EE101: Diode circuits

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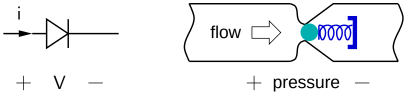
Diodes



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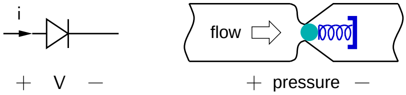

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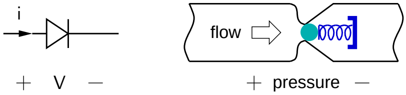

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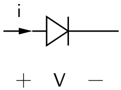

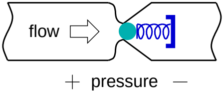

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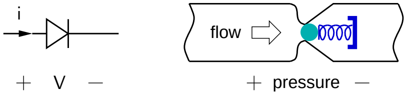

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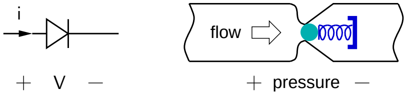

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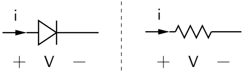
* Similarly, a diode presents a small resistance in the forward direction and a large resistance in the reverse direction.
* In the forward direction, the diode resistance $R_D = V/i$ would be a function of V. However, it is often a good approximation to treat it as a constant (small) resistance.
* In the reverse direction, the diode resistance is much larger and may often be treated as infinite (i.e., the diode may be replaced by an open circuit).

Simple models: $R_{\text{on}}/R_{\text{off}}$ model



$R = R_{\text{on}}$ if $V > 0$

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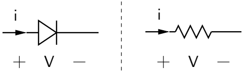

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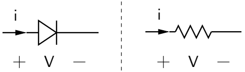

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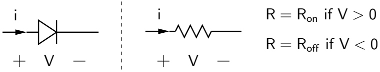

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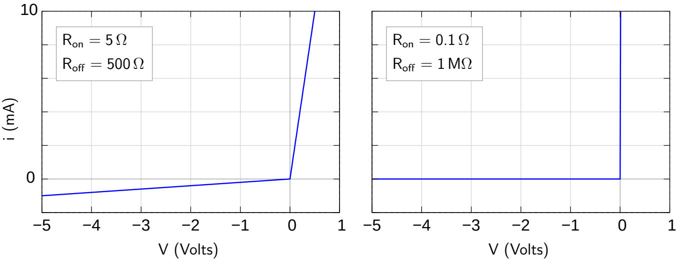
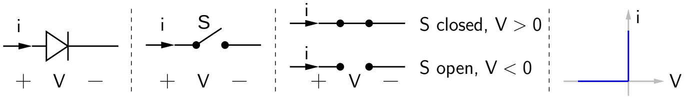
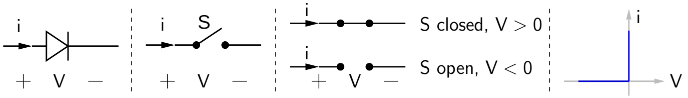
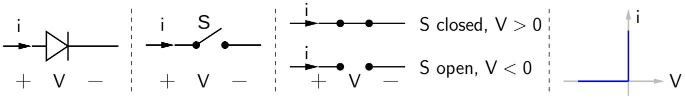


Simple models: ideal switch





* $V > 0$ Volts $\rightarrow$ S is closed (a perfect contact), and it can ideally carry any amount of current. The voltage drop across the diode is 0 V.



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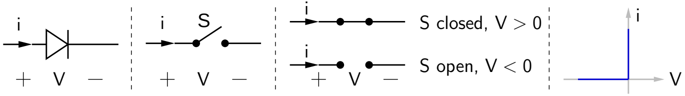

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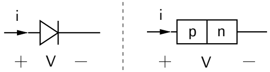
* The actual values of V and i for a diode in a circuit get determined by the i-V relationship of the diode *and* the constraints on V and i imposed by the circuit.

Shockley diode equation



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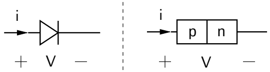


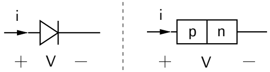
$$i = I_s \left[\exp\left(\frac{V}{V_T} \right) - 1 \right], \text{ where } V_T = k_B T/q\,.$$

$k_B =$ Boltzmann's constant $= 1.38 \times 10^{-23}\ J/K$.

$q =$ electron charge $= 1.602 \times 10^{-19}$ Coul.

$T =$ temperature in $^\circ K$.

$V_T \approx 25$ mV at room temperature (27 $^\circ$C).



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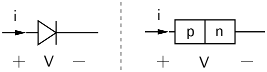

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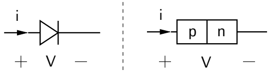

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* Although I_s is very small, it gets multiplied by a large exponential factor, giving a diode current of several mA for $V \approx 0.7\ V$.

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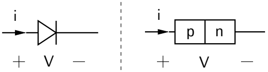

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* Although I_s is very small, it gets multiplied by a large exponential factor, giving a diode current of several mA for $V \approx 0.7\ V$.
* The "turn-on" voltage (V_{on}) of a diode depends on the value of I_s. V_{on} may be defined as the voltage at which the diode starts carrying a substantial forward current (say, a few mA).
  For a silicon diode, $V_{\text{on}} \approx 0.7\ V$.
  For a GaAs diode, $V_{\text{on}} \approx 1.1\ V$.

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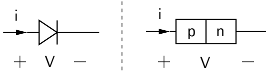

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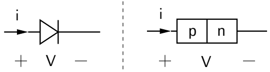

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V	$x = V/V_T$	e^x	i (Amp)
0.1	3.87	0.479×10^{2}	0.469×10^{-11}
0.2	7.74	0.229×10^{4}	0.229×10^{-9}
0.3	11.6	0.110×10^{6}	0.110×10^{-7}
0.4	15.5	0.525×10^{7}	0.525×10^{-6}
0.5	19.3	0.251×10^{9}	0.251×10^{-4}
0.6	23.2	0.120×10^{11}	0.120×10^{-2}
0.62	24.0	0.260×10^{11}	0.260×10^{-2}
0.64	24.8	0.565×10^{11}	0.565×10^{-2}
0.66	25.5	0.122×10^{12}	0.122×10^{-1}
0.68	26.3	0.265×10^{12}	0.265×10^{-1}
0.70	27.1	0.575×10^{12}	0.575×10^{-1}
0.72	27.8	0.125×10^{13}	0.125

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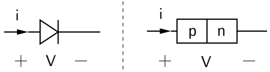

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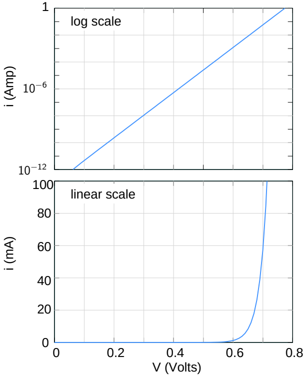
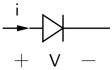
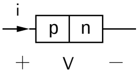


Shockley equation and simple models





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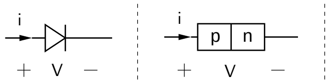

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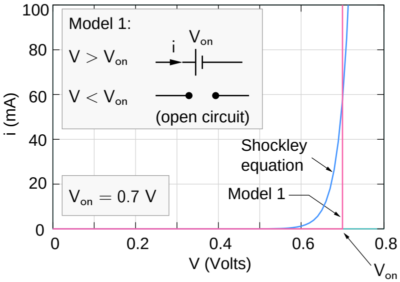

