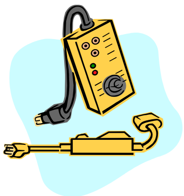
# SEMICONDUCTOR DIODES

## I. OBJECTIVES

a) The determination of the current-voltage characteristics for the rectifying diodes;
b) The determination of some static and differential parameters;



## II. COMPONENTS AND INSTRUMENTATION

For the experiments you will use Si diodes: a 1N400x rectifying diode; resistances with different values. The dc voltage is obtained from a double regulated power supply and the sinusoidal voltage (with variable amplitude and frequency) is obtained from a signal generator. To visualize the variable voltages and the diodes' characteristics you will use a dual channel oscilloscope. You will also use a multimeter or even two if necessary.


## III. THEORETICAL ASPECTS

### 1. The current-voltage characteristic of the diode

The current-voltage characteristic of the diode is plotted in Fig. 1. for a semiconductor diode made of silicon. The same characteristic is re-plotted in Fig. 2. with the expanded negative current scale and the compressed negative voltage scale to emphasis certain details. Remark that these changes of scale create o certain discontinuity in the origin.

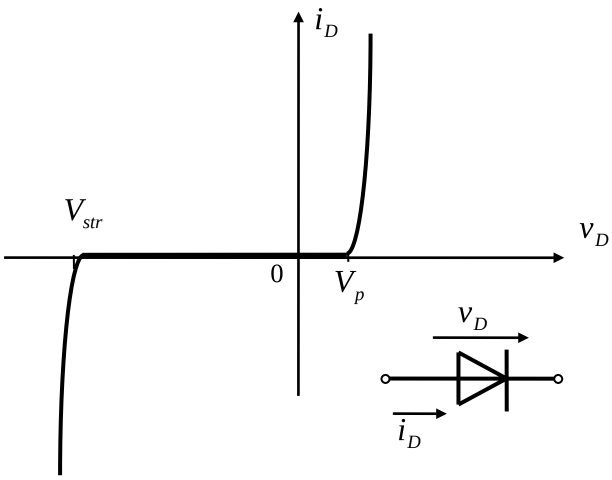



Fig. 1. The current-voltage characteristic of the silicon diode.

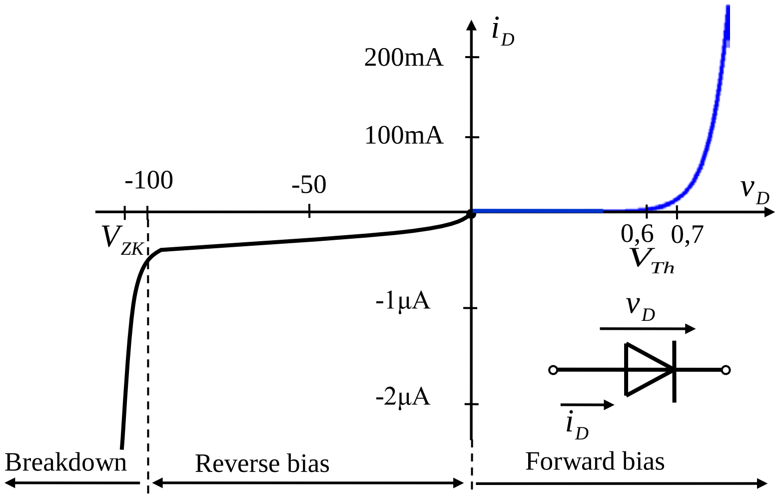



Fig. 2. Current-voltage characteristic of the silicon diode. Expanded negative current scale and compressed negative voltage scale.

The numeric values on the graphic are purely informative, for a small power diode. As one can observe on the graphic there are three distinct regions:

- Forward bias, $v_D > 0$
- Reverse bias, $-V_{ZK} < v_D < 0$,
- Breakdown, $v_D < -V_{ZK}$

- **Forward bias**

For the region of forward bias, $v_D > 0$, the current-voltage relation $i_D - v_D$ is closely approximated by the exponential equation:

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

$I_S$ - *saturation current* – is equal with the absolute value of the current through the diode in reverse biasing. It has a very low value, its order of magnitude being of nA, pA. The value of $I_S$ is a very strong function of temperature. As a rule of thumb, it can be said that $I_S$ doubles in value for every $5^{O}$C rise in temperature.

$V_T$ - is a constant called the *thermal voltage* given by:

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

where $K = 1.38 \cdot 10^{-23}$ j/K – the Boltzman constant

*T*=absolute temperature in [K]

$q = 1.602 \cdot 10^{-19}$ C – the magnitude of electronic charge

At room temperature ($\approx 20°$ C), $V_T = 25.2$ mV. In rapid, approximate circuit analysis we shall consider $V_T = 25$ mV,

*n* – a constant that depends of the material and of the physical structure of the diode. In general we can consider *n*=2 for discrete diodes and *n*=1 for diodes from integrated circuits.

