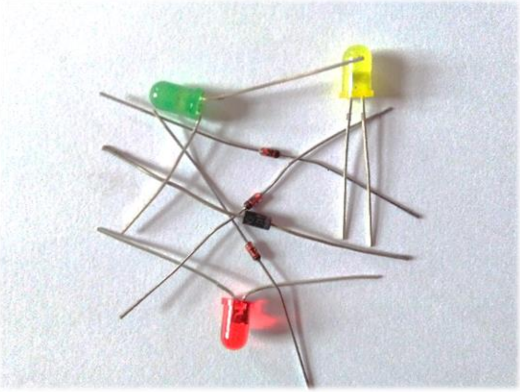
ELECTRONIC DEVICES

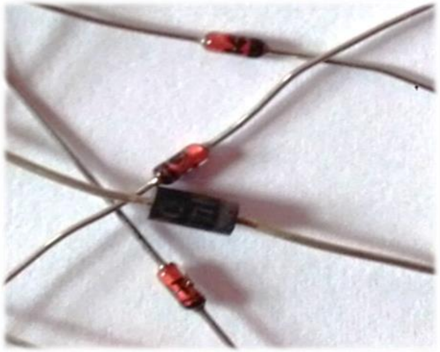
Assist. prof. Laura-Nicoleta IVANCIU, Ph.D.

C2 – Diodes. DR circuits.

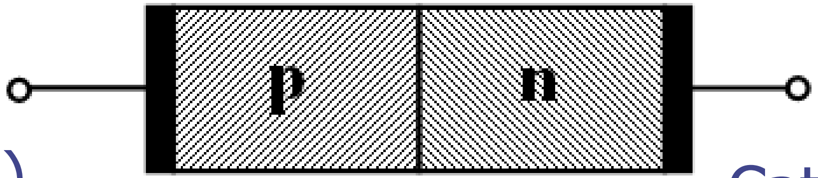


Contents

Physical structure. Symbol.

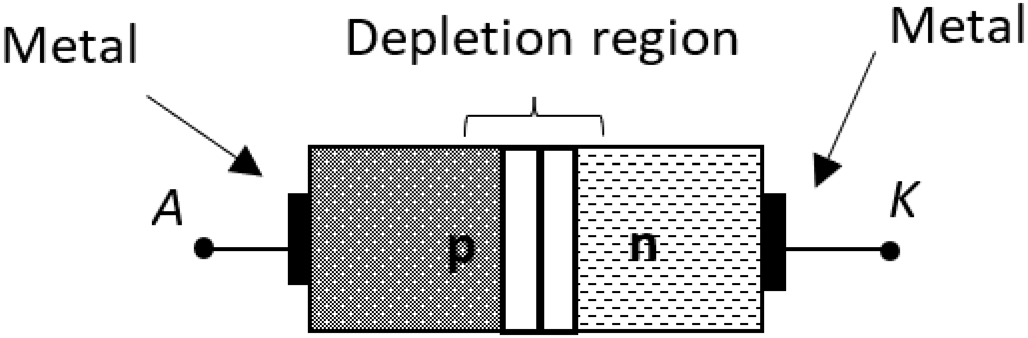


Physical structure – *pn* junction



Anode (A)

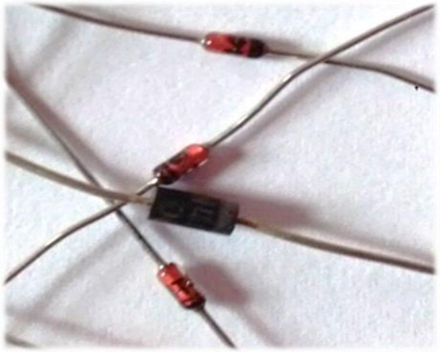
Cathode (K)



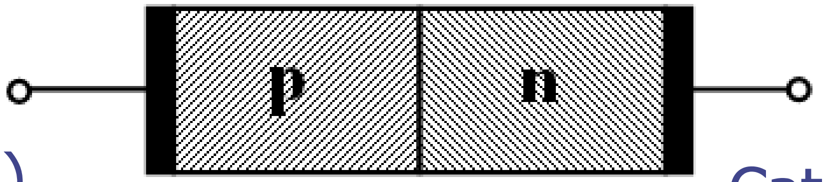
More details about the physical structure of a *pn* junction

- How does a diode work - the PN Junction (with animation) | Intermediate Electronics - YouTube

Physical structure. Symbol.



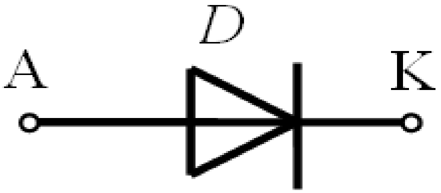
Physical structure – *pn* junction



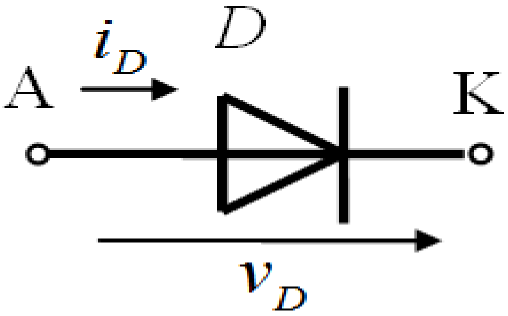
Anode (A)

Cathode (K)

circuit symbol



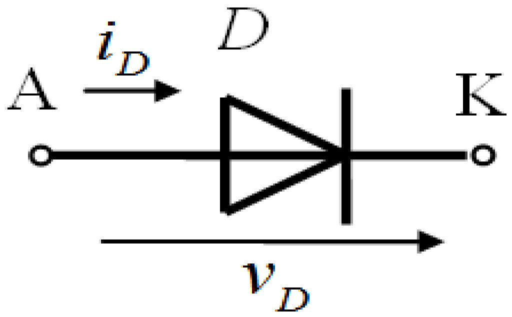
directions for current and voltage



The arrow in the diode’s symbol indicates the direction of the forward current flow.

Current-voltage characteristic

The current flowing through the diode is controlled by the voltage drop across the diode itself – **nonlinear** semiconductor device



Diode – one-way switch for current

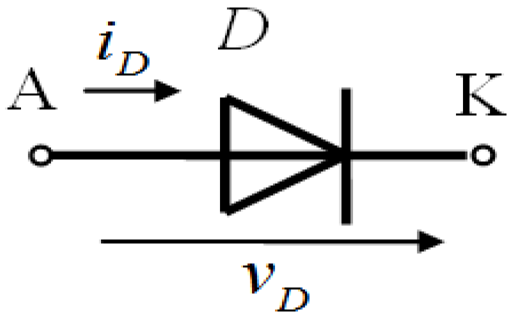
Nonlinear = ?

Semiconductor = ?

What materials are diodes made of?

Current-voltage characteristic

The current flowing through the diode is controlled by the voltage drop across the diode itself – **nonlinear** semiconductor device



Diode equation – William Shockley (Bell Labs, 1950)

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

I_S - saturation current (~ nA - pA)

n = 2 discrete diodes
n = 1 integrated diodes

$$V_T = \frac{KT}{q}$$

thermal voltage

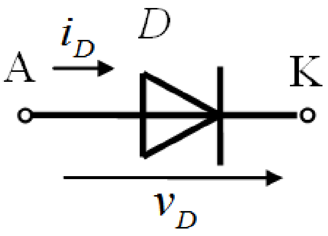
$$\boxed{V_T = 25\text{mV @ } 20^{\text{O}}\text{C}}$$

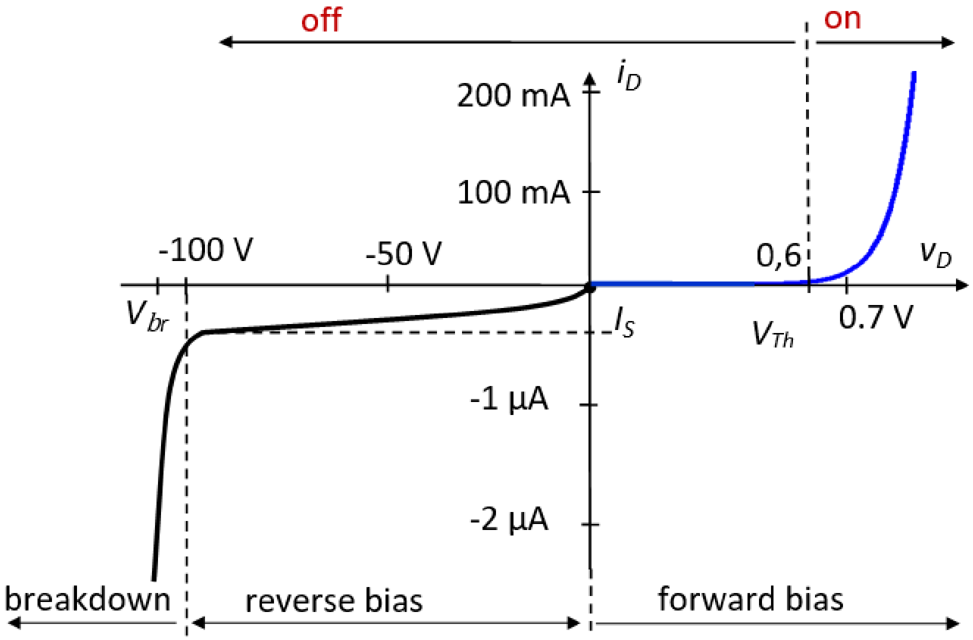
K - Boltzmann's constant
q – elementary charge (electric charge carried by a single electron)
T – absolute temperature measured in K

Current-voltage characteristic

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

Exponential model of the diode
(valid in forward and reverse regions)





$$i_D \cong I_S e^{\frac{v_D}{nV_T}}$$

$v_D = V_A - V_K$

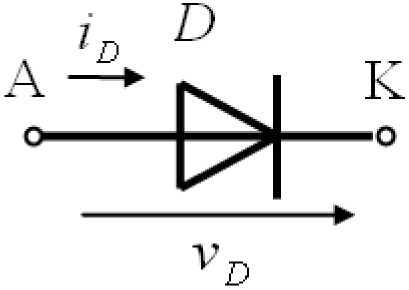
Threshold voltage

$$\boxed{V_{Th} \approx 0.6V}$$

Mind the scale for the Y-axis!