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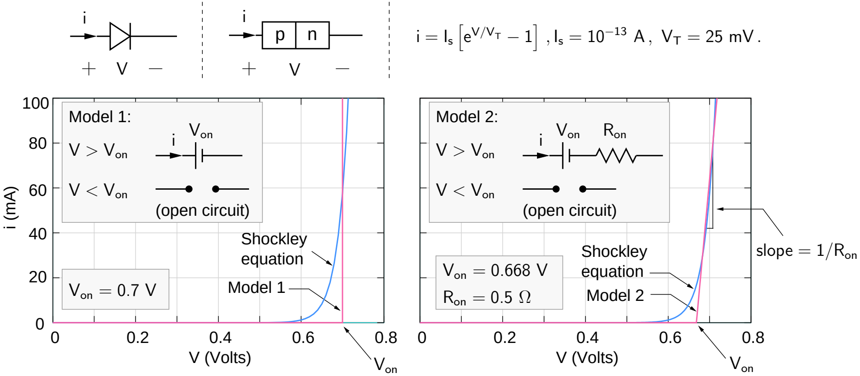

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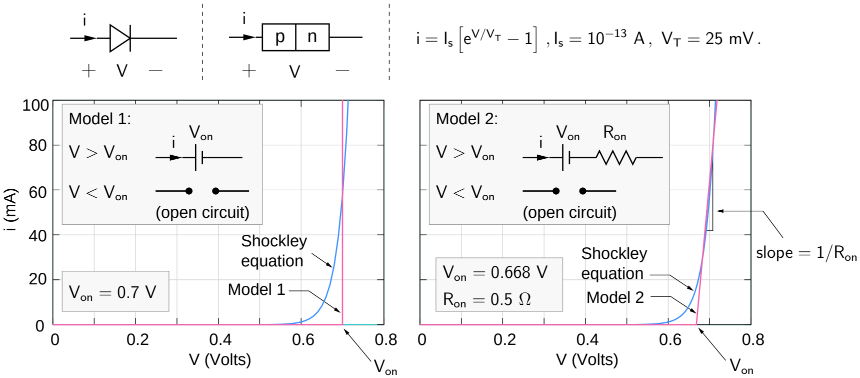

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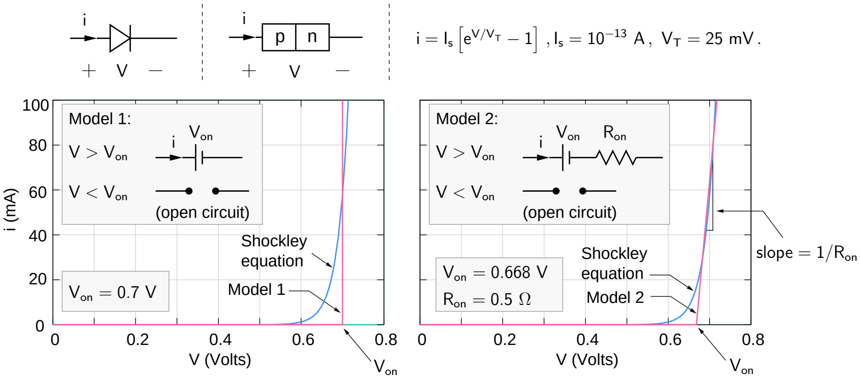

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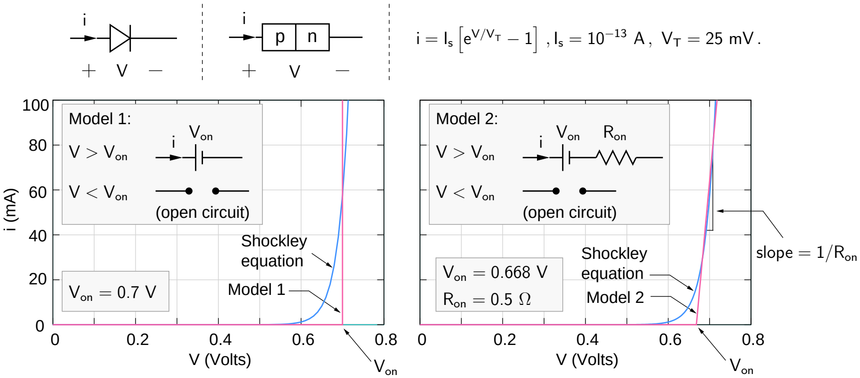

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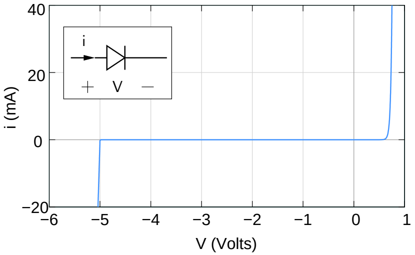
* Note that the "battery" shown in the above models is not a "source" of power! It can only absorb power (see the direction of the current), causing heat dissipation.

Reverse breakdown



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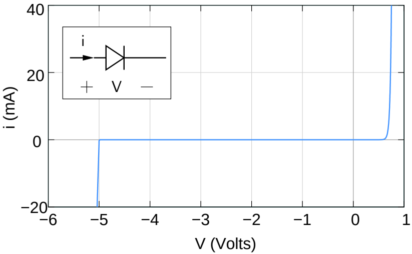

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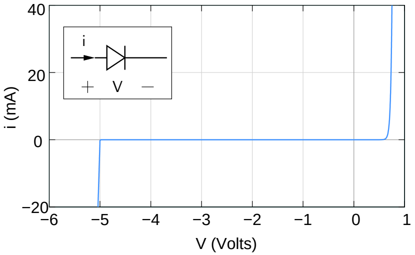

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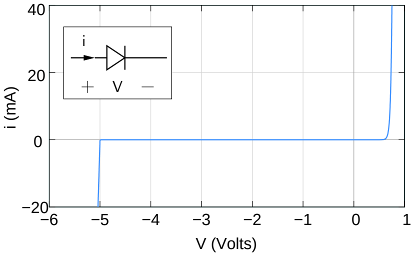

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* A real diode cannot withstand indefinitely large reverse voltages and "breaks down" at a certain voltage called the "breakdown voltage" (V_{BR}).
* When the reverse bias $V_R > V_{BR}$, the diode allows a large amount of current. If the current is not constrained by the external circuit, the diode would get damaged.

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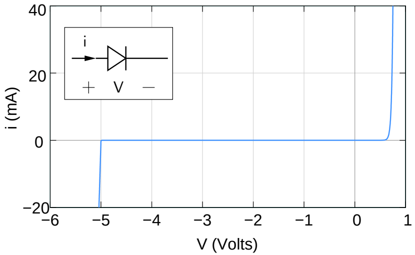

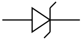

Symbol for a Zener diode

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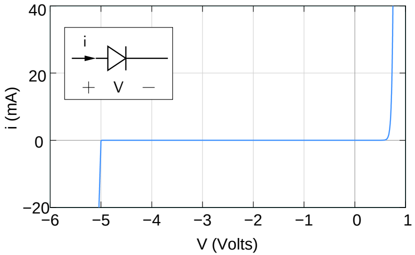
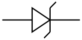
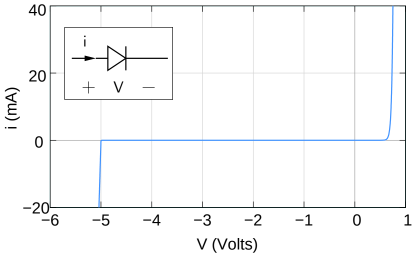


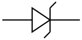


Symbol for a Zener diode

* A wide variety of diodes is available, with V_{BR} ranging from a few Volts to a few thousand Volts! Generally, higher the breakdown voltage, higher is the cost.