For currents $i_D >> I_S$ the exponential equation of the diode can be approximated by:

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

A glance at the $i_D - v_D$ characteristic reveals that we have a negligible small current for $v_D$ smaller than about 0.5V, after than the current considerably increases with the voltage. This value is called *threshold voltage* $V_{th}$=0.5V, or cut-in voltage. Anyway this value results as a consequence of the exponential relation. The voltage drop on a diode in permanent conduction lies in a narrow range, approximately 0.6V to 0.8 V for the low power diodes.

- **Reverse Bias**

The diode is reverse biased for $v_D < 0$. From the exponential equation of the diode results that for $v_D$ negative and few times larger, in absolute value, than $V_T$, the exponential term becomes negligible small compared to 1, the current through *D* becoming:

$$i_D \cong -I_S$$

Anyway, compared with the values of $i_D$ for conducting diode (forward bias), the reverse current may be considered zero.

- **Breakdown**

The breakdown of the diode takes place when the value of the reverse voltage increases over a certain value specific to every type of diode, value called *breakdown voltage* and denoted $-V_{ZK}$. This is the voltage at the knee of the characteristic, in the III$^{rd}$ quadrant, (Fig. 1. and Fig. 2.).

The reverse current in the breakdown region increases very fast with the $v_D$ voltage. Normally, the breakdown is not a destructive phenomenon by itself. But the diode can be destroyed by power dissipation, if the extern circuit does not limit the current at a safe value. That is why in practice it is avoided the use of a diode in a circuit in which the breakdown voltage may be exceeded. By the way of exception we mention here the Zener diodes which are specially manufactured to operate in the breakdown region as voltage regulators.

## 2. Parameters of the diode

To describe the behavior of the diode we can use the parameters of the diode defined by the ratio of two signals. We distinguish the static parameters and the dynamic (or small signal) parameters.

### 2.1. Static parameters

For the static regime (dc regime) we define the *static resistance* of the diode in the quiescent point:

$$r_D = \frac{V_D}{I_D}$$

The static resistance depends on the operation point Q, its value decreasing with the upward movement of the Q on the diode curve. The stronger the biasing of the diode the smaller is the value of $r_D$. The inverse of the static resistance is the static conductance $g_D$

$$g_D = \frac{1}{r_D} = \frac{I_D}{V_D}$$

### 2.2. Dynamic parameters

Let us consider the conceptual circuit in Fig. 3.a) and the corresponding graphical representation in Fig. 3 b).

The diode is biased in the quiescent point $Q$ $(V_D, I_D)$ through the dc voltage source $V_I$ ($V_D = V_I$). A time-varying signal $v_i(t)$ with a triangle waveform is superimposed on the $V_I$ dc voltage. The instantaneous voltage across the diode will be given by:

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

Correspondingly, the total instantaneous current will be:

$$i_D(t) = I_S e^{\frac{v_D}{nV_T}} = I_S e^{\frac{V_D + v_d}{nV_T}}$$

$$i_D(t) = I_S e^{\frac{V_D}{nV_T}} \cdot e^{\frac{v_d}{nV_T}}$$

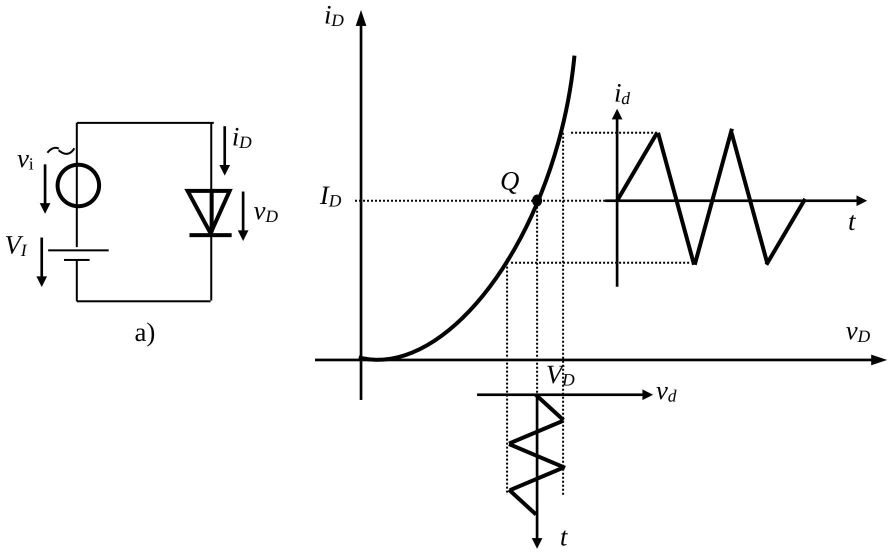



Fig. 3. The superposition of the variable quantities on the dc quantities:
a) circuit; b) graphical representation

