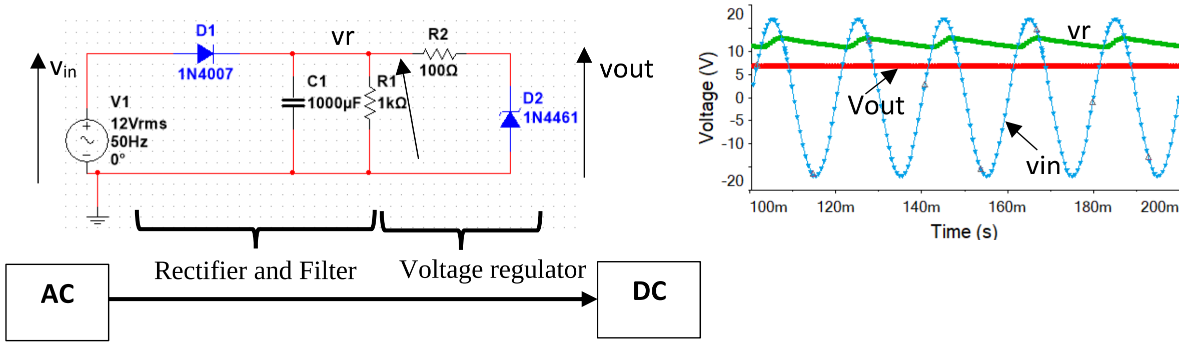
A Zener diode is similar to a normal diode in forward bias but is specifically designed to be used in the reverse breakdown region



Piecewise linear model of a Zener diode



Example:



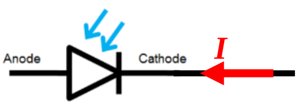
3.5.2 LED

A light-emitting diode (LED) is a semiconductor device that produces light when electrical current passes through it. The color of an LED is determined by the semiconducting material used.

In forward bias ($V_{AK}>V_d$), an LED allows current to flow and emits light when the voltage exceeds its turn-on voltage. In reverse bias, the LED blocks current flow and does not produce light, behaving like an open circuit.

3.5.3 Photodiode

A photodiode is a semiconductor device that converts light into an electrical current or voltage.



$$I = I(\text{Bias}) + I(\text{Light intensity}) = -I_s\left(e^{\frac{V}{nV_T}} - 1\right) + I_{PH} \approx I_{PH} \text{ if } V<0 \text{ (Reverse bias).}$$

A photodiode is generally operated in reverse bias (photoconductive mode), and the resulting current is almost entirely the photocurrent, which is proportional to the intensity of the incident light.

Example: Object detection