Reverse breakdown





Symbol for a Zener diode

* A wide variety of diodes is available, with V_{BR} ranging from a few Volts to a few thousand Volts! Generally, higher the breakdown voltage, higher is the cost.
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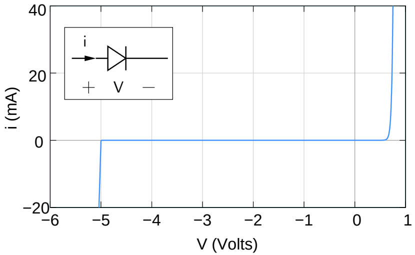

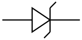

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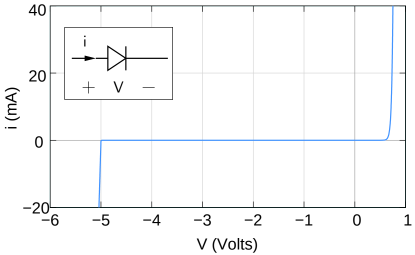

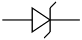

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* "Zener" diodes typically have V_{BR} of a few Volts, which is denoted by V_Z. They are often used to limit the voltage swing in electronic circuits.

Diode types

Apart from their use as switches, diodes are also used for several other purposes. The choice of materials used, fabrication techniques, and packaging depend on the functionality expected from the device.

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  An LED emits light of a specific wavelength (e.g., red, green, yellow, blue).

  White LEDs combine individual LEDs that emit the three primary colors (red, green, blue) or use a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light.

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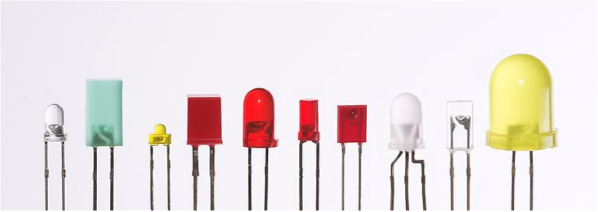

(source: wikipedia)

* **Solar cells** are generally silicon diodes designed to generate current efficiently when solar radiation is incident on the device. A "solar panel" has a large number of individual solar cells connected in series/parallel configuration.

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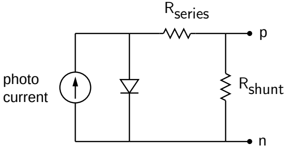

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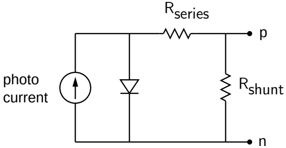

* **Photodiodes** are used to detect optical signals (DC or time-varying) and to convert them into electrical signals which can be subsequently processed by electronic circuits. They are used in fibre-optic communication systems, image processing, etc.

  A photodiode works on the same principle as a solar cell, i.e., it converts light into a current. However, its design is optimized for high-sensitivity, low-noise, or high-frequency operation, depending on the application.

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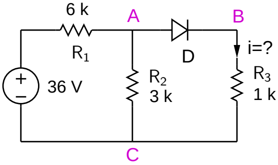
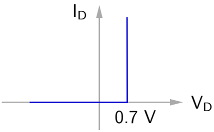
* Note that there are diode circuits in which the exponential nature of the diode I-V relationship is made use of. For these circuits, computer simulation would be required to solve the resulting non-linear equations.

Diode circuit example





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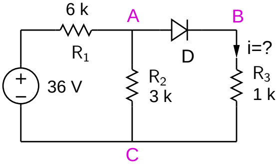

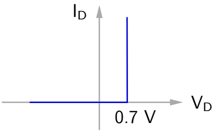

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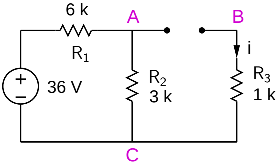

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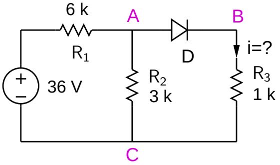

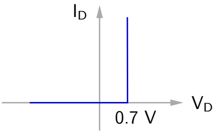

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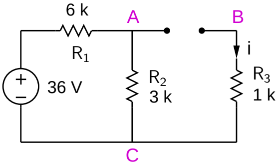

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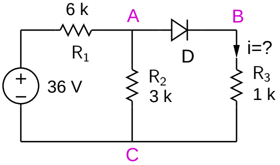

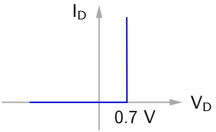

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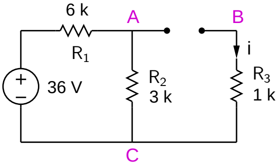

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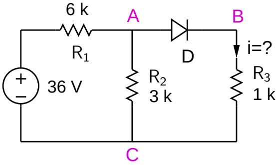

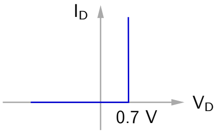

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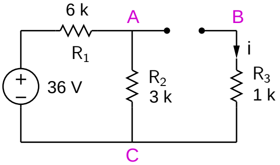

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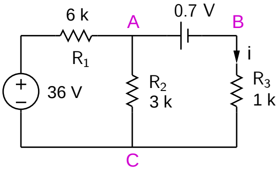

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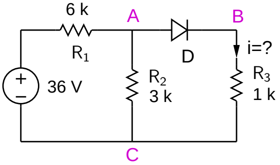

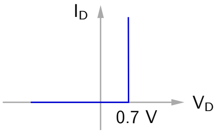

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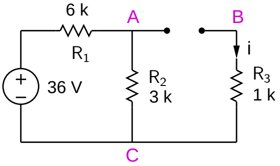

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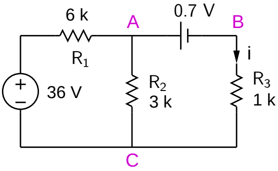

Taking $V_C = 0$ V,

$$\frac{V_A - 36}{6\ \text{k}} + \frac{V_A}{3\ \text{k}} + \frac{V_A - 0.7}{1\ \text{k}} = 0\,,$$

$\rightarrow\ V_A = 4.47$ V, $i = 3.77$ mA.

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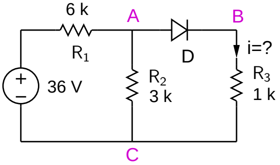

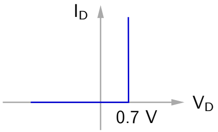

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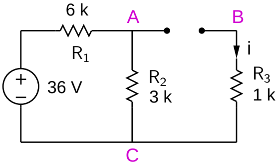

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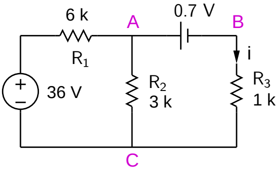

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Remark: Often, we can figure out by inspection if a diode is on or off.

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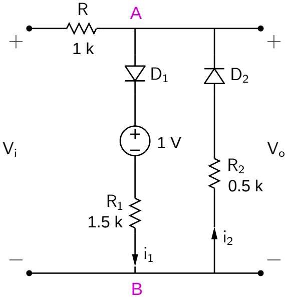

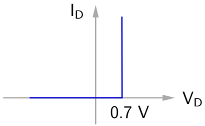

(a) Plot V_o versus V_i for $-5\ \mathrm{V} < V_i < 5\ \mathrm{V}$.

(b) Plot $V_o(t)$ for a triangular input:
-5 V to $+5$ V, 500 Hz.