Current-voltage characteristic

Numerical illustration



D is a rectifier diode, 1N400x with I_S = 14 nA, n = 2

Assuming a voltage drop across the diode

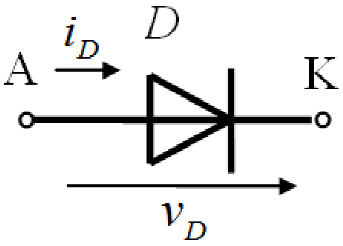
$$v_D = 0.7\text{V}$$

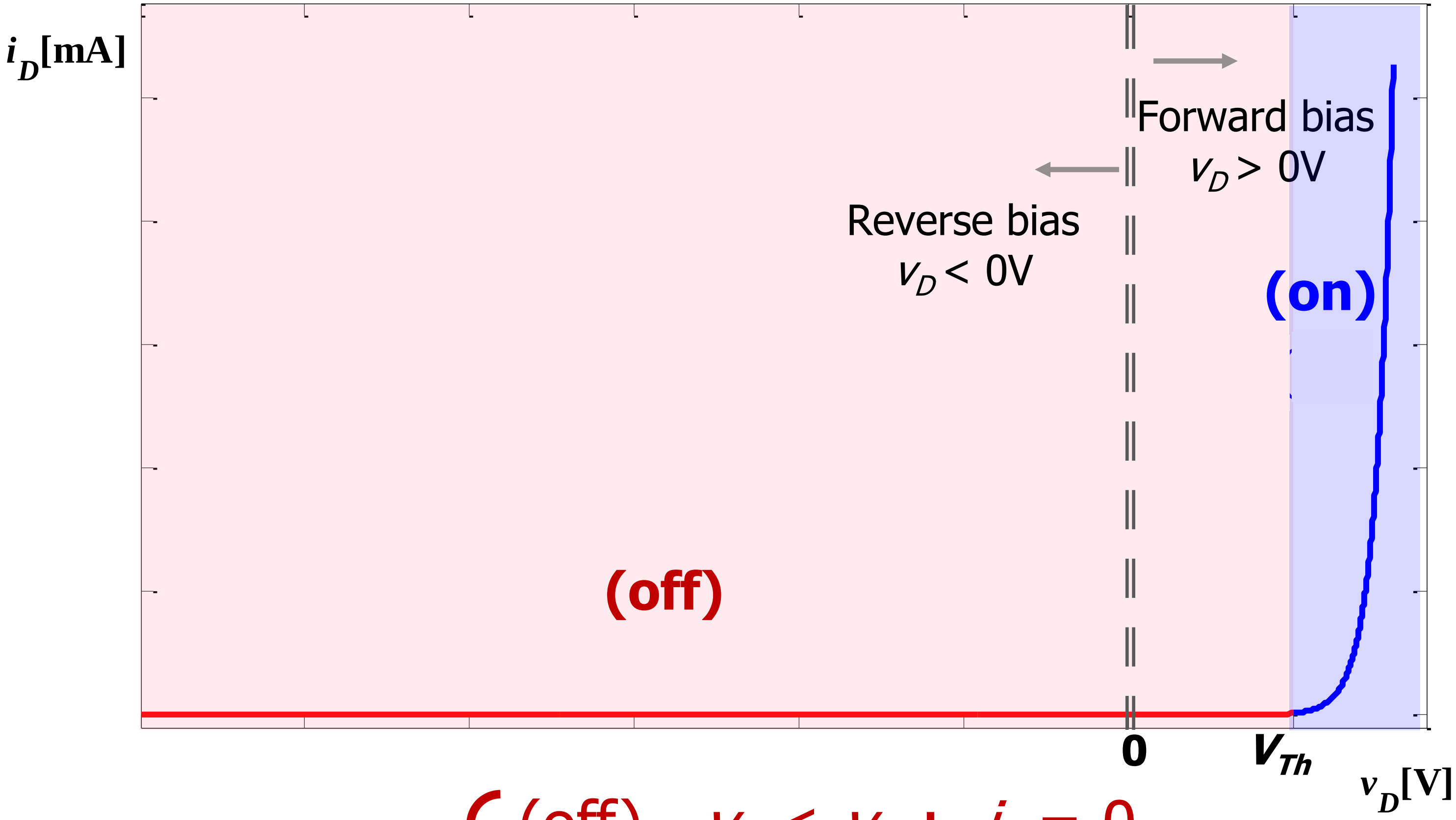
the current through the diode results as:

$$i_D = 14 \cdot 10^{-9} (e^{\frac{700}{2 \cdot 25}} - 1) = 16.8\text{mA}$$

Operating regions

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





$V_{Th} \approx 0.6$ V

$$\begin{cases} \text{(off)} \quad v_D < V_{Th}; \quad i_D = 0 \\ \text{(on)} \quad v_D > V_{Th}; \quad i_D > 0 \end{cases}$$

Operating (quiescent) point

$$Q(V_D; I_D)$$

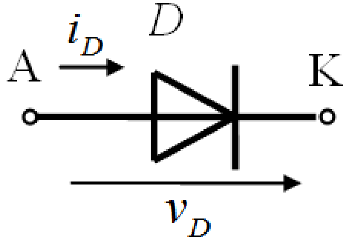
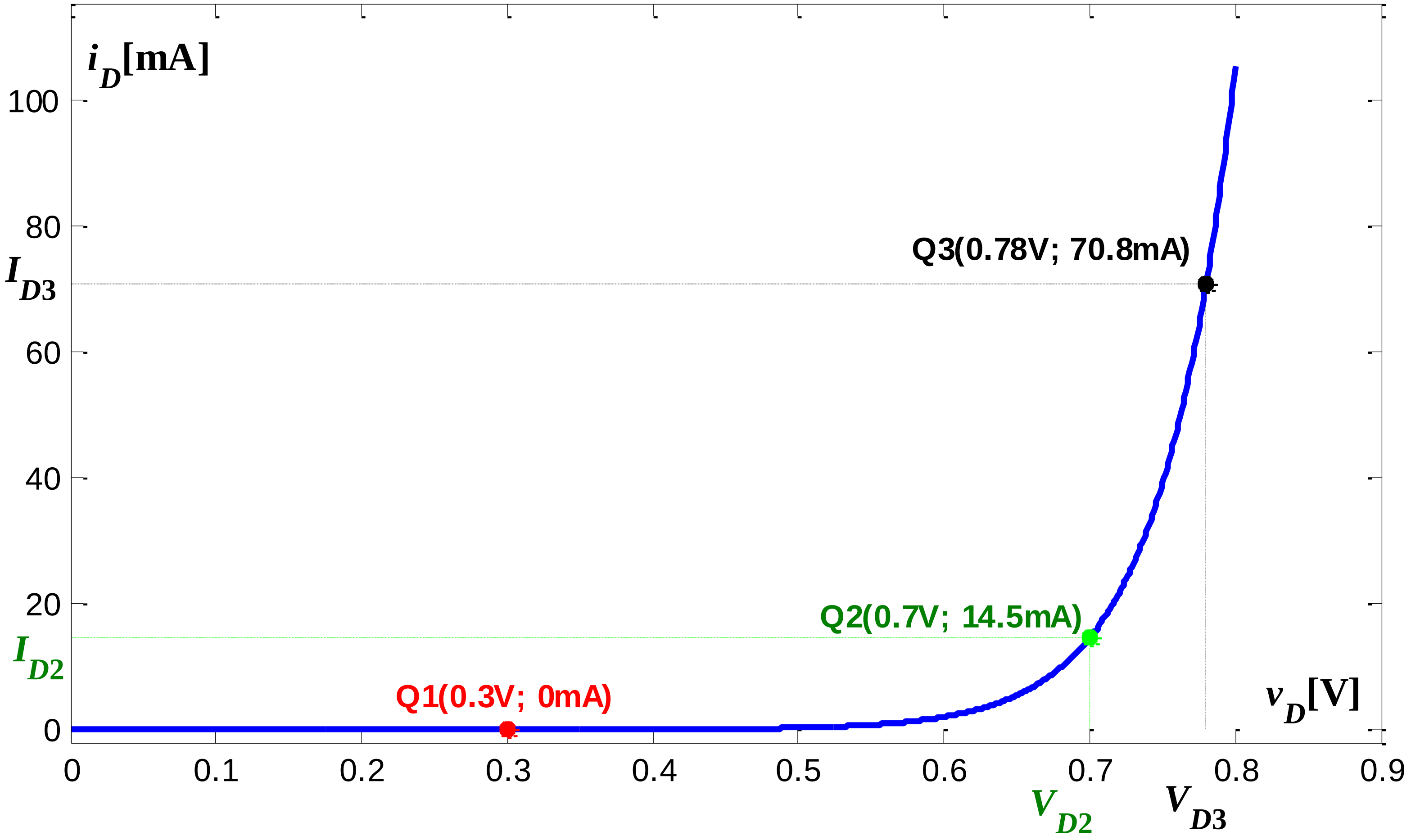


