ELECTRONIC DEVICES

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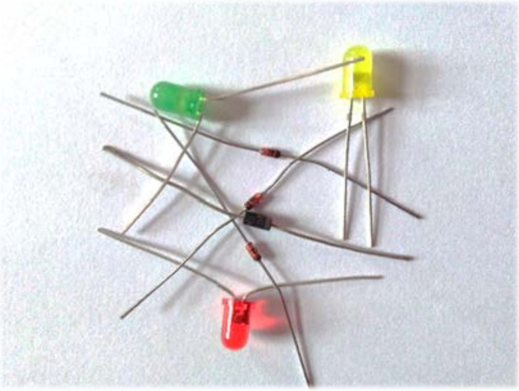
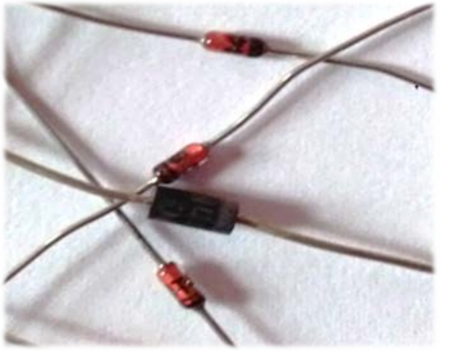
C2 – Diodes. DR circuits.



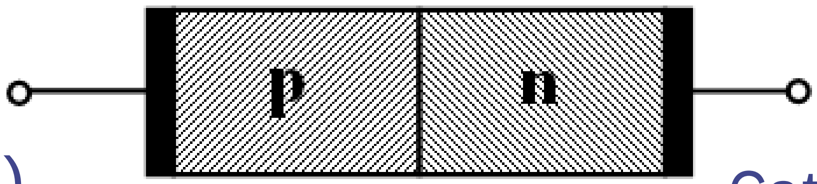
Contents

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

Physical structure. Symbol.



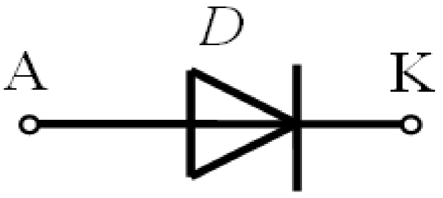
Physical structure – *pn* junction



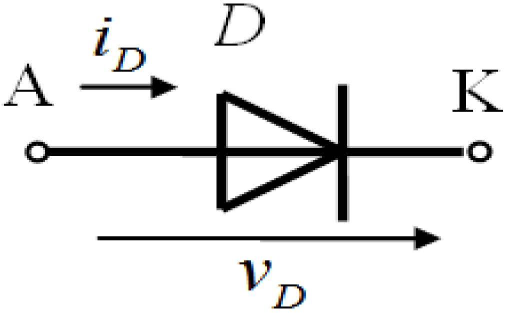
Anode (A)

Cathode (K)

circuit symbol



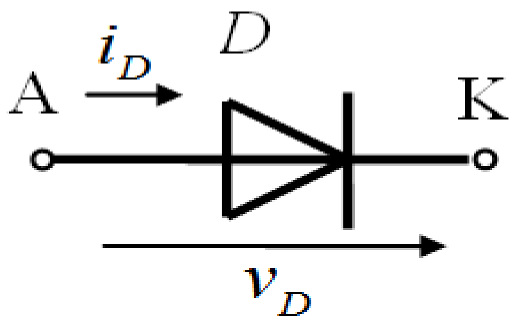
directions for current and voltage



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 equation – William Shockley (Bell Labs, 1950)

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

I_S - saturation current (~ nA - pA)