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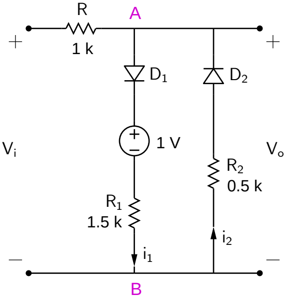

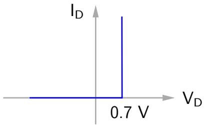

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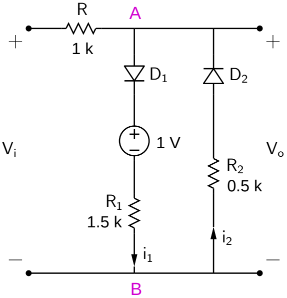

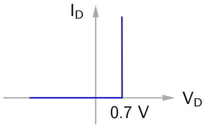

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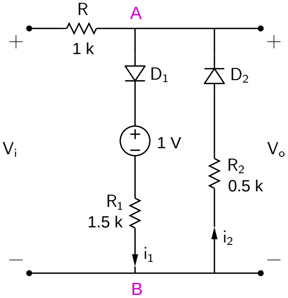
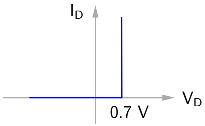
Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

Diode circuit example





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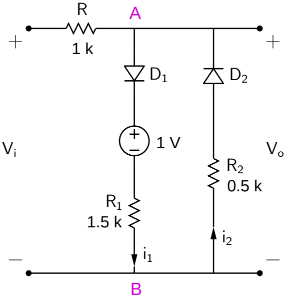
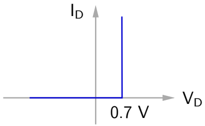
$\Rightarrow$ $V_{AB} > 1.7\ V \Rightarrow D_2$ cannot conduct.

Diode circuit example





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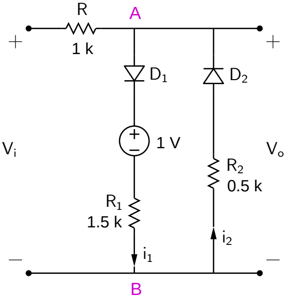
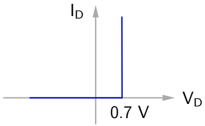
Similarly, if D_2 is on, $V_{BA} > 0.7\ V$, i.e., $V_{AB} < -0.7\ V$ $\Rightarrow$ D_1 cannot conduct.





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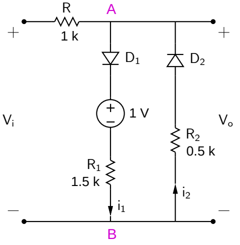
Clearly, D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)



Diode circuit example (continued)

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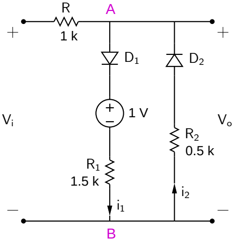
* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.
  $\rightarrow i_2 = -\dfrac{V_i + 0.7}{R + R_2}$, and

  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2} V_i - 0.7 \frac{R}{R + R_2} . \qquad (2)$$

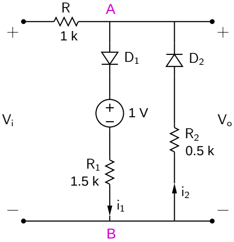


Diode circuit example (continued)

* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

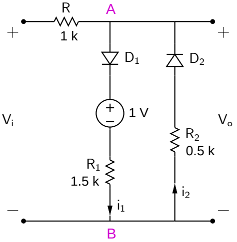
* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.
  $\rightarrow i_2 = -\dfrac{V_i + 0.7}{R + R_2}$, and
  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\, V_i - 0.7\, \frac{R}{R + R_2}\,. \qquad (2)$$

* For $V_i > 1.7\ V$, D_1 conducts. $\rightarrow V_o = 0.7 + 1 + i_1 R_1$.
  Use KVL to get i_1: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.
  $\rightarrow i_1 = \dfrac{V_i - 1.7}{R + R_1}$, and
  $$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1}\, V_i + 1.7\, \frac{R}{R + R_1}\,. \qquad (3)$$



Diode circuit example (continued)

* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)
* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.
  $\rightarrow i_2 = -\dfrac{V_i + 0.7}{R + R_2}$, and
  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\, V_i - 0.7\, \frac{R}{R + R_2}\,. \qquad (2)$$
* For $V_i > 1.7\ V$, D_1 conducts. $\rightarrow V_o = 0.7 + 1 + i_1 R_1$.
  Use KVL to get i_1: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.
  $\rightarrow i_1 = \dfrac{V_i - 1.7}{R + R_1}$, and
  $$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1}\, V_i + 1.7\, \frac{R}{R + R_1}\,. \qquad (3)$$
* Using Eqs. (1)-(3), we plot V_o versus V_i.
  (SEQUEL file: `ee101_diode_circuit_1.sqproj`)



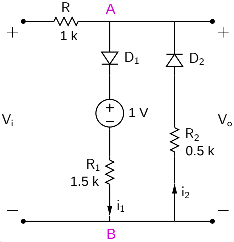
Diode circuit example (continued)

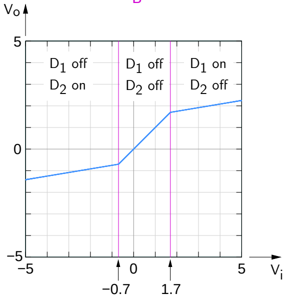
* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.
  $\rightarrow i_2 = -\dfrac{V_i + 0.7}{R + R_2}$, and
  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\, V_i - 0.7\, \frac{R}{R + R_2}\ . \qquad (2)$$

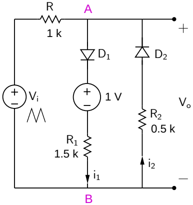
* For $V_i > 1.7\ V$, D_1 conducts. $\rightarrow V_o = 0.7 + 1 + i_1 R_1$.
  Use KVL to get i_1: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.
  $\rightarrow i_1 = \dfrac{V_i - 1.7}{R + R_1}$, and
  $$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1}\, V_i + 1.7\, \frac{R}{R + R_1}\ . \qquad (3)$$

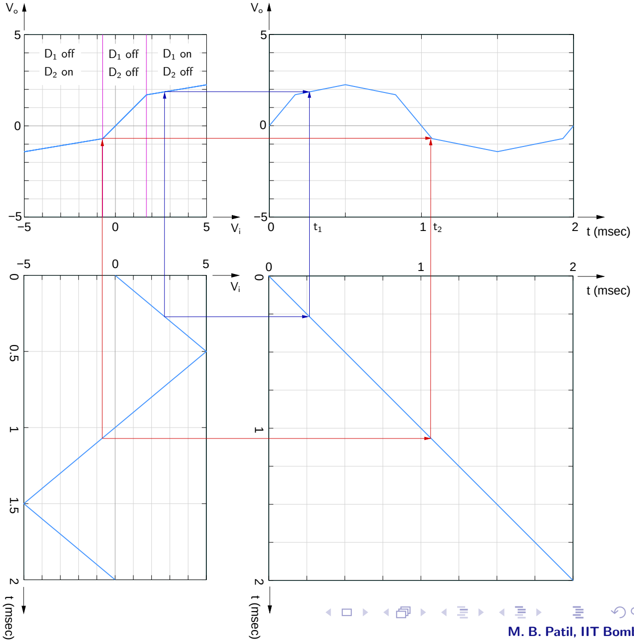
* Using Eqs. (1)-(3), we plot V_o versus V_i.
  (SEQUEL file: `ee101_diode_circuit_1.sqproj`)





Diode circuit example (continued)

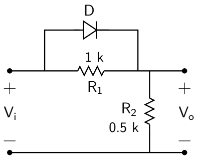


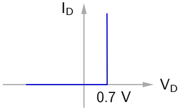


Point-by-point construction of V_o versus t:

Two time points, t_1 and t_2, are shown as examples.

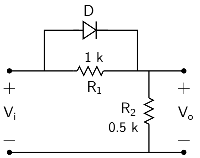
Diode circuit example

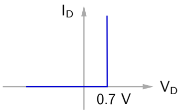




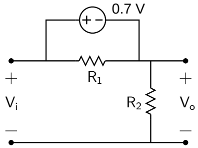
Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.