Illustration for 1N400x with I_S = 14 nA, n = 2



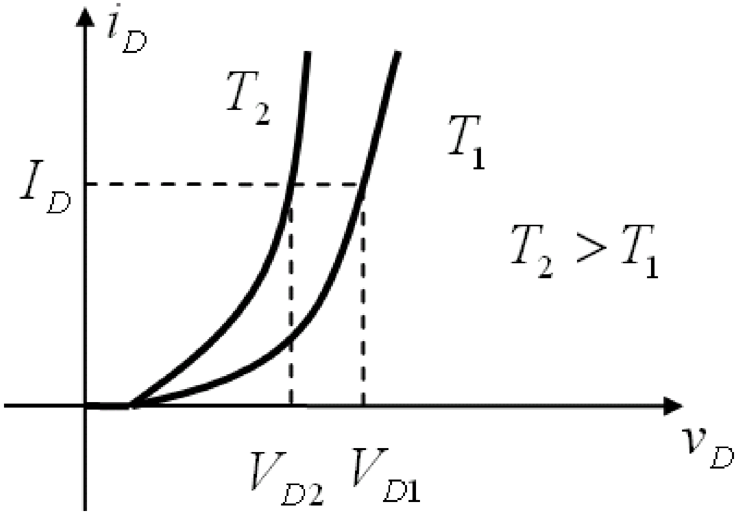
Operating (quiescent) point

Temperature dependence

$$i_D \cong I_S e^{\frac{v_D}{nV_T}}$$

I_S, V_T - depend directly on the temperature

At a **constant current,** the voltage across the diode **decreases** by ~2 mV for every 1°C increase in temperature



$$TC = -2\text{mV}/^{\text{O}}\text{C}$$ negative temperature coefficient

20°C $\quad v_D = 650\,\text{mV}$

40°C $\quad v_D = 610\,\text{mV}$

$$v_D(T_2) = v_D(T_1) + TC \cdot (T_2 - T_1)\Big|_{I_D-cst}$$

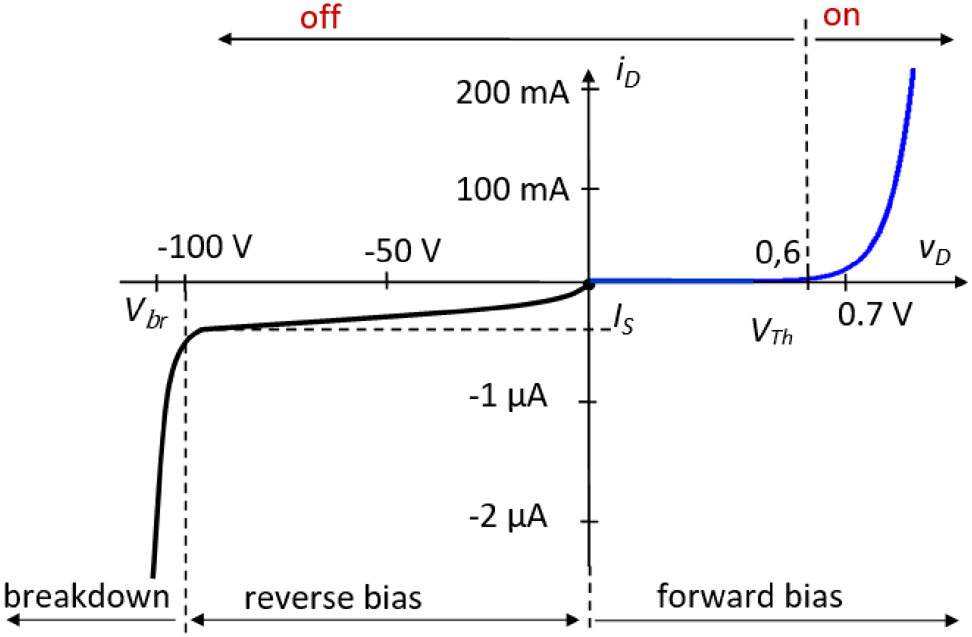
At a **constant voltage** across the diode, the current **increases** with the temperature

Operating (quiescent) point

Example

Determine the operating region (*forward bias/reverse bias/breakdown*) and the state (*on/off*) of a Si diode for the following quiescent points Q(V_D, I_D):

i) (0.2 V; 1 nA)
ii) (-10 V; -2.3 nA)
iii) (-100 V; -2 µA).



Parameters of the diode

The parameters of the diode are defined (and computed) in the operating (quiescent) point, Q(V_D, I_D)

- Static parameters – defined in static regime (dc)
  - static resistance r_D

$$r_D = \left.\frac{V_D}{I_D}\right|_Q$$

- Dynamic parameters – defined in variable regime (ac)

  a.k.a. small signal parameters

  - dynamic (small signal resistance) r_d

$$g_D = \frac{1}{r_D} = \left.\frac{I_D}{V_D}\right|_Q$$

Parameters of the diode

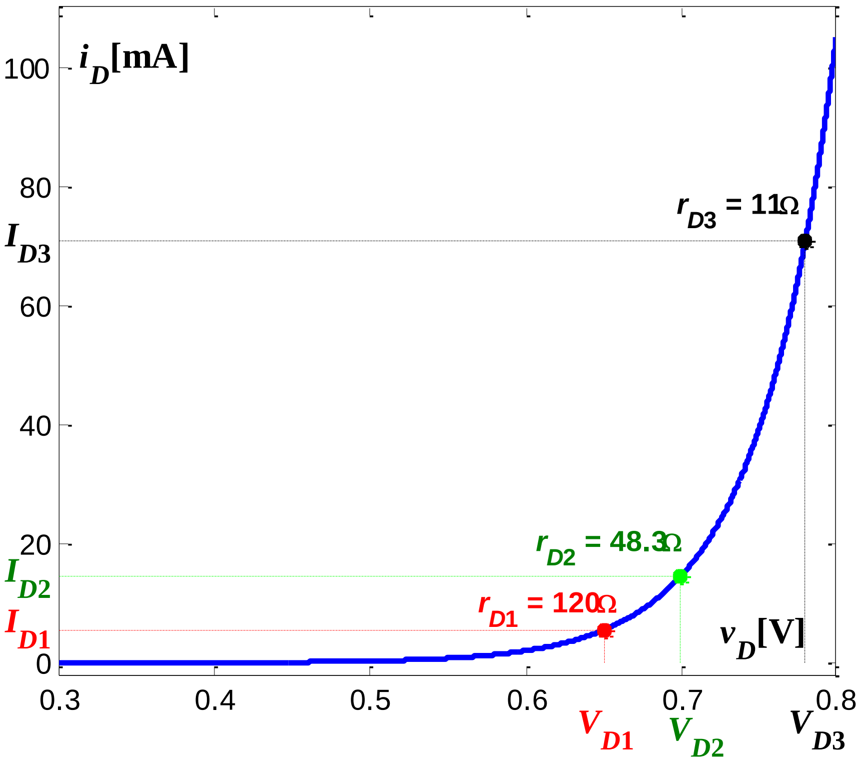
➢ Static parameters

$$r_D = \left.\frac{V_D}{I_D}\right|_Q$$

static resistance

$$g_D = \frac{1}{r_D} = \left.\frac{I_D}{V_D}\right|_Q$$

static conductance



Example:

Q_1(0.65 V; 5.4 mA)

$$r_{D1} = \frac{0.65}{5.4} = 120\Omega$$

Q_2(0.7 V; 14.5 mA)

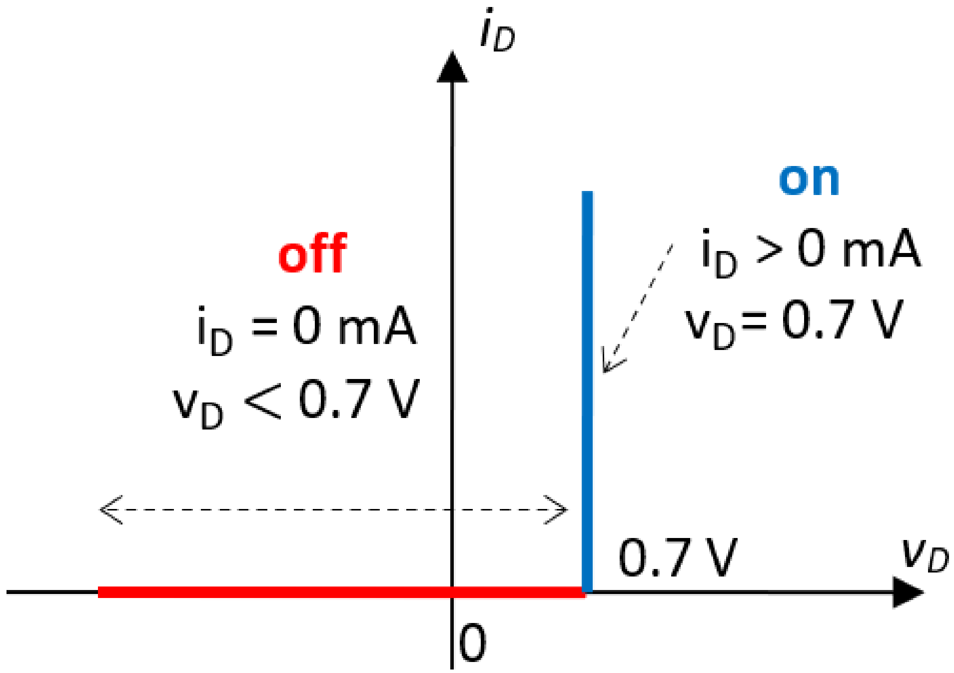
$$r_{D2} = \frac{0.7}{14.5} = 48.3\Omega$$

Q_3(0.78 V; 70.8 mA)

$$r_{D3} = \frac{0.78}{70.8} = 11\Omega$$

As the current increases, the diode goes in deeper conduction and its static resistance decreases.