n=2 discrete diodes

n=1 integrated diodes

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

thermal voltage

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

K - Boltzmann's constant

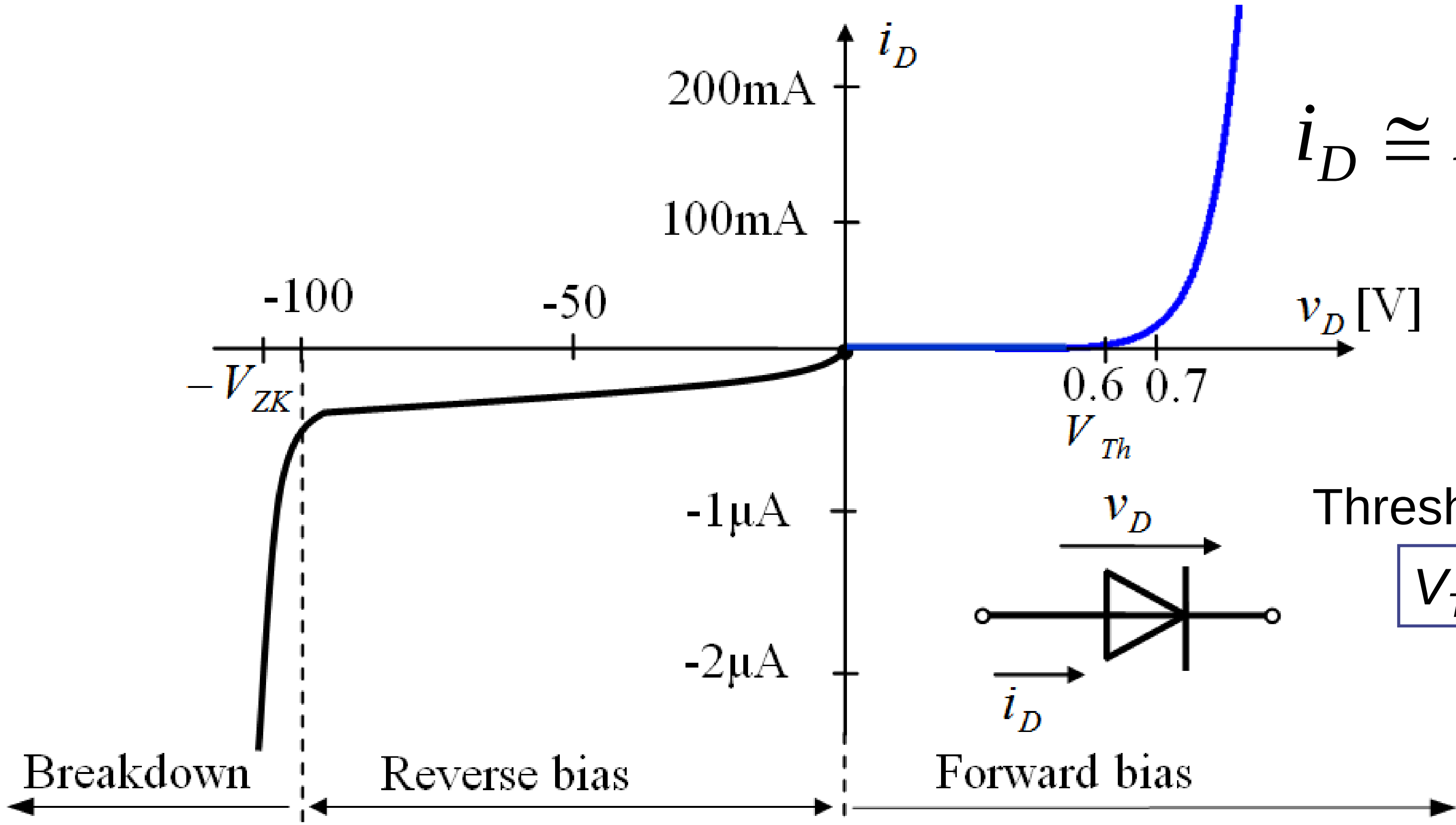
q – elementary charge (electric charge carried by a single electron)

T – absolute temperature measured in K

Current-voltage characteristic

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

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



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

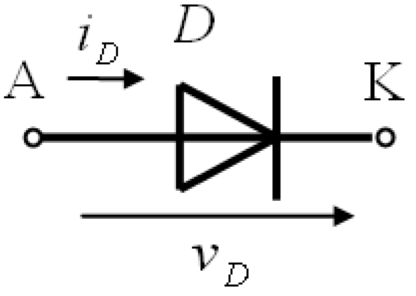
Threshold voltage

$V_{Th} \approx 0.6V$

!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

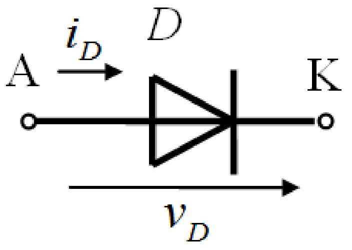
$$v_D = 0.7\text{V}$$

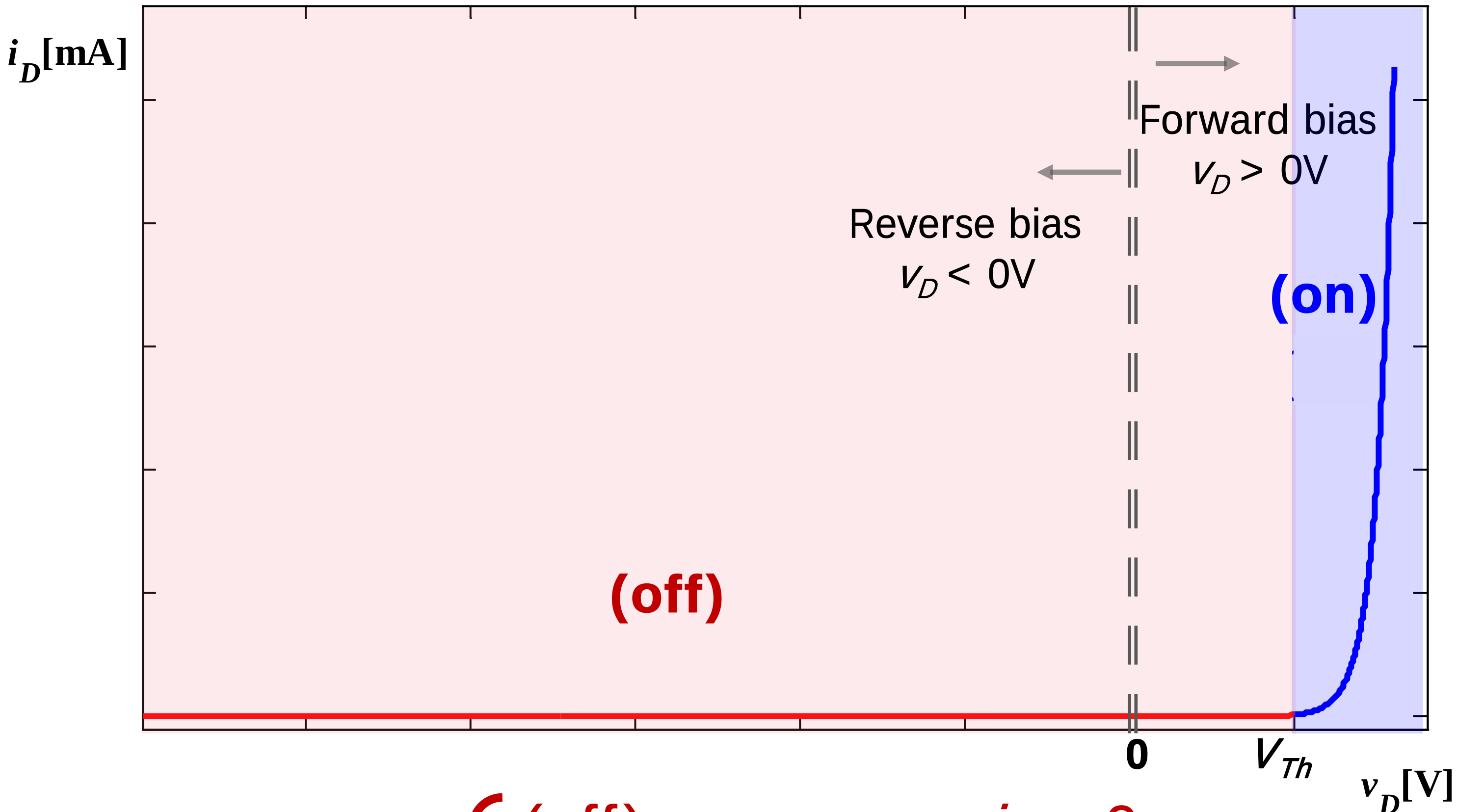
the current through the diode results as:

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

Operating regions

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





$V_{Th} \approx 0.6$ V

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

Operating (quiescent) point

$$Q(V_D; I_D)$$

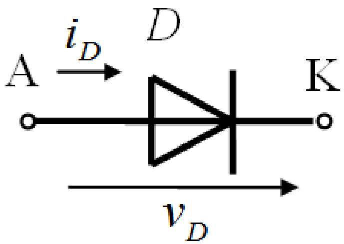
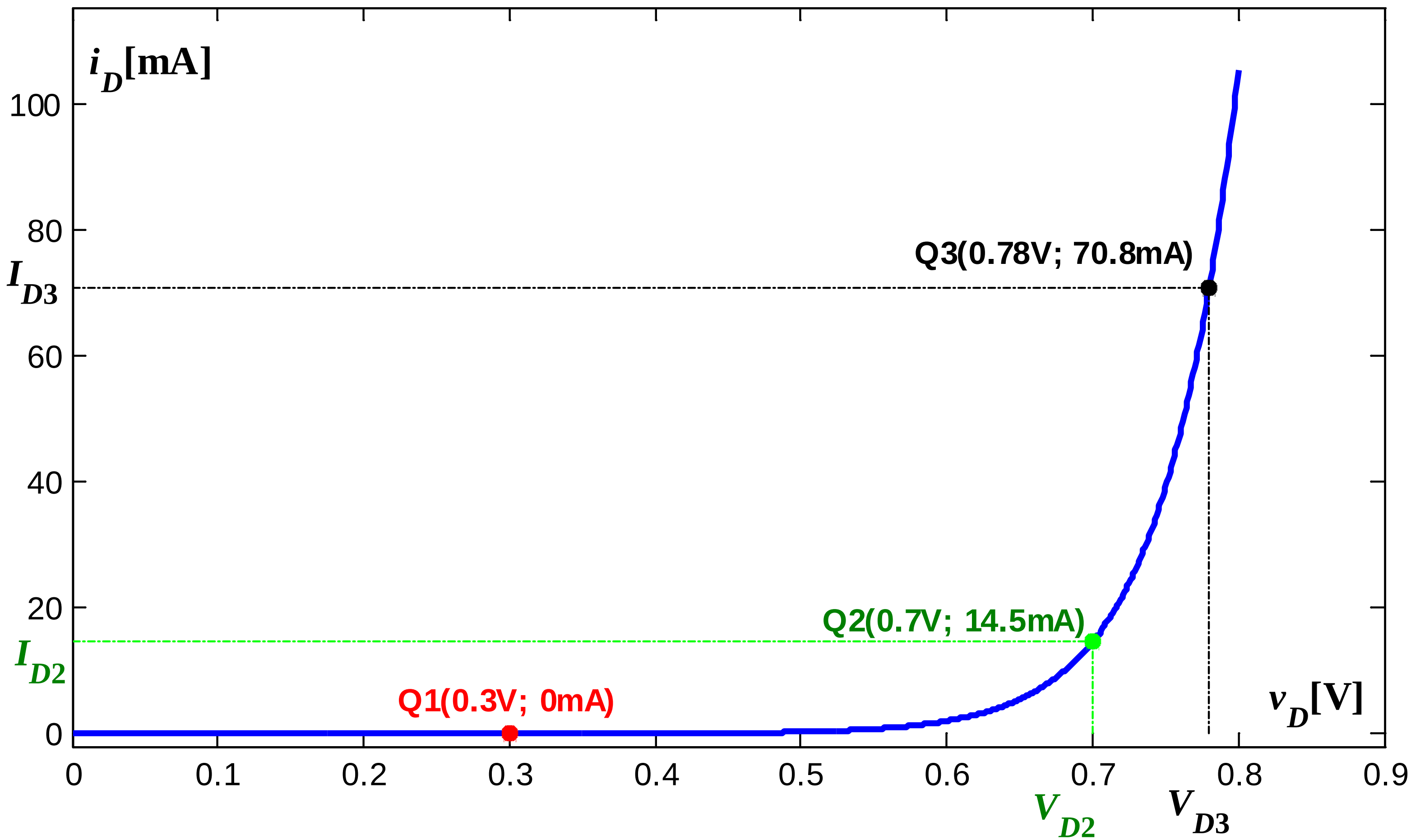