Diode circuit example





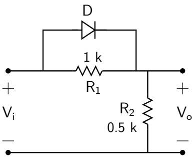
Plot V_o versus V_i for -5 V $< V_i < 5$ V .

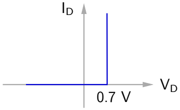


D on

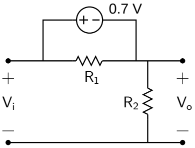
$V_o = V_i - 0.7$

Diode circuit example



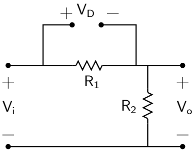


Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.



D on

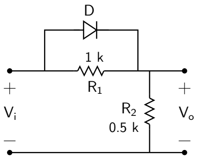
$V_o = V_i - 0.7$

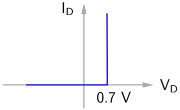


D off

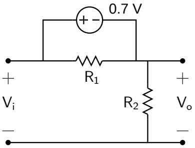
$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

Diode circuit example



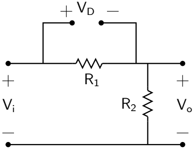


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

$$V_o = V_i - 0.7$$

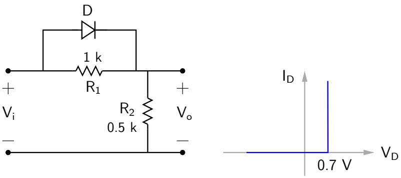


D off

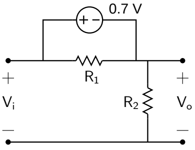
$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

At what value of V_i will the diode turn on?

Diode circuit example

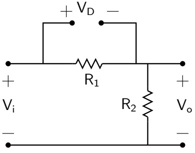


Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.



D on

$V_o = V_i - 0.7$

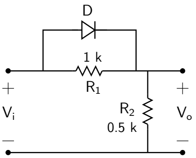


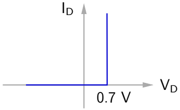
D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

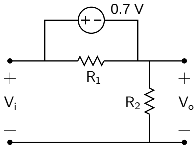
At what value of V_i will the diode turn on?

In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.



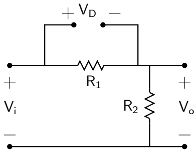


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

$V_o = V_i - 0.7$



D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

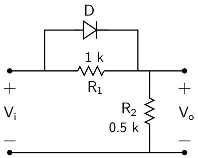
At what value of V_i will the diode turn on?

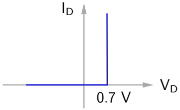
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2} V_i$.

For D to change to the on state, $V_D = 0.7\ V$.

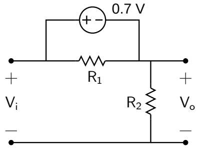
i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

Diode circuit example



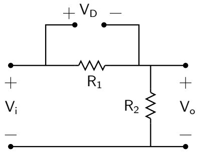


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



D on

$V_o = V_i - 0.7$



D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

At what value of V_i will the diode turn on?

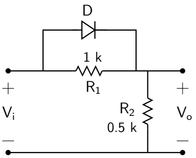
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

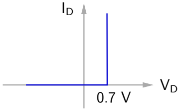
For D to change to the on state, $V_D =\ 0.7\ V$.

i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

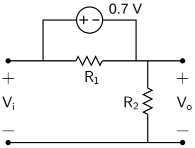
(SEQUEL file: `ee101_diode_circuit_2.sqproj`)

Diode circuit example



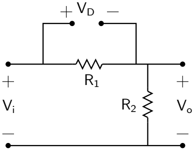


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



D on

$V_o = V_i - 0.7$



D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

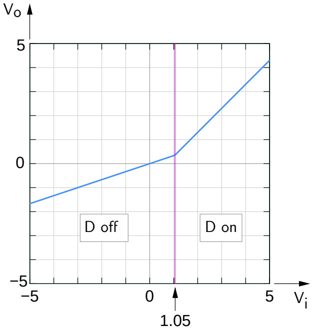
At what value of V_i will the diode turn on?

In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

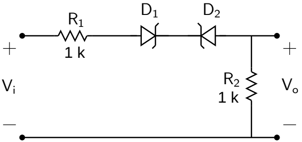
For D to change to the on state, $V_D = 0.7\ V$.

i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

(SEQUEL file: `ee101_diode_circuit_2.sqproj`)



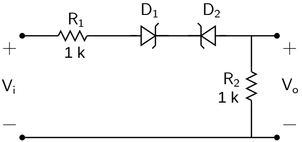
Diode circuit example



$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

Diode circuit example

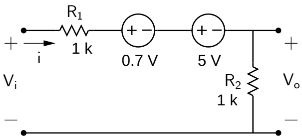


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

For a current to flow, we have two possibilities:

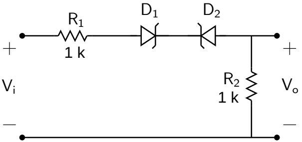
D_1 on (forward), D_2 in reverse breakdown



$$V_o = i\,R_2 = \frac{V_i - 5.7}{R_1 + R_2}\,R_2$$

Since $i > 0$, this can happen only when $V_i > 5.7$ V.

Diode circuit example

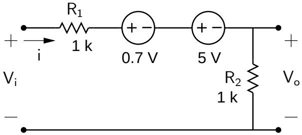


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

For a current to flow, we have two possibilities:

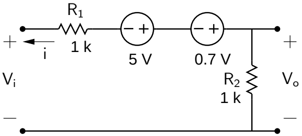
D_1 on (forward), D_2 in reverse breakdown



$$V_o = i\,R_2 = \frac{V_i - 5.7}{R_1 + R_2}\,R_2$$

Since $i > 0$, this can happen only when $V_i > 5.7$ V.

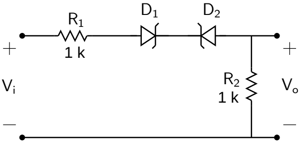
D_2 on (forward), D_1 in reverse breakdown



$$V_o = -i\,R_2 = \frac{V_i + 5.7}{R_1 + R_2}\,R_2$$

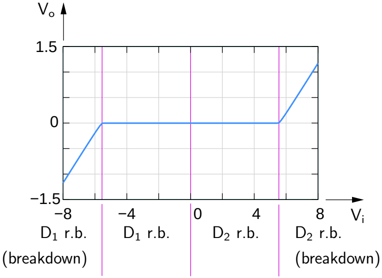
Since $i > 0$, this can happen only when $V_i <$ -5.7 V.

Diode circuit example



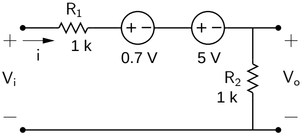
$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.



For a current to flow, we have two possibilities:

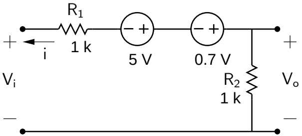
D_1 on (forward), D_2 in reverse breakdown



$$V_o = i\,R_2 = \frac{V_i - 5.7}{R_1 + R_2}\,R_2$$

Since $i > 0$, this can happen only when $V_i > 5.7$ V.

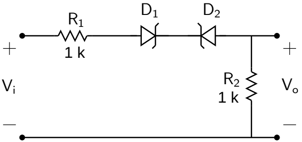
D_2 on (forward), D_1 in reverse breakdown



$$V_o = -i\,R_2 = \frac{V_i + 5.7}{R_1 + R_2}\,R_2$$

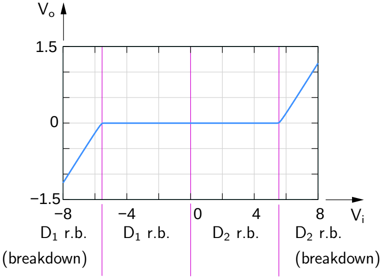
Since $i > 0$, this can happen only when $V_i <$ -5.7 V.