Constant voltage drop model



off

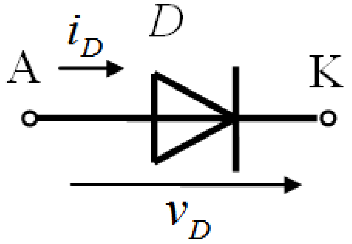
$i_D = 0$ mA

$v_D < 0.7$ V

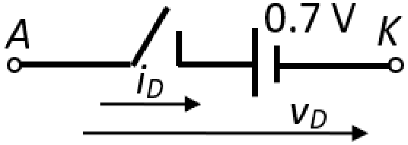
on

$i_D > 0$ mA

$v_D = 0.7$ V



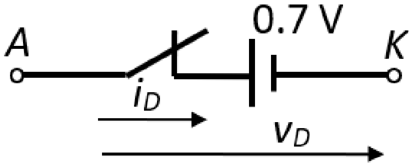
D – (off)



$v_D < 0.7$ V

$i_D = 0$ mA

D – (on)



$v_D = 0.7$ V

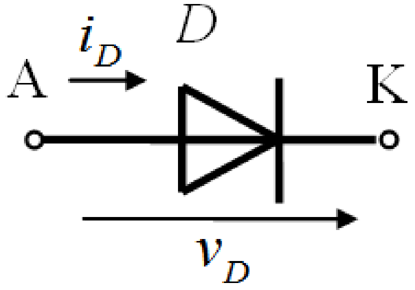
$i_D > 0$ mA

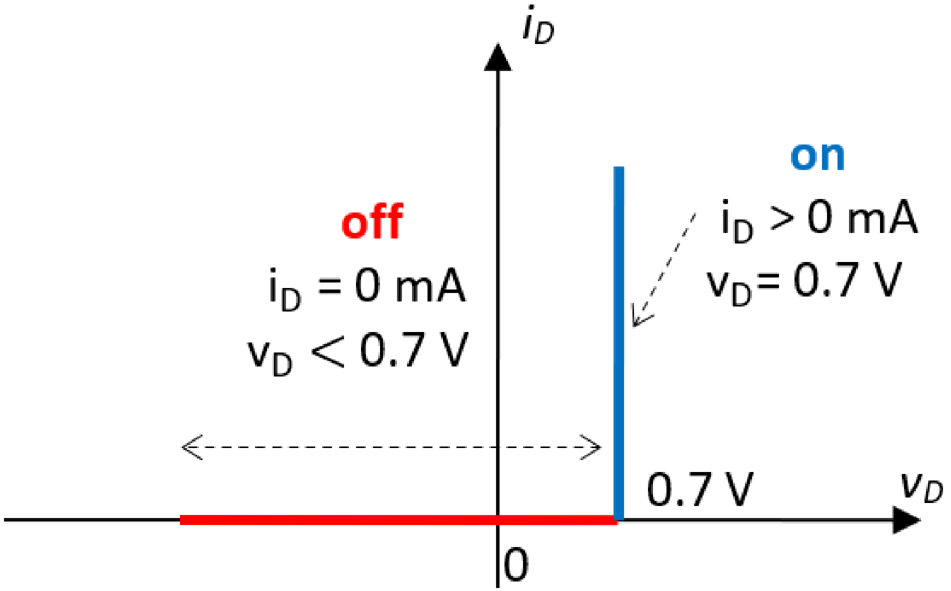
Constant voltage drop model

Example

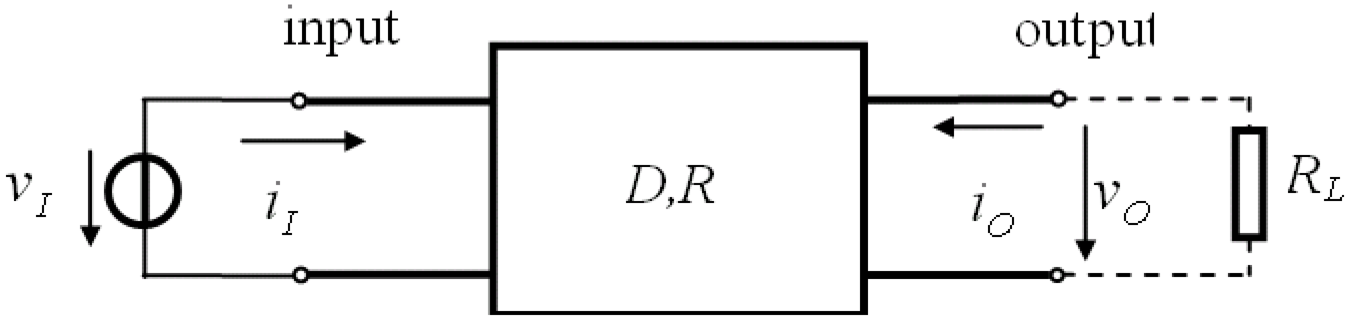
Assuming the constant voltage drop model ($v_{D,\ on}$= 0.7 V), determine the state (*on/off*) of the diode for the following pairs of values:

i) i_D = 0 mA and v_D = - 0.7 V
ii) i_D = 0 mA and v_D = - 7 V
iii) i_D = 15 mA and v_D = 0.7 V
iv) i_D = 0 mA and v_D = 0.2 V





Two-port DR networks. DR switching circuits.



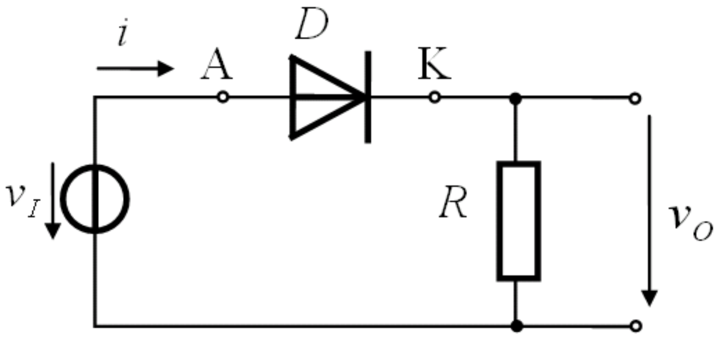
Two-port network = circuit w/ two ports – input, output

Two-port DR network = DR circuit w/ two ports – input, output

Switching two-port DR network = DR circuit w/ two ports, D – (on), (off)

The analysis of switching two-port DR networks works with the constant voltage drop model of the diode.

Voltage transfer characteristic



Voltage transfer characteristic (VTC)

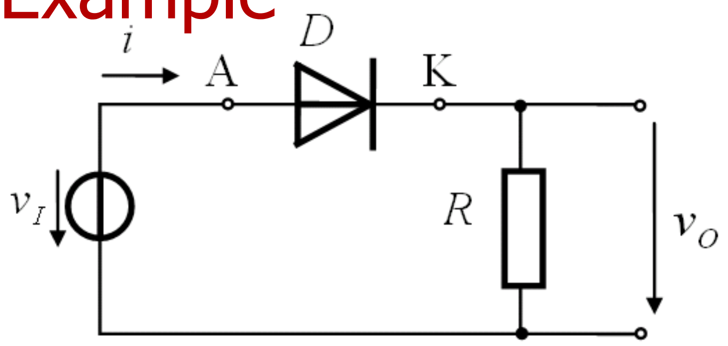
graphical illustration of $v_O(v_I)$

Steps for deducing the VTC:

- Take into account all possible situations that result from the combination of diode states (*on/off*)
- For each situation,
  - draw the equivalent circuit
  - find v_O
  - determine the range of v_I
- Plot the VTC.

Two-port DR networks analysis

Example



Deduce and plot VTC $v_O(v_I)$

Step 1. Write down KVL and Ohm's law for the circuit (circuit's equations)

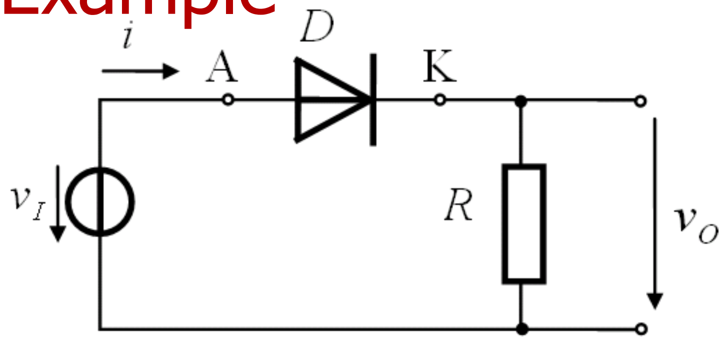
Step 2. Draw the equivalent circuits for D-(on) and D-(off)

Step 3. Find v_O and the range for v_I by replacing the diode's equations in the circuit's equations.

Step 4. Write down the complete expression of VTC $v_O(v_I)$ and plot it, for D-(on) and D-(off).

Two-port DR networks analysis

Example



Deduce and plot VTC $v_O(v_I)$

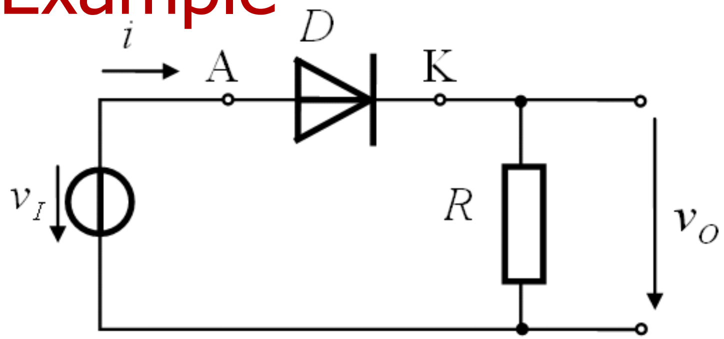
Step 1. Write down KVL and Ohm's law for the circuit (circuit's equations)

$$\boxed{\begin{array}{l} -v_I + v_D + v_O = 0 \\ v_O = i_D R \end{array}}$$

Always valid, regardless of the state of the diode!

