

Laboratory Exercise 1

Diodes

The aim of the exercise

The main aim of the exercise is to understand principles of operation of different diodes. The measurements of static and small signal parameters will be conducted.

Backgrounds

Ideal diode

A DC volt-ampere characteristic of the ideal p-n diode is determined by the following exponential function:

$$I = I_{s0} \left(\exp\left(\frac{U}{U_T}\right) - 1 \right) \quad (1)$$

where: I_{s0} – is the saturation current, $U_T = kT/q$ – is the thermal voltage, where T is the junction temperature [K], $k = 1.38 \cdot 10^{-23}$ J/K – is Boltzmann's constant, and $q = 1.6 \cdot 10^{-19}$ C – is the electrical charge of an electron. At a temperature of 300 K, $U_T = 0.026$ V.

The curve illustrating the above dependence is shown in Fig. 1.



Fig.1. DC volt-ampere characteristic of the ideal diode.

An operating point **A** lying on the curve fragment corresponding to the forward biased diode state is shown in Fig. 1. For a chosen operating point two parameters can be defined which characterise the behaviour of the diode within the electrical circuit. These are: static resistance and dynamic resistance. The static resistance is defined by the slope angle of the straight line connecting the diode operation point with the origin of the I-U axes and is given by the following expression:

$$R = \frac{U}{I} = \frac{U}{I_{s0} \left(\exp\left(\frac{U}{U_T}\right) - 1 \right)} \quad (2)$$

Whereas the diode dynamic resistance is defined by the slope angle of the tangent to the volt-ampere DC characteristic at the operation point and is expressed as:

$$r_d = \frac{dU}{dI} = \frac{U_T}{I_{s0} \exp\left(\frac{U}{U_T}\right)} \quad (3)$$

Fig. 1 shows two lines corresponding to the static resistance R and the dynamic resistance r_d for the operating point A.

Dynamic resistance of a diode is the parameter used in the simplest model of the diode for the forward bias state. Such a model is shown in Fig. 2. The ideal diode, which is a non-linear element shown in Fig. 2a, is substituted by a serial connection of a voltage source U_p and resistance r_d . This connection is shown in Fig. 2b. Model parameters U_p and r_d are determined by the tangent line as depicted in Fig. 1 and the diode characteristic is approximated by a piecewise-linear curve illustrated in Fig. 2c.

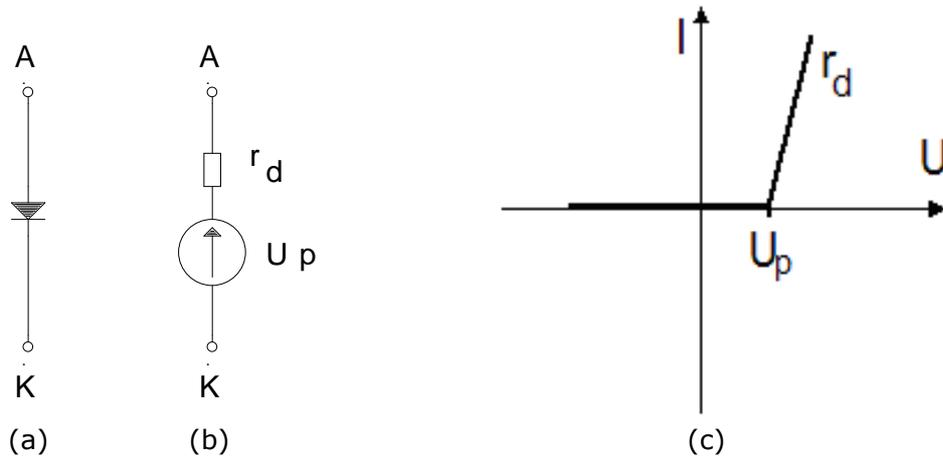


Fig.2. The ideal diode (a), its equivalent circuit (b) and the corresponding piecewise-linear I-U characteristic (c)

Real diode

For the real diode, there is a number of phenomena which were not taken into account in determining the equation of the ideal diode. Namely these are: the existence of ohmic resistances not adjacent to the p-n junction, leakage currents due to the surface phenomena, charge recombination and generation for the forward biasing, and finally the phenomena of field and avalanche recombination of carriers for the backward biasing. Due to these effects the DC volt-ampere characteristic of the real diode has the shape as shown in Fig. 3.