Diode circuit example



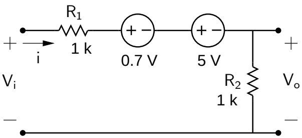
$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.



For a current to flow, we have two possibilities:

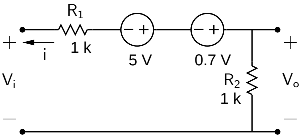
D_1 on (forward), D_2 in reverse breakdown



$$V_o = i\,R_2 = \frac{V_i - 5.7}{R_1 + R_2}\,R_2$$

Since $i > 0$, this can happen only when $V_i > 5.7$ V.

D_2 on (forward), D_1 in reverse breakdown

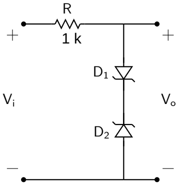


$$V_o = -i\,R_2 = \frac{V_i + 5.7}{R_1 + R_2}\,R_2$$

Since $i > 0$, this can happen only when $V_i <$ -5.7 V.

(SEQUEL file: ee101_diode_circuit_3.sqproj)

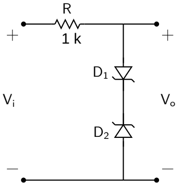
Diode circuit example (voltage limiter)



$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

Diode circuit example (voltage limiter)

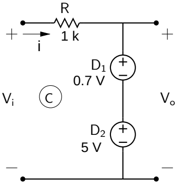


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

For a current to flow, we have two possibilities:

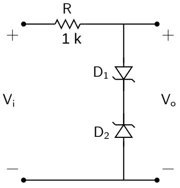
D_1 on (forward), D_2 in reverse breakdown



$V_o = 5.7$ V

$V_i > 5.7$ V

Diode circuit example (voltage limiter)

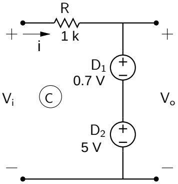


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

For a current to flow, we have two possibilities:

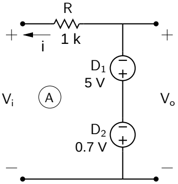
D_1 on (forward), D_2 in reverse breakdown



$V_o = 5.7$ V

$V_i > 5.7$ V

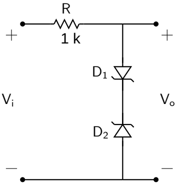
D_2 on (forward), D_1 in reverse breakdown



$V_o = -5.7$ V

$V_i < -5.7$ V

Diode circuit example (voltage limiter)

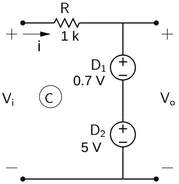


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

For a current to flow, we have two possibilities:

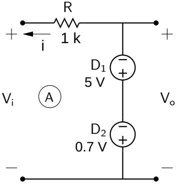
D_1 on (forward), D_2 in reverse breakdown



$V_o = 5.7$ V

$V_i > 5.7$ V

D_2 on (forward), D_1 in reverse breakdown

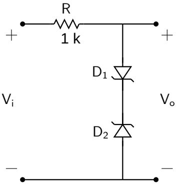


$V_o = -5.7$ V

$V_i < -5.7$ V

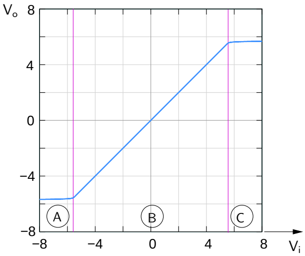
In the range, $-5.7 \text{ V} < V_i < 5.7 \text{ V}$, no current flows, and $V_o = V_i$. B

Diode circuit example (voltage limiter)



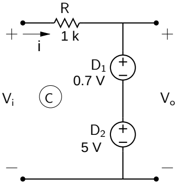
$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.



For a current to flow, we have two possibilities:

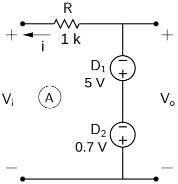
D_1 on (forward), D_2 in reverse breakdown



$V_o = 5.7$ V

$V_i > 5.7$ V

D_2 on (forward), D_1 in reverse breakdown

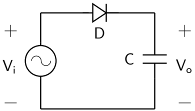


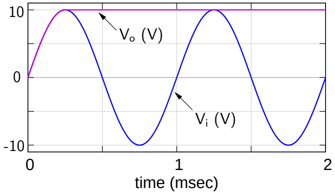
$V_o = -5.7$ V

$V_i < -5.7$ V

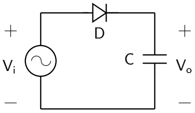
In the range, $-5.7\text{ V} < V_i < 5.7\text{ V}$, no current flows, and $V_o = V_i$. B

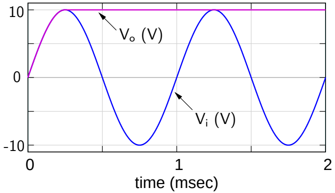
Peak detector





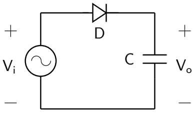
Peak detector

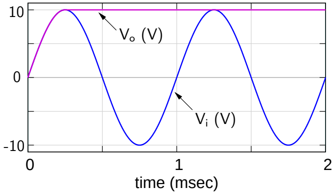




Let $V_o(t) = 0\ V$ at $t = 0$, and assume the diode to be ideal, with $V_{\rm on} = 0\ V$.

Peak detector

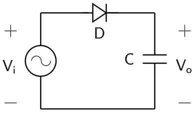


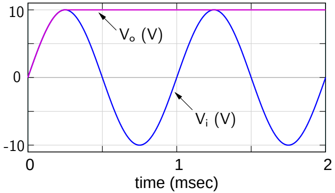


Let $V_o(t) = 0\ V$ at $t = 0$, and assume the diode to be ideal, with $V_{\text{on}} = 0\ V$.

For $0 < t < T/4$, V_i rises from 0 to V_m. As a result, the capacitor charges.

Peak detector





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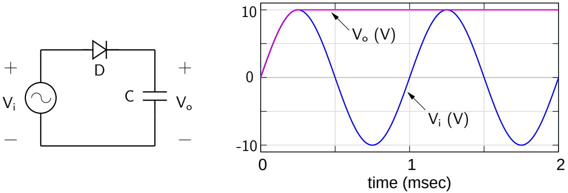
For $0 < t < T/4$, V_i rises from 0 to V_m. As a result, the capacitor charges.

Since the on resistance of the diode is small, time constant $\tau \ll T/4$; therefore the charging process is instantaneous $\Rightarrow V_o(t) = V_i(t)$.

Peak detector



Let $V_o(t) = 0\ V$ at $t = 0$, and assume the diode to be ideal, with $V_{\text{on}} = 0\ V$.

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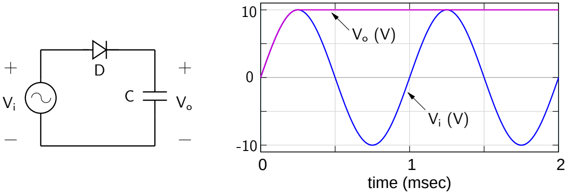
For $t > T/4$, V_i starts falling. The capacitor holds the charge it had at $t = T/4$ since the diode prevents discharging.

Peak detector



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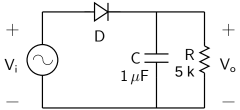
For $0 < t < T/4$, V_i rises from 0 to V_m. As a result, the capacitor charges.