Using the relationship: $I_D = I_S e^{\frac{V_D}{nV_T}}$

we obtain: $i_D(t) = I_D e^{\frac{v_d}{nV_T}}$

If the amplitude $\hat{V}_d$ of the signal $v_d(t)$, is sufficiently small such that:

$$\frac{\hat{V}_d}{nV_T} << 1$$

the previous exponential equation can be expanded in Taylor series and keeping the first two terms of the expansion we have:

$$i_D(t) \cong I_D + I_D \frac{v_d(t)}{nV_T}$$

This is the *small-signal approximation***.** The amplitude $\hat{V}_d$ of the signals for which the approximation holds is:

$$\hat{V}_D << nV_T$$

If by "<<" we understand for example 5 times smaller and we consider $n$=2 and $V_T$ =25 mV, the small signal approximation means $\hat{V}_D < 10$ mV.

$$i_D(t) \cong I_D + \frac{I_D}{nV_T} v_d(t)$$

The instantaneous current through the diode is:

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

where $$i_d(t) = \frac{I_D}{n \cdot V_T} \cdot v_d(t)$$

The quantity $\frac{I_D}{nV_T}$ has the dimension of a conductance and it is called the *small-signal conductance* $g_d$ or the dynamic conductance. Its inverse is the *small-signal resistance* or dynamic resistance:

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

Take notice of the fact that $r_d$ is defined in each quiescent point and that its value decreases with the increases of the biasing current.

On the graphical representation in Fig. 2.5.7b) we observe that the *small signal approximation is equivalent with the assumption that the signal amplitude is sufficiently small such that the swing around the quiescent point is limited to an almost linear segment*. The slope of this segment is equal to the dynamic conductance of the diode in that point.

Another method to define the dynamic resistance is:

$$r_d = \left.\frac{dv_D}{di_D}\right|_Q$$

# IV. PREPARATION

## 1. P. TESTING THE DIODES

The ohmmeter is quite useful for the quick analysis of diodes with junctions because the ohmmeter's equivalent circuit contains a voltage source (a battery) and a resistance.

- With the ohmmeter set on the diodes symbol, what should be on the display of ohmmeter, if the positive lead of the instrument is connected to the anode of the diode and the negative lead is connected to the cathode of the diode? What is the state of diode in this case?

## 2. P. RECTIFYING DIODES

### 2.1. P. CURRENT- VOLTAGE CHARACTERISTIC $i_D(v_D)$

- How does the $i_D(v_D)$ characteristic of a diode look like?

The IN400x diodes are characterised by the equation:

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

$$I_s = 2.3 * 10^{-9}\ \text{A}$$

$$n \cong 2$$

$$V_T = 25\ \text{mV, at } 27^0\ \text{C}$$

- In the points from the diode's characteristics in which $I_{D1}$ = 30 mA and $I_{D2}$ = 100 mA, compute the values of the static resistances, using the formulas:

$$r_{D1} = \frac{V_{D1}}{I_{D1}} \quad \text{and} \quad r_{D2} = \frac{V_{D2}}{I_{D2}}$$

- What are the values of the differential resistance ($r_{d1}$ and $r_{d2}$) in the same points as before?

$$r_d = \frac{\Delta V_D}{\Delta I_D}$$

For each of two above operating points you will consider another one, close by. For example: for $D_1$ you can consider $D_1$' in which: $I_{D1}$ = 33 mA, then: $\Delta I_{D1} = I_{D1} - I_{D1}'$

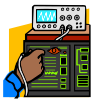
### 2.2. P. THE CHARACTERISTIC ON THE OSCILLOSCOPE USING AN EARTHED SOURCE

In order to see the characteristic on the oscilloscope you can use the assembly from Fig. 5. The resistance, $R_T$, has the role of a current - voltage transducer, necessary to visualize the current through the diode.

- Why can't the ground (GND) of the oscilloscope be connected between D and R, if $v_I$ is a earthed (non floating) source (Fig. 5.)?
- What quantities will appear on the two axes of the oscilloscope (X and Y)?
- In which quadrant will the oscillograms be?