Two-port DR networks analysis

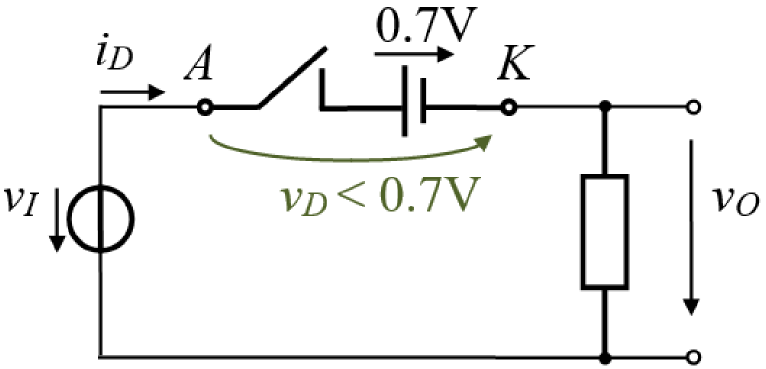
Example



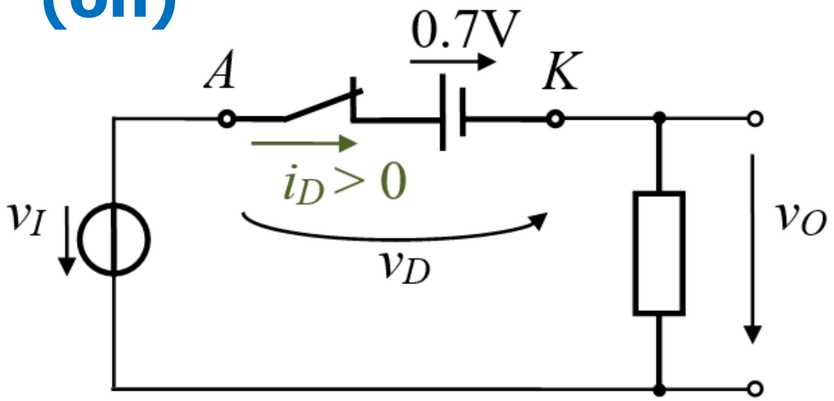
Deduce and plot VTC v_O (v_I)

Step 2. Draw the equivalent circuits for D-(on) and D-(off)

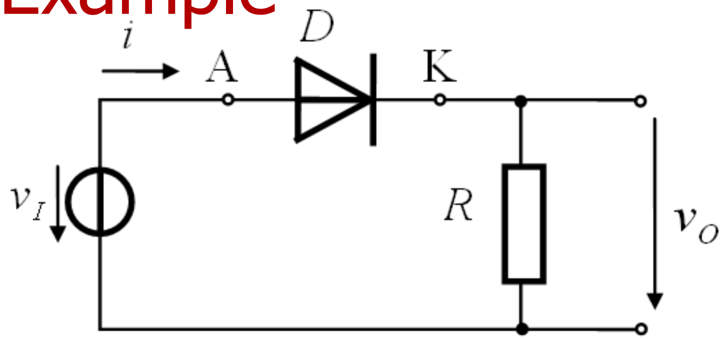
D – **(off)**



D – **(on)**



Example

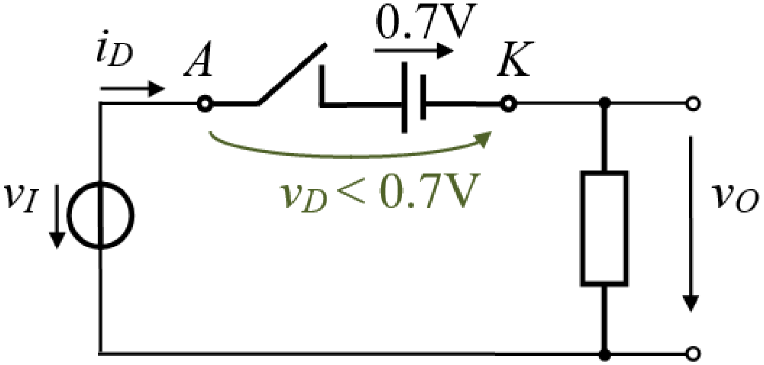


Deduce and plot VTC $v_O(v_I)$

Step 3. Find v_O and the range for v_I by replacing the diode's equations in the circuit's equations.

$$\boxed{\begin{aligned} -v_I + v_D + v_O &= 0 \\ v_O &= i_D R \end{aligned}}$$

D – (off) $\begin{cases} v_D < 0.7\text{V} \\ i_D = 0\text{A} \end{cases}$



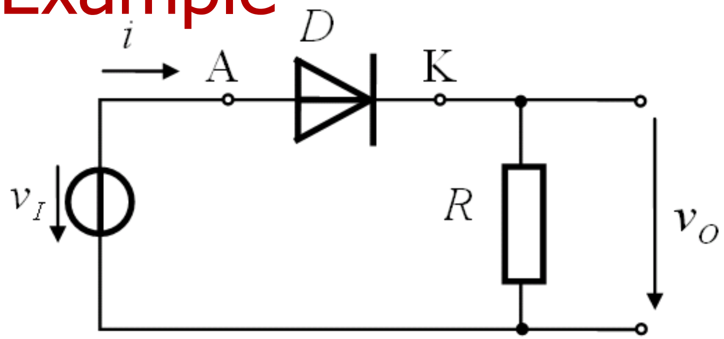
$$\boxed{v_O = i_D R = 0} \qquad \boxed{v_O = 0}$$

$$v_D = v_I - v_O \qquad v_D < 0.7 \qquad v_I - v_O < 0.7$$

$$v_I - 0 < 0.7 \qquad \boxed{v_I < 0.7\text{V}}$$

Example

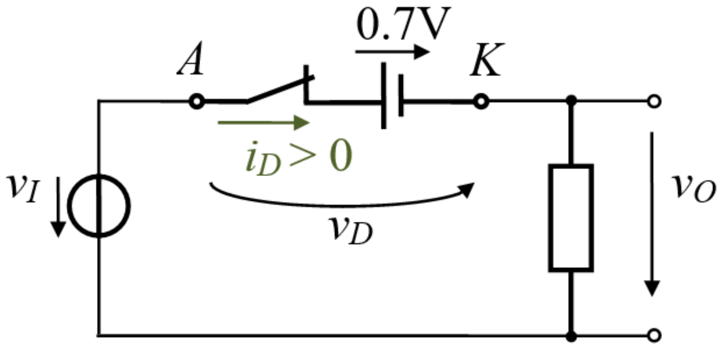
Deduce and plot VTC $v_O(v_I)$



Step 3. Find v_O and the range for v_I by replacing the diode's equations in the circuit's equations.

$$\boxed{\begin{array}{l} -v_I + v_D + v_O = 0 \\ v_O = i_D R \end{array}}$$

$D-$ (on) $\left\{ \begin{array}{l} v_D = 0.7\text{V} \\ i_D > 0\text{A} \end{array} \right.$



$$\boxed{-v_I + 0.7 + v_O = 0}$$

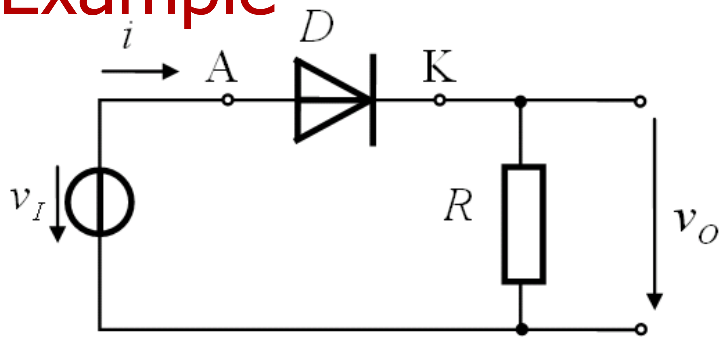
$$\boxed{v_O = v_I - 0.7}$$

$$i_D = \frac{v_O}{R} \qquad \frac{v_O}{R} > 0 \qquad v_O > 0$$

$$v_I - 0.7 > 0$$

$$\boxed{v_I > 0.7\text{V}}$$

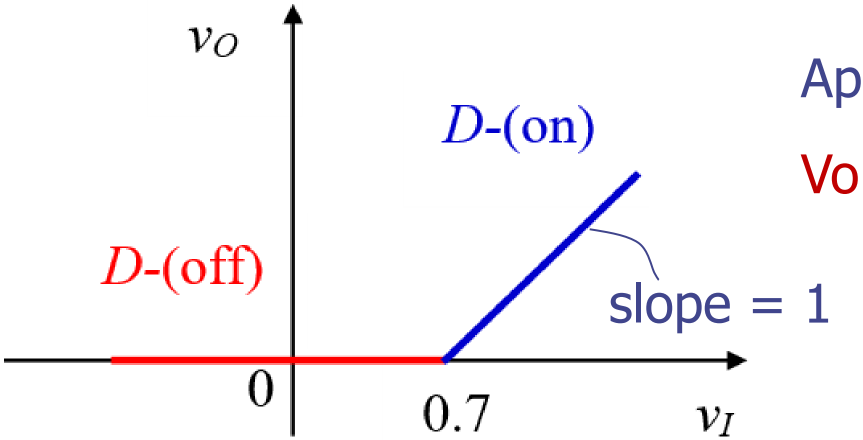
Example



Deduce and plot VTC $v_O\,(v_I)$

Step 4. Write down the complete expression of VTC $v_O\,(v_I)$ and plot it, for D-(on) and D-(off).

$$v_O = \begin{cases} 0, & v_I < 0.7\text{V} \\ v_I - 0.7\text{V}, & v_I > 0.7\text{V} \end{cases}$$