Illustration for 1N400x with I_S = 14 nA, n = 2

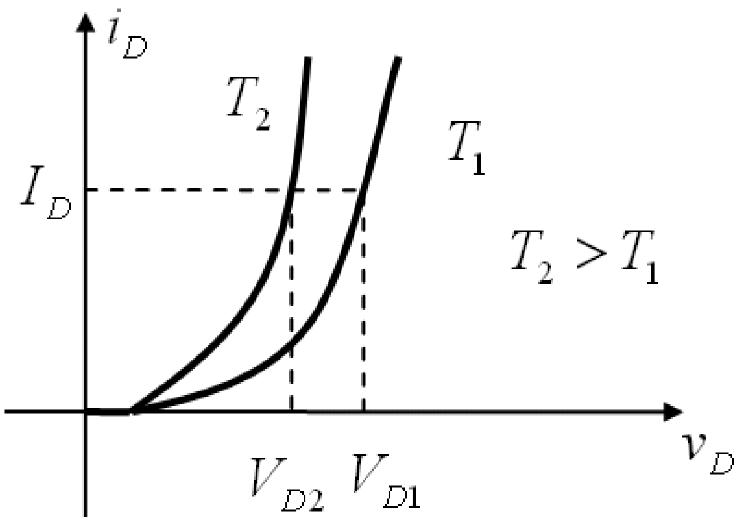


Temperature dependence

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

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

$20^{\text{O}}\,\text{C}$	$v_D = 650\,\text{mV}$
$40^{\text{O}}\,\text{C}$	$v_D = 610\,\text{mV}$

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

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

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
- Dynamic parameters – defined in variable regime (ac)

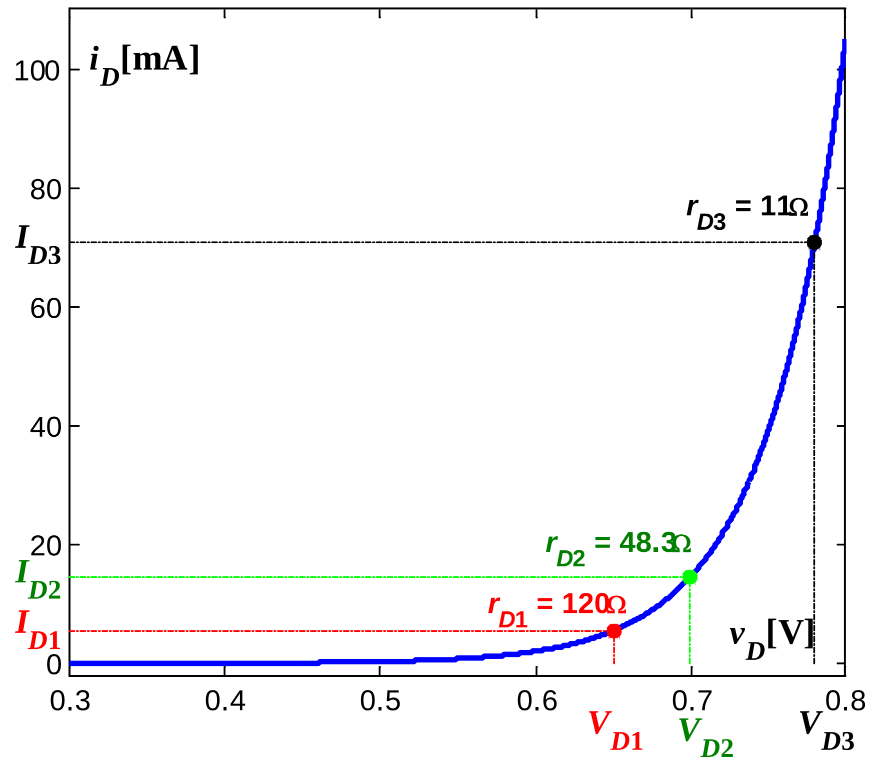
  a.k.a. small signal parameters
  - dynamic (small signal resistance) r_d

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:

$Q_1(0.65\text{V}; 5.4\text{mA})$ $$r_{D1} = \frac{0.65}{5.4} = 120\Omega$$

$Q_2(0.7\text{V}; 14.5\text{mA})$ $$r_{D2} = \frac{0.7}{14.5} = 48.3\Omega$$

$Q_3(0.78\text{V}; 70.8\text{mA})$ $$r_{D3} = \frac{0.78}{70.8} = 11\Omega$$

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

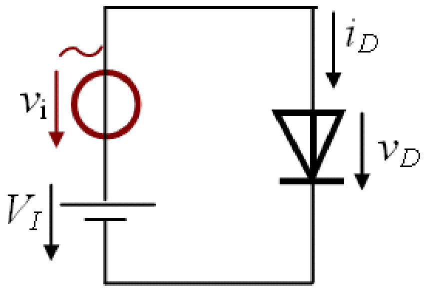
OPTIONAL

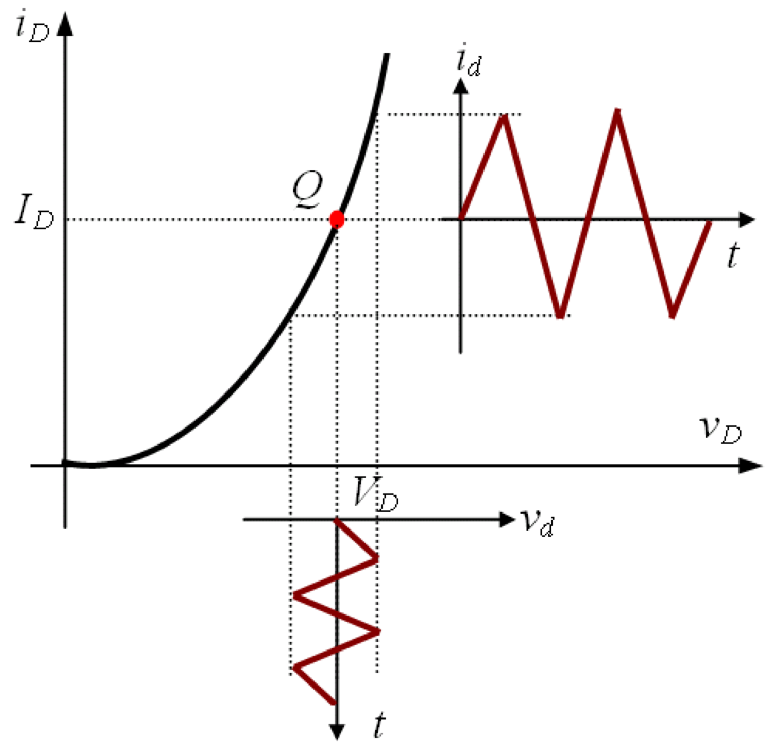
➢ Dynamic (small signal) parameters

A small ac signal is superimposed on the dc quantities

$$v_D(t) = V_D + v_d(t)$$

$$i_D(t) = I_D + i_d(t)$$





Dynamic (small signal) resistance:

$$r_d = \left.\frac{v_d}{i_d}\right|_Q \qquad r_d = \left.\frac{\delta v_D}{\delta i_D}\right|_Q$$

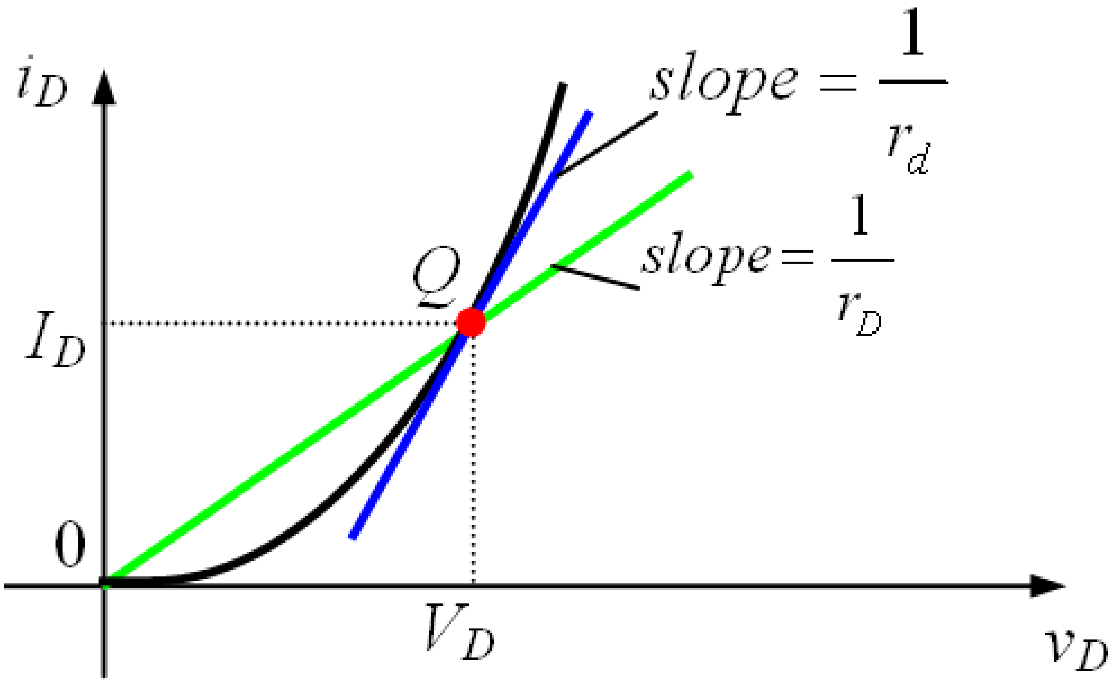
Small signal approximation:

linear region around Q

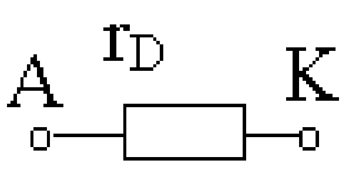
$$r_d = \frac{nV_T}{I_D}$$

OPTIONAL

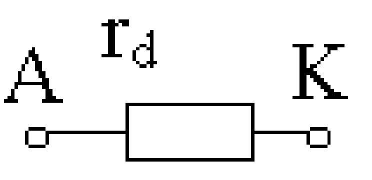
Interpretation of r_D and r_d



D modelling in the OP



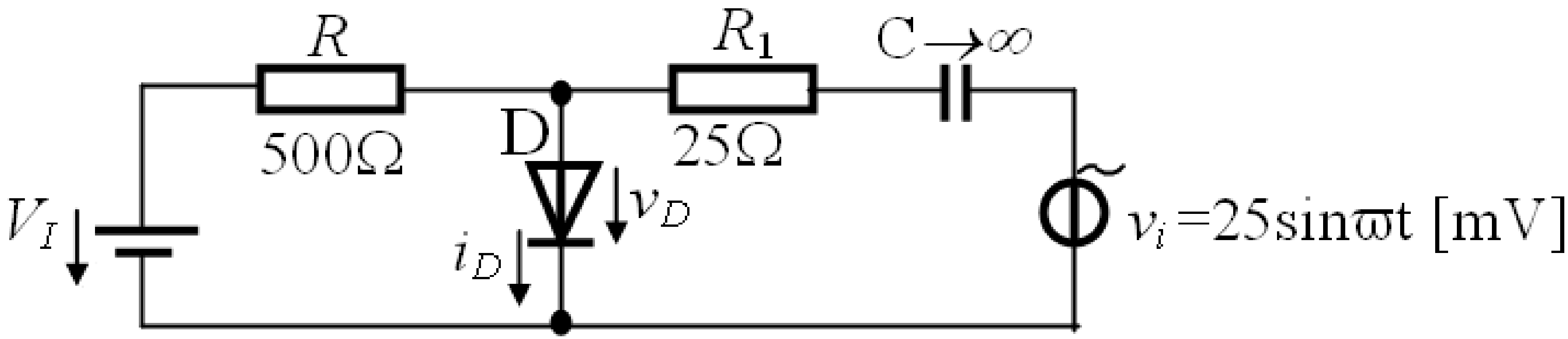
direct current



small signal variation

OPTIONAL

Example



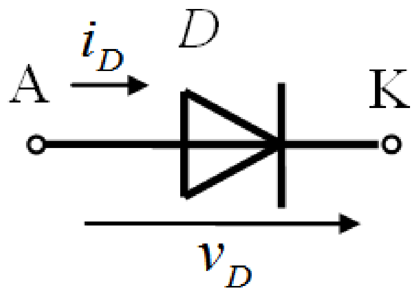
a) Draw the dc equivalent circuit.

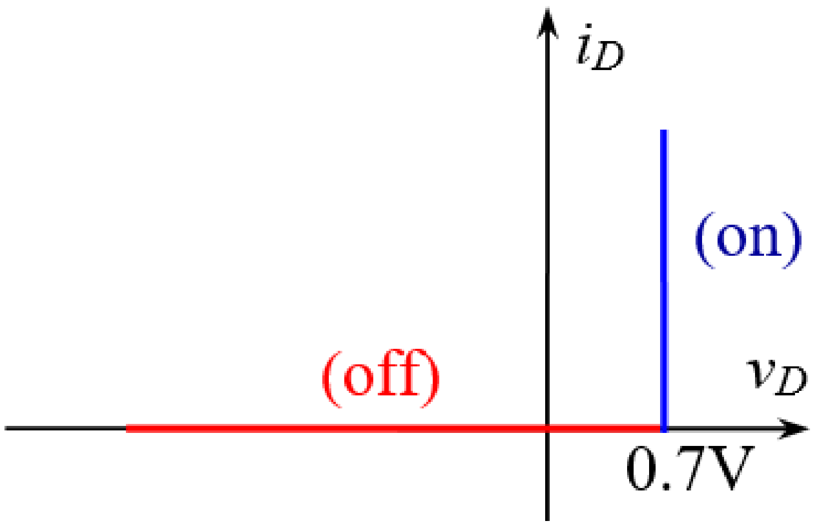
b) Assuming Q(0,64V; 4,7mA), what is the value of the static resistance?

c) Draw the small-signal equivalent circuit.

d) What is the value of the small-signal resistance in Q?

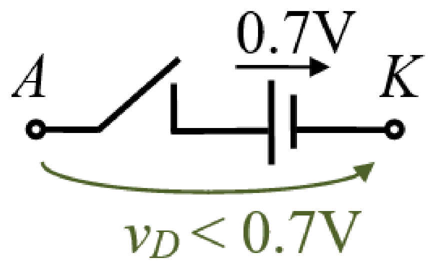
Constant voltage drop model





$v_D < 0.7$ V

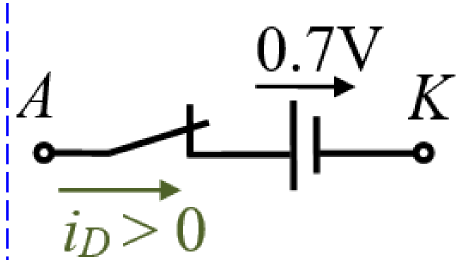
D – **(off)**



$$\begin{cases} v_D < 0.7 \text{ V} \\ i_D = 0 \end{cases}$$

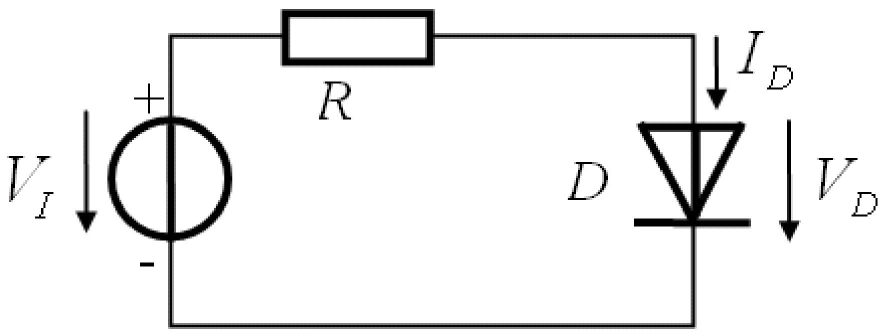
$v_D > 0.7$ V

D – **(on)**



$$\begin{cases} v_D = 0.7 \text{ V} \\ i_D > 0 \end{cases}$$

➢ Circuit with a dc voltage source and a resistor



Compute $Q(V_D, I_D)$

Diode equation: $I_D = I_S e^{\frac{V_D}{nV_T}}$

KVL: $V_I = I_D R + V_D$

$$\Rightarrow V_I - V_D = R I_S e^{\frac{V_D}{nV_T}}$$

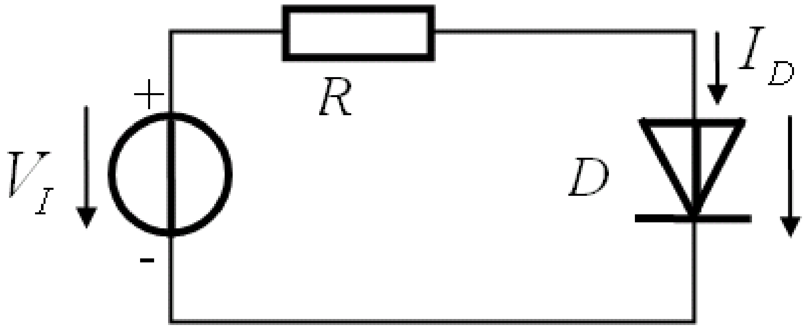
Transcendental equation

Two solving methods:

1. Graphical method

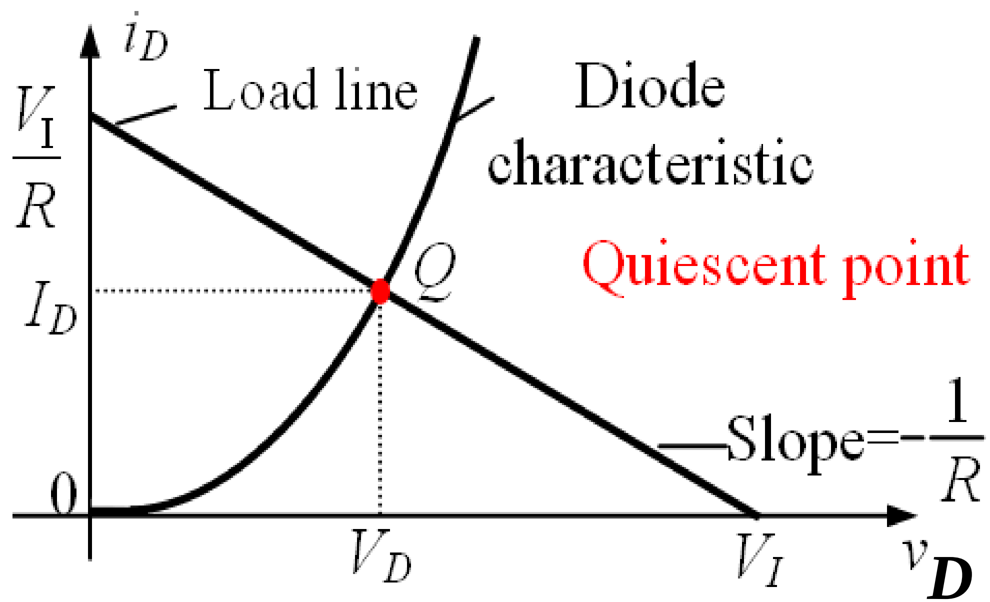
2. Numerical method (successive approximation)

- Graphical method



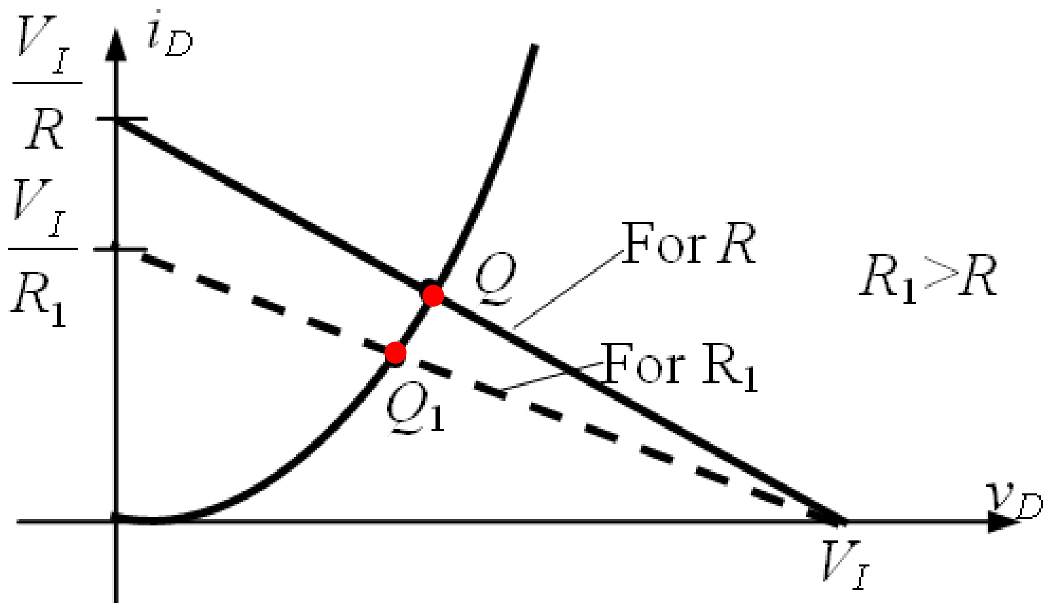
Diode equation: $$I_D = I_S e^{\frac{V_D}{nV_T}}$$