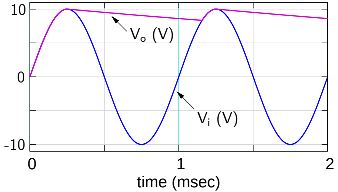
Since the on resistance of the diode is small, time constant $\tau \ll T/4$; therefore the charging process is instantaneous $\Rightarrow V_o(t) = V_i(t)$.

For $t > T/4$, V_i starts falling. The capacitor holds the charge it had at $t = T/4$ since the diode prevents discharging.

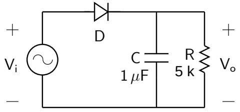
SEQUEL file: `ee101_diode_circuit_5.sqproj`

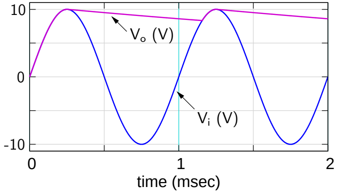
Peak detector (continued)



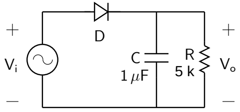


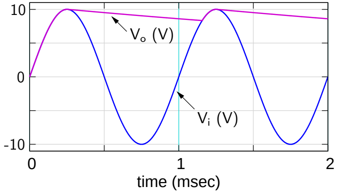
Peak detector (continued)





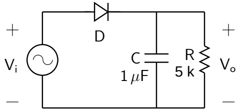
If a resistor is added in parallel, a discharging path is provided for the capacitor, and the capacitor voltage falls after reaching the peak.

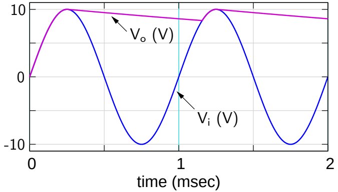




If a resistor is added in parallel, a discharging path is provided for the capacitor, and the capacitor voltage falls after reaching the peak.

When $V_i > V_o$, the capacitor charges again. The time constant for the charging process is $\tau = R_{\mathrm{Th}} C$, where $R_{\mathrm{Th}} = R \parallel R_{\mathrm{on}}$ is the Thevenin resistance seen by the capacitor, R_{on} being the on resistance of the diode.





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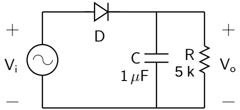
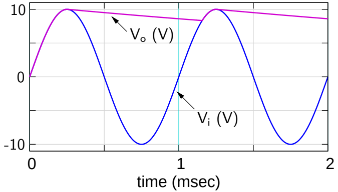
Since $\tau \ll T$, the charging process is instantaneous.





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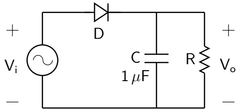
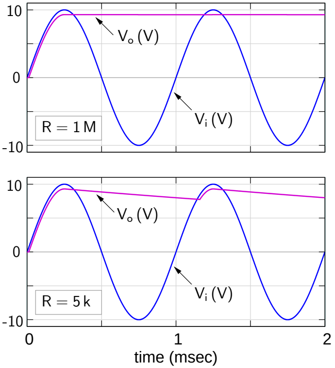
Since $\tau \ll T$, the charging process is instantaneous.

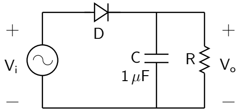
SEQUEL file: `ee101_diode_circuit_5a.sqproj`

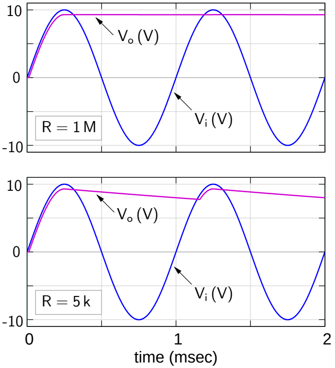
Peak detector (with $V_{on} = 0.7\ V$)





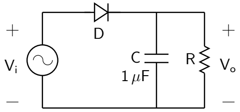
Peak detector (with $V_{\text{on}} = 0.7\ V$)

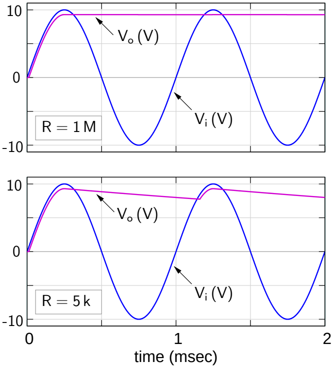




With $V_{\text{on}} = 0.7\ V$, the capacitor charges up to $(V_m - 0.7\ V)$.

Peak detector (with $V_{on} = 0.7\ V$)

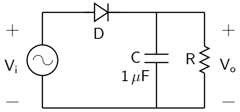


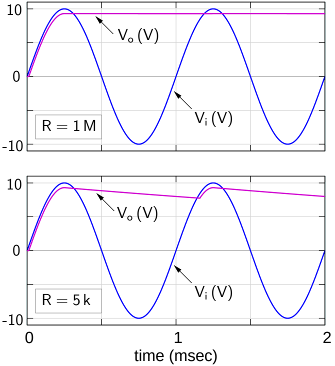


With $V_{on} = 0.7\ V$, the capacitor charges up to $(V_m - 0.7\ V)$.

Apart from that, the circuit operation is similar.

Peak detector (with $V_{on} = 0.7\ V$)



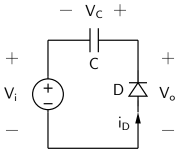


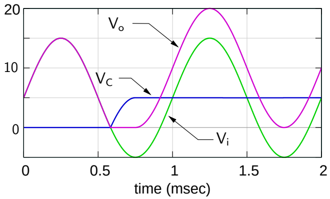
With $V_{on} = 0.7\ V$, the capacitor charges up to $(V_m - 0.7\ V)$.

Apart from that, the circuit operation is similar.

SEQUEL file: `ee101_diode_circuit_5a.sqproj`

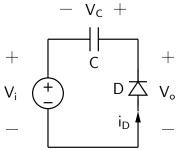
Clamped capacitor

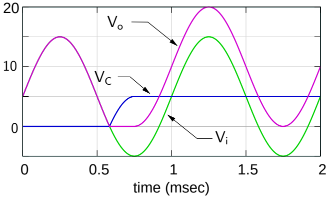




* Assume $V_{on} = 0\ V$ for the diode.
  When D conducts, $V_D = -V_o = 0 \Rightarrow V_C + V_i = 0$, i.e., $V_C = -V_i$.

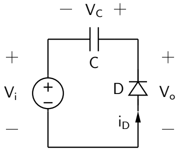
Clamped capacitor

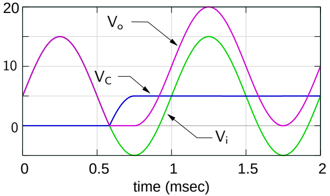




* Assume $V_{on} = 0\ V$ for the diode.
  When D conducts, $V_D = -V_o = 0 \Rightarrow V_C + V_i = 0$, i.e., $V_C = -V_i$.
* V_C can only increase with time (or remain constant) since i_D can only be positive.

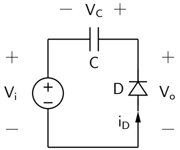
Clamped capacitor

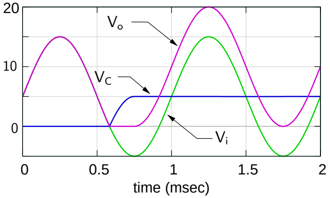




* Assume $V_{on} = 0\ V$ for the diode.
  When D conducts, $V_D = -V_o = 0 \Rightarrow V_C + V_i = 0$, i.e., $V_C = -V_i$.
* V_C can only increase with time (or remain constant) since i_D can only be positive.
* The net result is that the capacitor gets charged to a voltage $V_C = -V_i$, corresponding to the maxmimum negative value of V_i, and holds that voltage thereafter. Let us call this voltage V_C^0 (a constant).