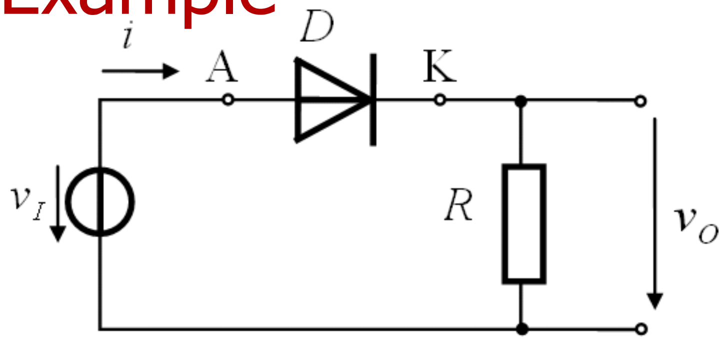


Application:

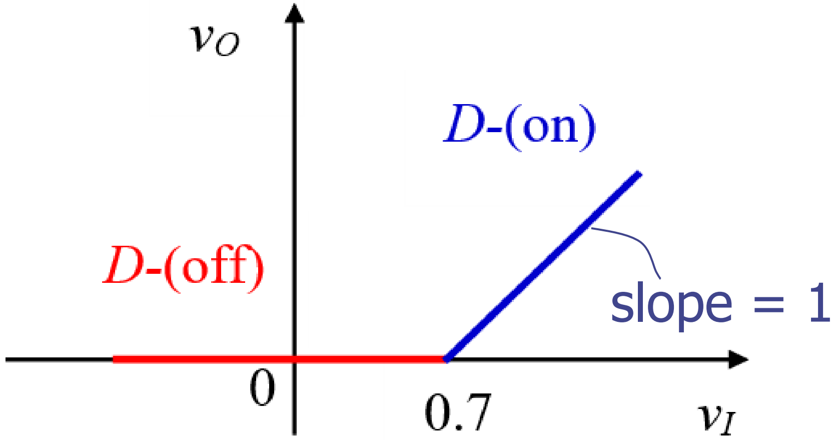
Voltage rectifier

Two-port DR networks analysis

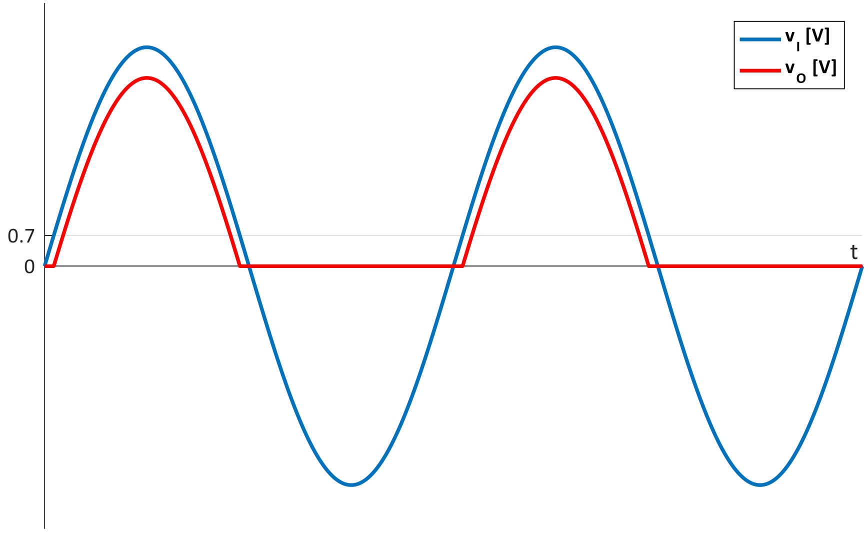
Example



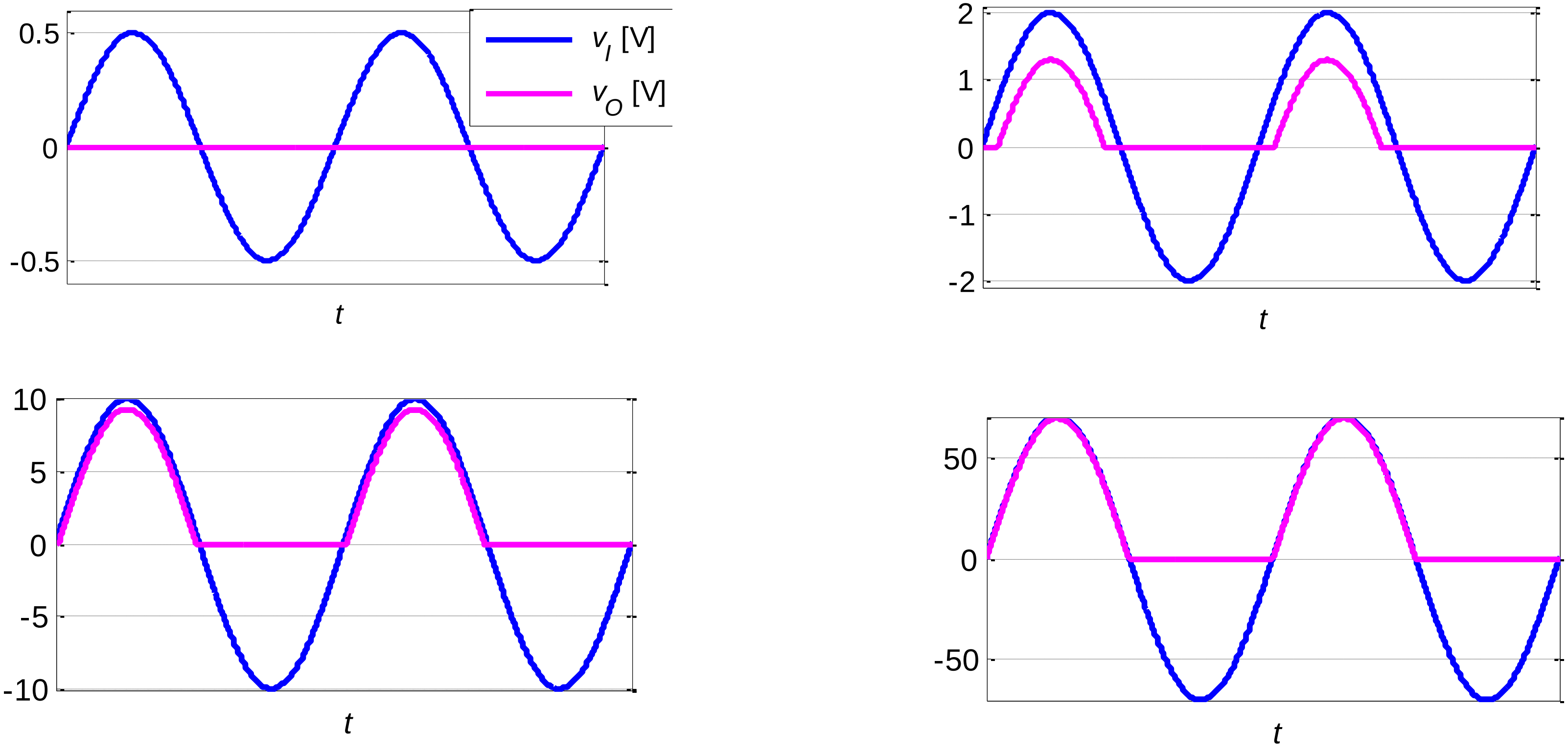
$$v_O = \begin{cases} 0, & v_I < 0.7\text{V} \\ v_I - 0.7\text{V}, & v_I > 0.7\text{V} \end{cases}$$



Waveforms



Influence of V_{Th} and $V_{D,on}$

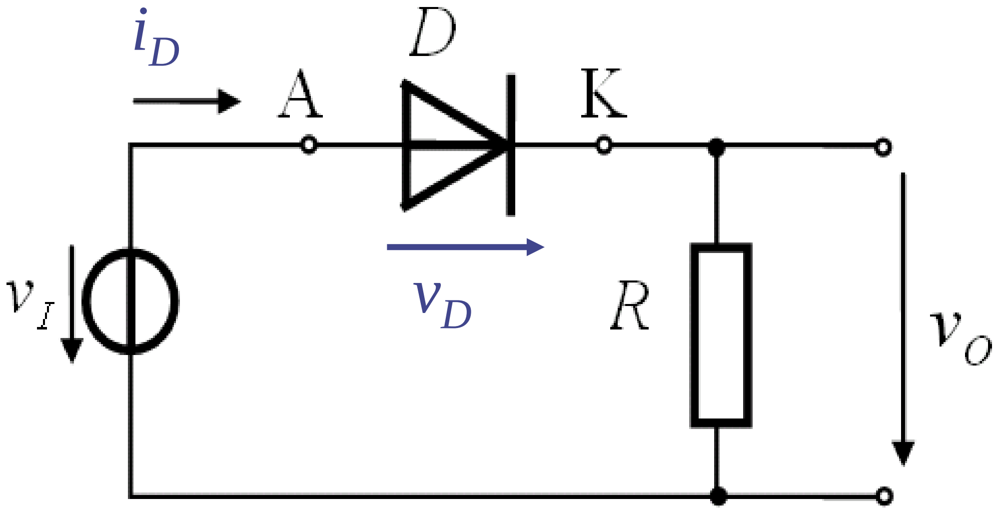


If the input voltage is large enough (**>>** 0.7 V)

- V_{Th} can be considered 0 V
- $V_{D,on}$ can be neglected, meaning that for D – (on), $v_O = v_I$

Two-port DR networks analysis

Example



a) Plot the output voltage if the input is a sine wave, 3 V amplitude.