# V. EXPLORATIONS AND RESULTS

## 1. TESTING THE DIODES



**Exploration**

- With the digital ohmmeter you will check the status of the junctions of the rectifying diode. If the ohmmeter has the symbol of the diodes drawn on one of its domains, do the measurement within that domain, otherwise use any domain you want;
- Connect the rectifying diode with the anode to the (+) lead of the ohmmeter (forward bias of the diode) and then read the value;
- Reverse the direction of the diode's connection (reverse bias) and read this value too;

**Results**

- The values obtained after the 4 measurements (2 for each diode - in forward and reverse bias)
- If the diode is good, the results should be found in Table 1.

If you obtain other situations, the diode is damaged (short circuit or open circuit).

Table 1

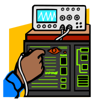
| | The ohmmeter's domain | |
|---|---|---|
| | With D's symbol | Without D's symbol |
| D – forward bias | $v_D$ | resistance |
| D – reverse bias | 1 or over the scale | 1 or over the scale |

## 2. RECTIFYING DIODES

For the experiments you will use a 1N400x semiconductor diode, where x can take any value between 1 and 7.

### 2.1. CURRENT-VOLTAGE CHARACTERISTIC $i_D(v_D)$

**The point by point method**



**Exploration**

Build the assembly from Fig. 4.

**<u>D – forward bias (direct)</u>**

- $V_I$ – use a dc adjustable voltage source
- The miliammeter shows the current $i_D$ and the voltmeter shows the voltage $v_D$
- Modify the voltage $V_I$ in the domain [0, 12] [V] and measure some pairs of ($i_D$, $v_D$).

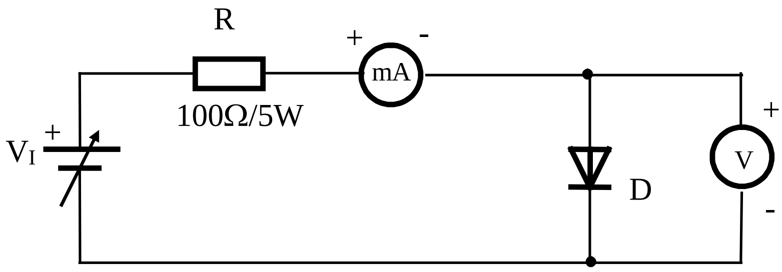



Fig. 7. Arrangement for plotting the diode terminal characteristic

**D – reverse bias**

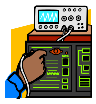
- Replace the positive voltage source $V_I$ from the schematic in Fig. 7 with a negative voltage source (-20, 0) [V].

- Modify the voltage $V_I$ in the domain [0, -20] [V] and measure some pairs of ($i_D$, $v_D$).

**Results**

- Table with the values of $i_D$, $v_D$ for all the points measured in experiment 2.1 (both forward and reverse bias);
- Graphic $i_D(v_D)$;
- Which is the diode's threshold value?
- Choose two operating points ($I_{D1}$, $V_{D1}$) and ($I_{D2}$, $V_{D2}$) for D, at $I_{D1} \cong 30$ mA and $I_{D2} \cong 100$ mA.
- Compute the static resistances $r_{D1}$ and $r_{D2}$ and differential resistances $r_{d1}$ and $r_{d2}$ in these points. For the computation of differential resistances, use the values from the operating point and a point close by (according to the table with $i_D$, $v_D$)

## 2.2. THE CHARACTERISTIC ON THE OSCILLOSCOPE USING AN EARTHED SOURCE



**Exploration**

Build the assembly from Fig. 5 using an earthed source (signal generator).

- $v_I$ – sinusoidal voltage with 10V amplitude and 100Hz frequency, obtained from the signal generator;
- Visualise the diode's characteristic on the oscilloscope (XY mode), by connecting the signal from point A to one channel, and the signal from point B to the other one..
- Visualise the diode's characteristic for a 2 kHz frequency of the input signal.

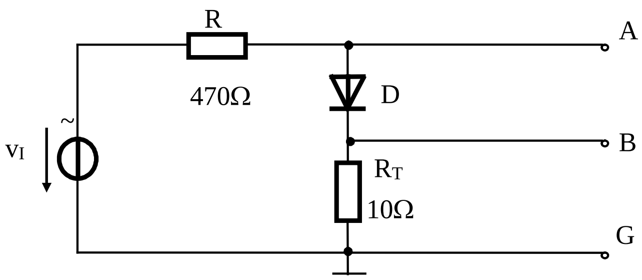



Fig. 5. Arrangement for displaying the $i_D(v_D)$ characteristic using an earthed source

**Results**

- Draw the characteristics that you have obtained on the oscilloscope for the frequencies of 100 Hz and 2 kHz of the input sinusoidal signal.
- In which quadrant are the obtained characteristics?

**REFERENCES**

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