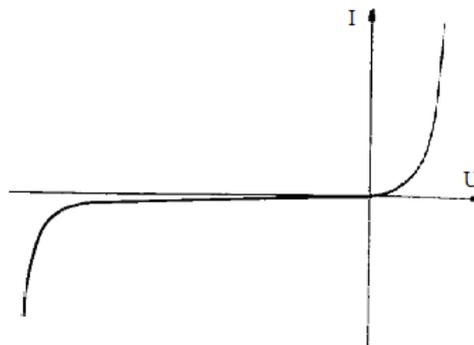


Fig.3. A typical volt-ampere characteristic of the real p-n diode

In order to model the real diode by employing the characteristics of the ideal diode the equivalent circuit shown in Fig. 4 can be used. This circuit still does not take into account the field breakdown and avalanche breakdown effects. This model consists of the ideal diode D_j , a serial resistance R_s and a leakage conductance G_u .

In some applications it is recommended to use a static model of the real diode obtained by approximation of the real characteristic of a diode by three straight line segments. An example of such an approximation is shown in Fig. 5. The parameters U_P and U_Z represents the on-voltage and breakdown voltage respectively. Slope angles of each of these line segments are mean value resistances R_F , R_R and R_B , corresponding to diode forward biasing, reverse biasing and diode breakdown respectively. The resistance R_R depends on the type of the semiconductor material used for diode fabrication, mainly. For example, for silicon diodes the value of this resistance is two orders higher than for germanium diodes and can reach values as high as 1000 M Ω . Resistances R_F and R_B have similar values irrespectively of the semiconductor type and take values from 1 Ω to 100 Ω .

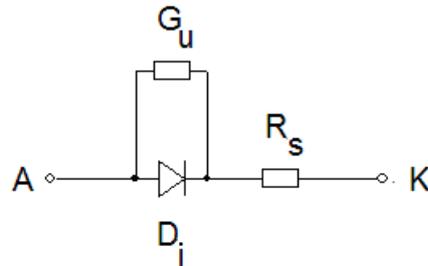


Fig.4. An equivalent circuit of the real diode

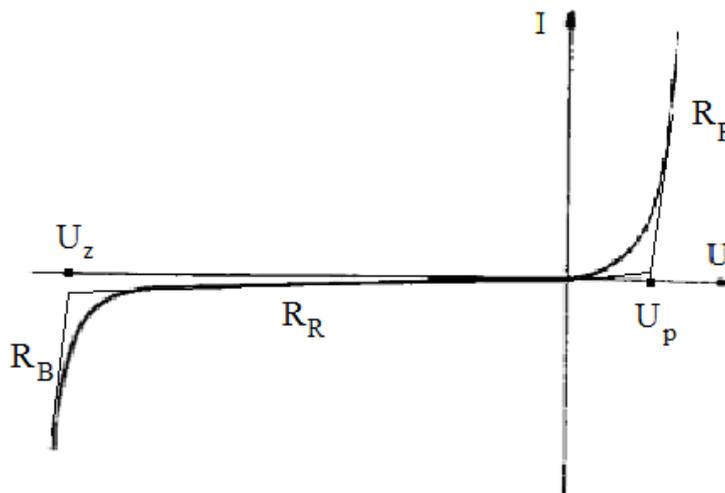


Fig.5. Piecewise-linear approximation of the DC volt-ampere characteristic of the real diode

Small signal parameters

The common feature of bipolar devices is that they are controlled by current; it means, that each change of the operating state demands changes in the carriers' concentration to deliver or to take some carriers of the electric charges. It is the similar problem as during overloading the capacitor – it demands some time. That is why every change must take some time; no process is rapid and each process is characterised by some inertia. It is convenient to apply the scheme in Fig. 6 where D_j represents the ideal diode, R_s – the serial resistance and C_j – the junction capacitance and C_d – the diffusion capacitance.