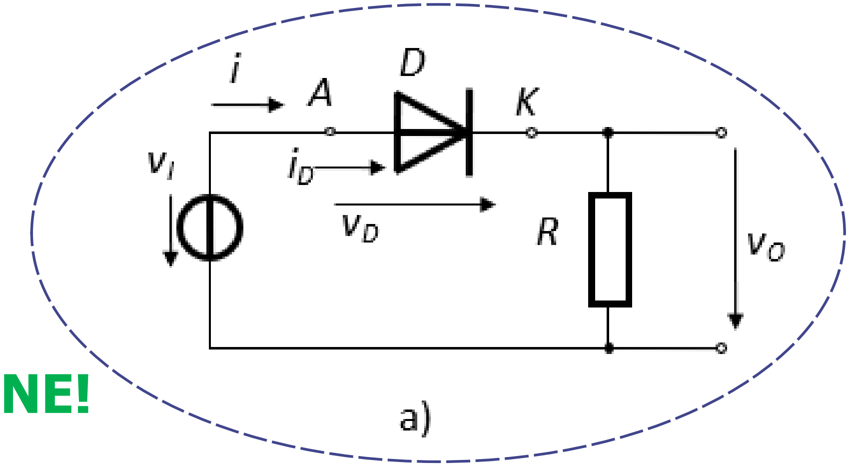
b) What is the peak forward current through D for R = 2 kΩ?

c) What is the peak reverse voltage V_{DR} across D (v_{DR}=- v_D)?

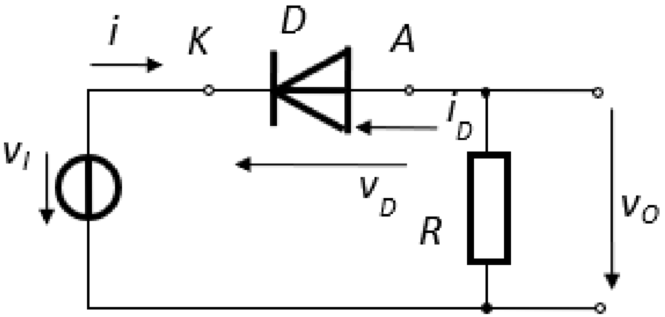
d) Repeat the above points, assuming the diode is reversed in the circuit.

Example – other versions of the simple DR circuit

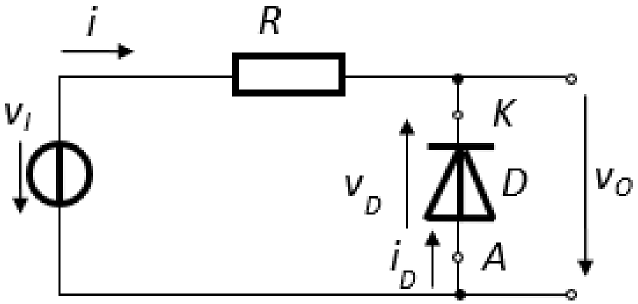
DONE!



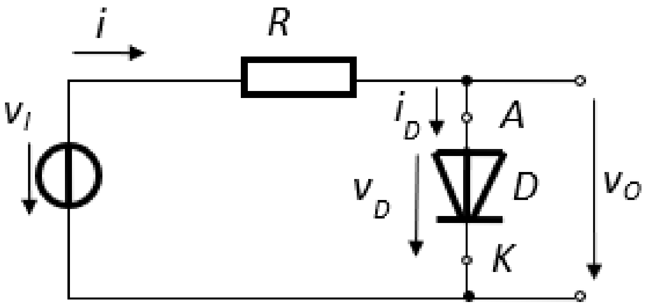
a)



b)



c)

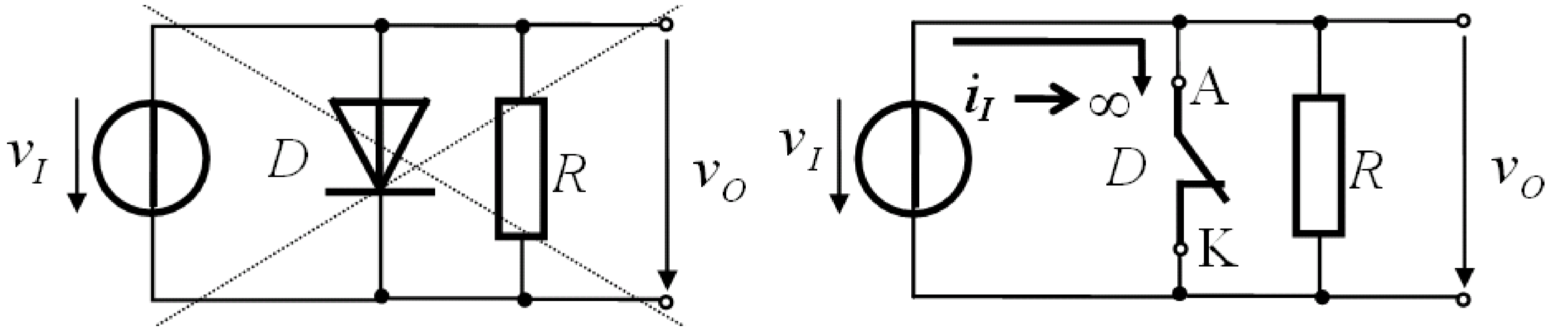


d)

Other series connections

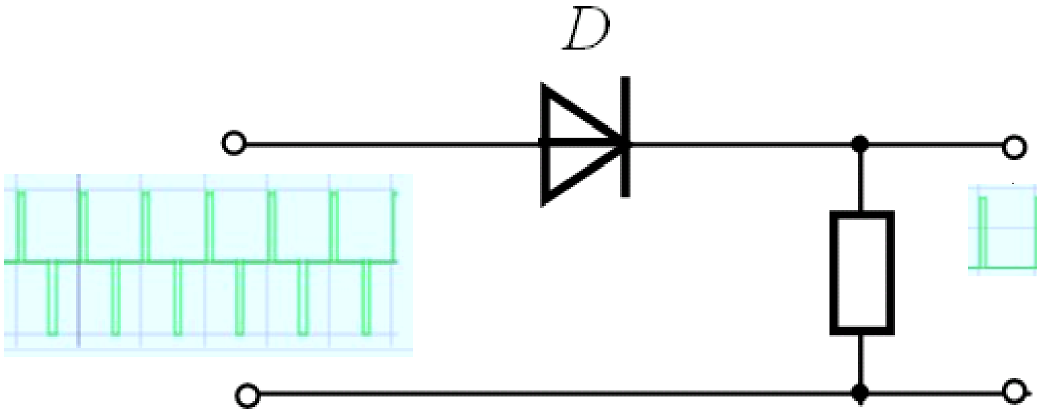
- Reverse the diode
- Change the places of D and R (output voltage collected from D)

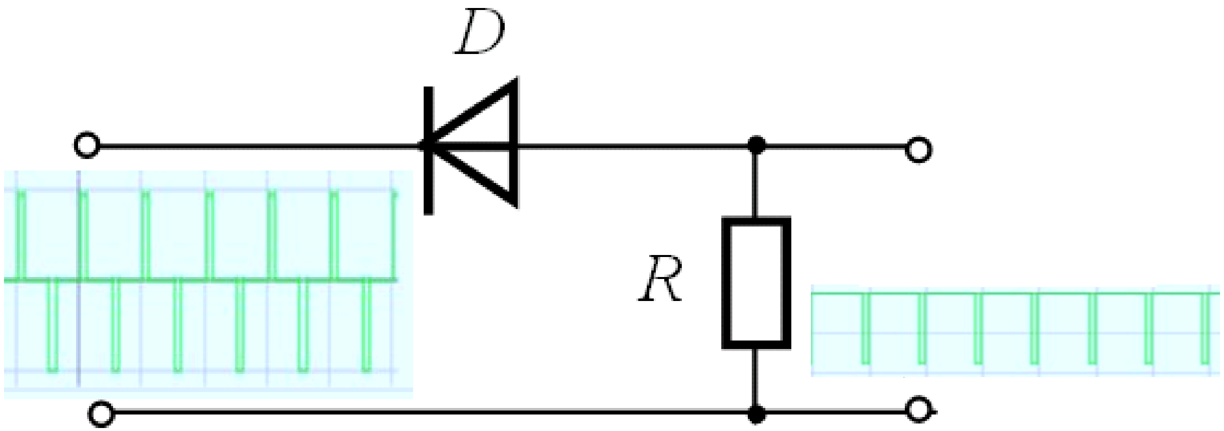
Forbidden connection!



Never connect a voltage source so that during normal operation, the source can be short-circuited.

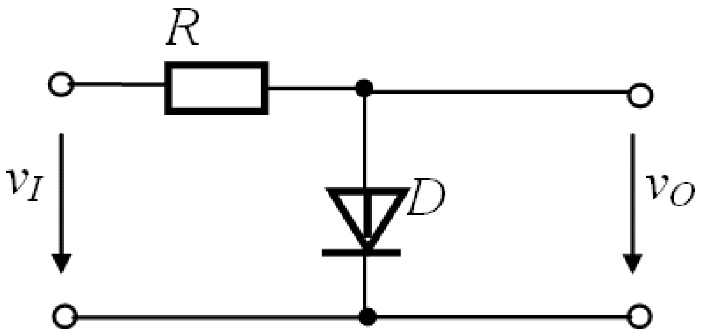
- Pulses selector

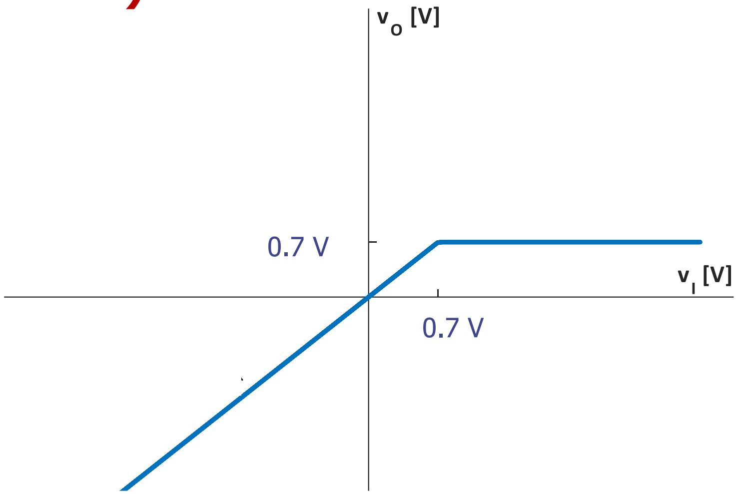




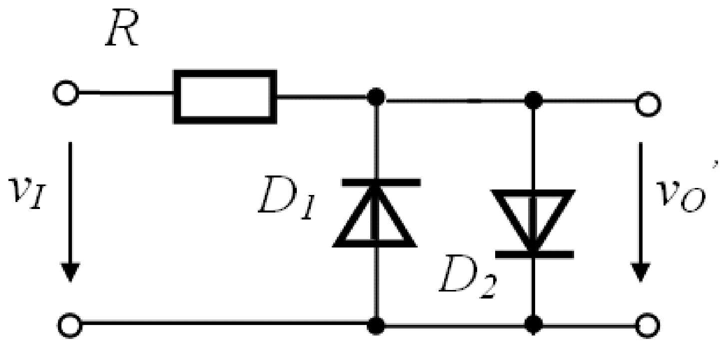
Voltage limiters (clamp networks)