KVL
(load line equation): $$V_I = I_D R + V_D$$

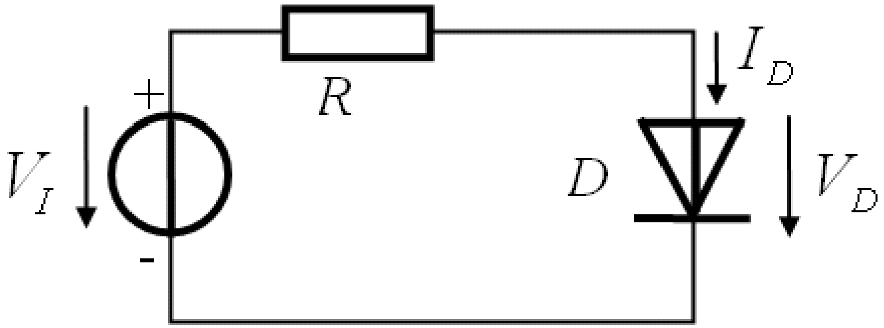


➢ Graphical method

Effect of *R* on the quiescent point, Q



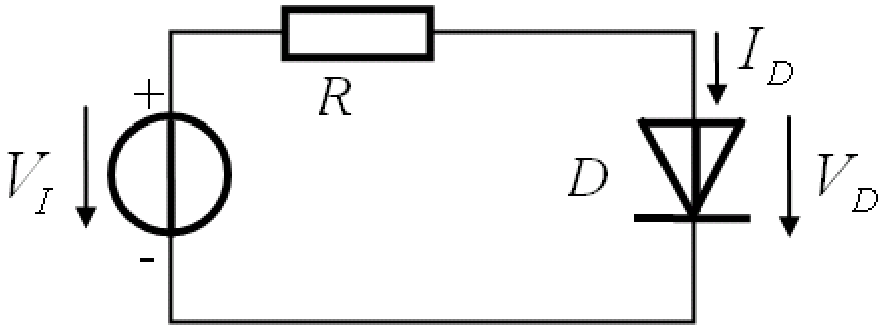
➢ Numerical method - simplified



Assume the voltage drop across the diode V_D = **0.7 V** and compute the current I_D using the load line equation

$$V_D = 0.7V \qquad I_D = \frac{V_I - V_D}{R}$$

Example



V_I = 9 V, R = 0.5 KΩ

What is the operating (quiescent) point Q of the diode D?

$V_D > 0.6\text{V}$ $\quad D-(\text{on})$

Assume V_D **= 0.7 V** across the conducting diode

$$I_D = \frac{V_I - V_D}{R} \qquad I_D = \frac{9-0.7}{0.5} = 16.6\text{mA} \qquad \boxed{Q(0.7\text{V}, 16.6\text{mA})}$$

OPTIONAL

Numerical method - iterative

1. Consider an initial value of diode voltage, eg. $V_D^{(0)} = 0.7$ V and compute current $I_D^{(0)}$ using the load line equation

$$(V_D^{(0)}, I_D^{(0)}) \text{ – initial solution}$$

2. Using $I_D^{(0)}$, compute voltage $V_D^{(1)}$ from diode equation, then current $I_D^{(1)}$ from the load line equation

$$(V_D^{(1)}, I_D^{(1)}) \text{ – solution after first iteration}$$

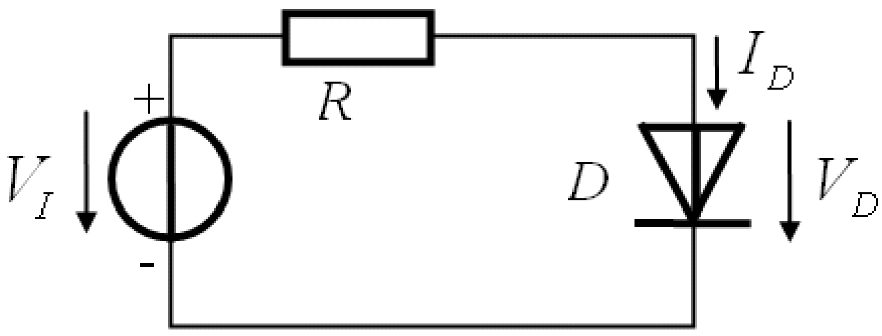
Repeat step **2** if more accurate values are required.

For quick, first order analysis of the circuit,

the **initial solution** is considered!

OPTIONAL

Example



V_I =3 V, R = 0.5 KΩ,

D is 1N400x , I_S = 14 nA, n =2.

What is the operating (quiescent) point Q of diode D?

Quick, first order analysis:

$V_D > 0.6\text{V}$ D – (on)

Assume V_D **= 0.7 V** across the conducting diode

$$I_D = \frac{V_I - V_D}{R} \qquad I_D = \frac{3-0.7}{0.5} = 4.6\text{mA} \qquad Q(0.7\text{V},\ 4.6\text{mA})$$

OPTIONAL

Example

Detailed analysis

$$I_D = \frac{V_I - V_D}{R} \qquad I_D = I_S e^{\frac{V_D}{nV_T}} \qquad V_D = nV_T \ln\frac{I_D}{I_S}$$

Step 1

$$V_D^{(0)} = 0.7\text{V} \qquad I_D^{(0)} = \frac{3-0.7}{0.5} = 4.6\text{mA}$$

Step 2

$$V_D^{(1)} = n \cdot V_T \cdot \ln\frac{I_D^{(0)}}{I_S} = 2 \cdot 0.025 \cdot \ln\frac{4.6\text{mA}}{14\text{nA}} = 0.635\text{V}$$

$$I_D^{(1)} = \frac{V_I - V_D^{(1)}}{R} = \frac{3-0.635}{0.5} = 4.73\text{mA}$$

Step 3

$$V_D^{(2)} = n \cdot V_T \cdot \ln\frac{I_D^{(1)}}{I_S} = 2 \cdot 0.025 \cdot \ln\frac{4.73\text{mA}}{14\text{nA}} = 0.637\text{V}$$

$$I_D^{(2)} = \frac{V_I - V_D^{(2)}}{R} = \frac{3-0.637}{0.5} = 4.726\text{mA}$$

$$Q(0.637\text{V}; 4.726\text{mA})$$

Summary

Our first encounter with the diode revealed details regarding:

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

Next week: DR switching circuits.