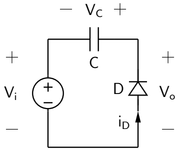
Clamped capacitor

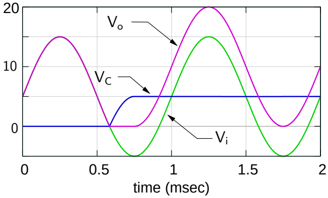




* Assume $V_{on} = 0\ V$ for the diode.
  When D conducts, $V_D = -V_o = 0 \Rightarrow V_C + V_i = 0$, i.e., $V_C = -V_i$.
* V_C can only increase with time (or remain constant) since i_D can only be positive.
* The net result is that the capacitor gets charged to a voltage $V_C = -V_i$, corresponding to the maxmimum negative value of V_i, and holds that voltage thereafter. Let us call this voltage V_C^0 (a constant).
* $V_o(t) = V_C(t) + V_i(t) = V_C^0 + V_i(t)$, which is a "level-shifted" version of V_i.

Clamped capacitor

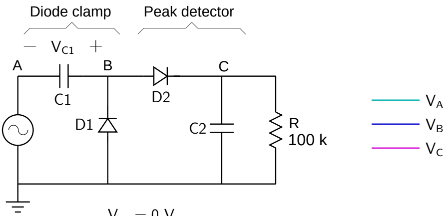


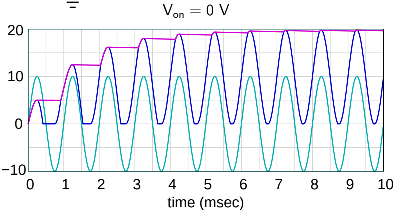


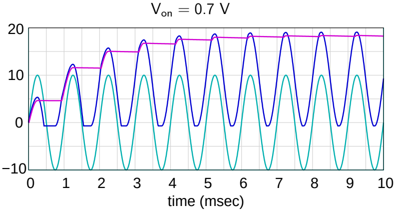
* Assume $V_{\text{on}} = 0\ V$ for the diode.
  When D conducts, $V_D = -V_o = 0 \Rightarrow V_C + V_i = 0$, i.e., $V_C = -V_i$.
* V_C can only increase with time (or remain constant) since i_D can only be positive.
* The net result is that the capacitor gets charged to a voltage $V_C = -V_i$, corresponding to the maxmimum negative value of V_i, and holds that voltage thereafter. Let us call this voltage V_C^0 (a constant).
* $V_o(t) = V_C(t) + V_i(t) = V_C^0 + V_i(t)$, which is a “level-shifted” version of V_i.

(SEQUEL file: `ee101_diode_circuit_6.sqproj`)

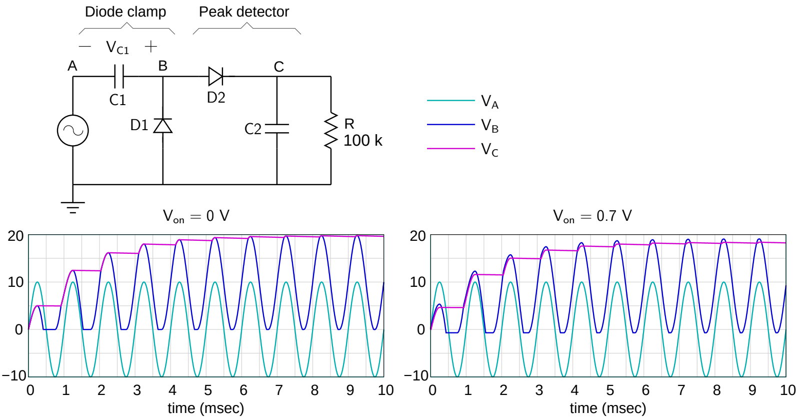
Voltage doubler





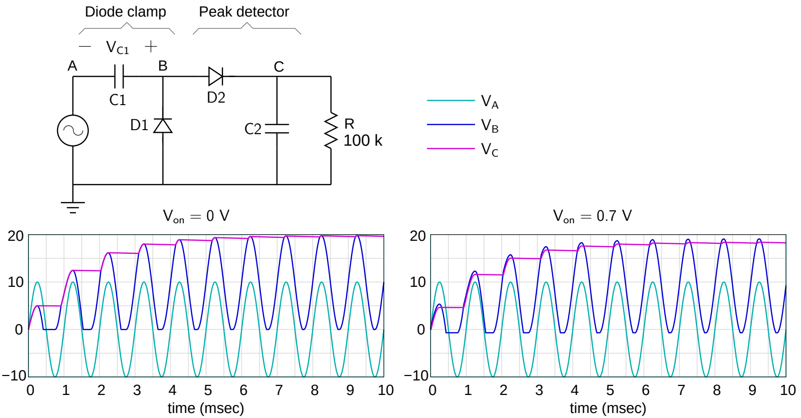


Voltage doubler



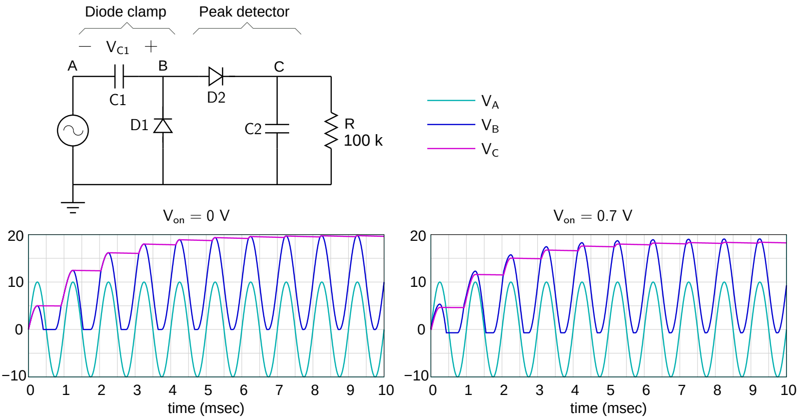
* The diode clamp shifts V_A up by V_m (the amplitude of the AC source), making V_B go from 0 to 2 V_m.

Voltage doubler



* The diode clamp shifts V_A up by V_m (the amplitude of the AC source), making V_B go from 0 to 2 V_m.
* The peak detector detects the peak of V_B (2 V_m w.r.t. ground), and holds it constant.

Voltage doubler



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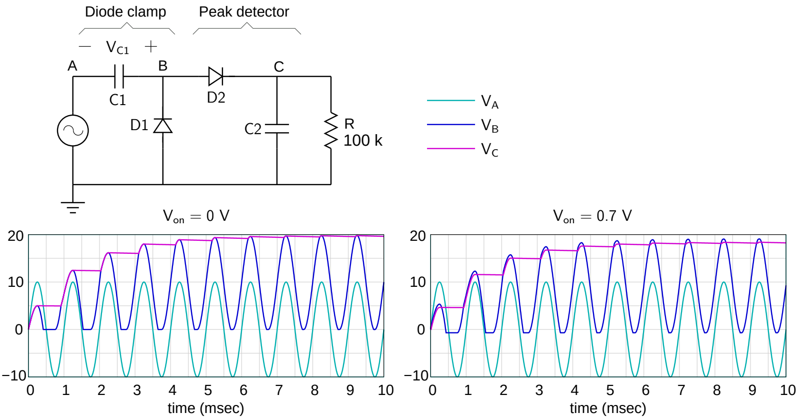
* Note that it takes a few cycles to reach steady state. Plot V_{C1}, i_{D1}, i_{D2} versus t and explain the initial behaviour of the circuit.

Voltage doubler



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  (SEQUEL file: `ee101_voltage_doubler.sqproj`)