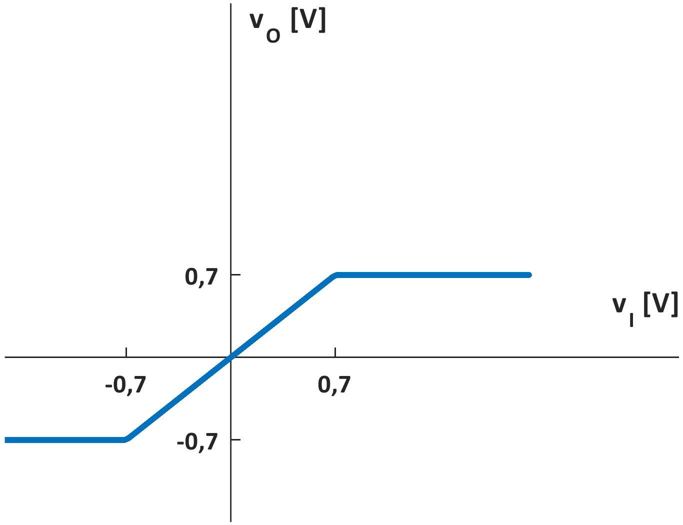
simple



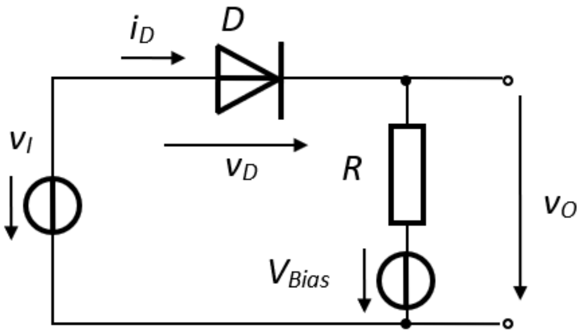


double





Voltage limiters (clamp networks)



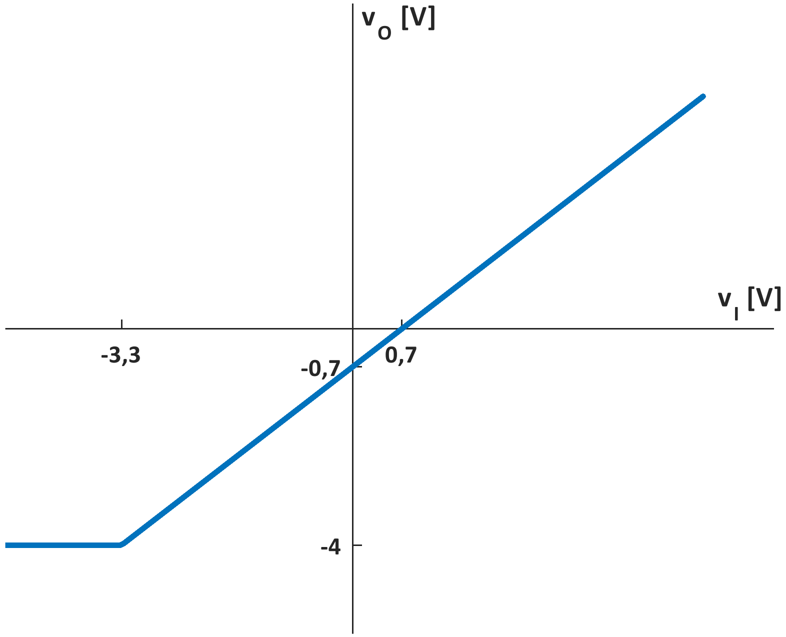
$V_{Bias} = -4$ V

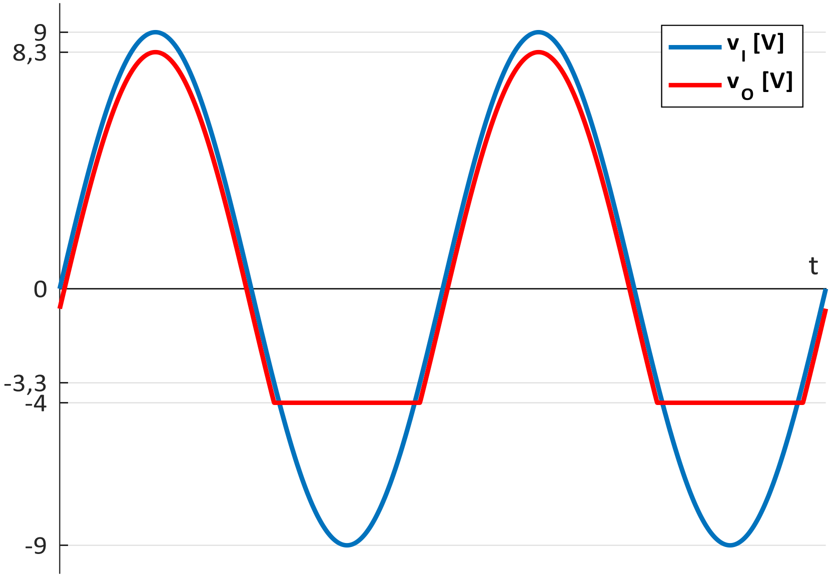
D - on

$v_O = v_I - 0.7$ V
$v_I > -3.3$ V

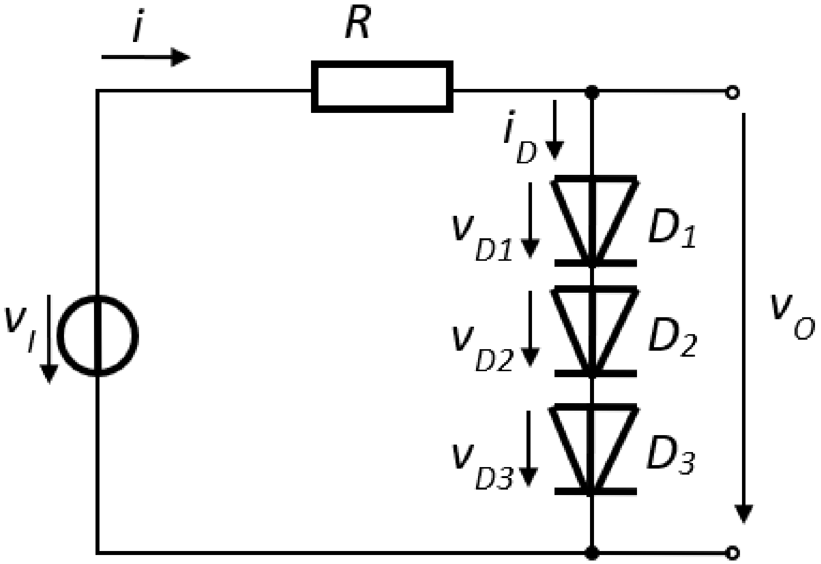
D - off

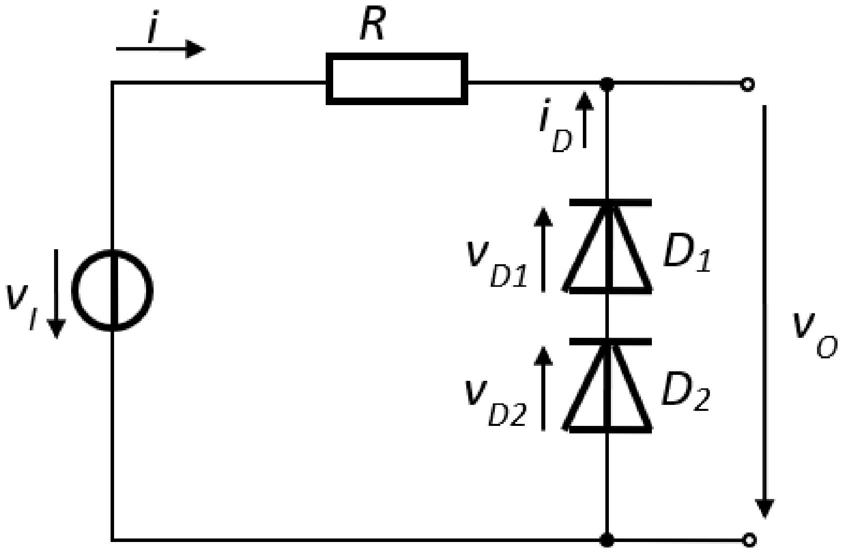
$v_O = -4$ V
$v_I < -3.3$ V





- Voltage limiters (clamp networks)





Summary

Our first encounter with the diode revealed details regarding:

- Physical structure. Symbol.
- Current-voltage characteristic
- Operating regions
- Parameters of the diode
- Constant voltage drop model
- Analysis of two-port DR networks

Next week: Multi-port DR circuits. DC switching circuits.