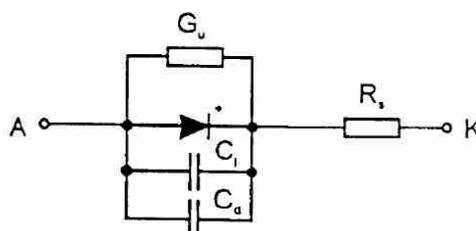


Fig. 6. The equivalent circuit for dynamic states

The junction capacity is connected with the region of the space charge on the junction. This charge is created when the mobile carriers are taken and some uncompensated dopants are still in the region of the junction. So at the n-side, atoms of donors create the positive layer of the charge, and at the p-side the negative charge is created by acceptors. The dimensions of these layers are not constant, they change when the operating conditions vary. The C_j capacity is a non-linear one (see the diagram in Fig. 7.)

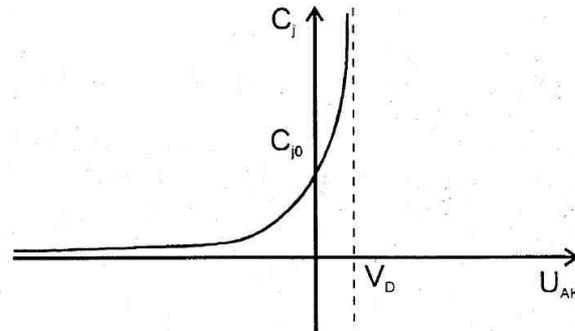


Fig.7. The junction capacity versus bias voltage

Though, it gains its maximum value in forward bias state, its influence on the transient processes is the biggest in a reverse bias when the capacity of diffusion has a very small value that may be omitted.

$$C_j = \frac{C_{j0}}{\left(1 + \frac{U_R}{U_D}\right)^m} \quad (4)$$

where: U_R – is a reverse bias; U_D – the diffusion potential; C_{j0} – the junction capacity for $U_R = 0$; and m – the coefficient that equals to 1/2 for step junction and 1/3 for a linear one.

The capacity C_d is connected with the injection of minor carriers through the junction during forward biasing. The concentration gains the higher value than the one that is without bias (the redundant concentration). So the carriers diffuse to the regions n and p and their concentrations become lower - Fig. 8.

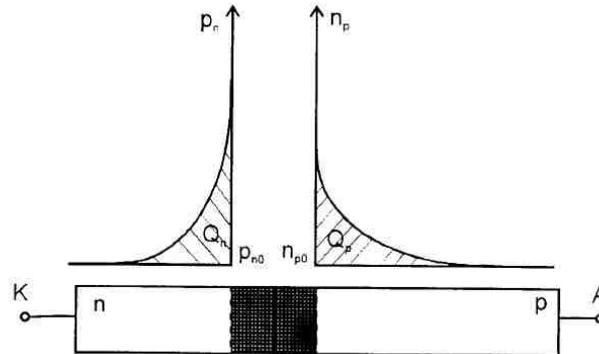


Fig. 8. The distribution of the carriers in p-n diode during forward bias

Switching

The main role of the diode in switching circuits is to allow the current flow in one direction and to block it in the reverse one. The ideal diode should have 0 value resistance forward biased and unlimited reverse biased, and should have 0 inertia during switching. Of course, the real diode does not fulfil these conditions. The basic switching scheme is introduced in Fig. 9. The rectangular impulses Eg switch the diode. If R is much higher than the resistance of the diode in the forward direction and also much lower than the diode resistance at the reverse bias, the switching is so called the „current switching“. Fig. 10 shows the changes of the voltage and the current during current switching.

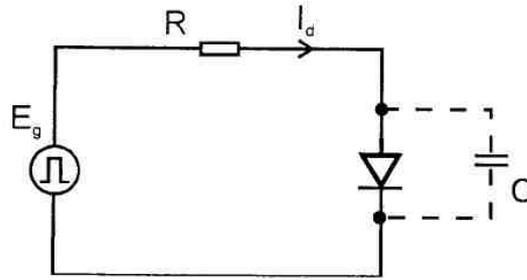


Fig. 9. The basic switching scheme

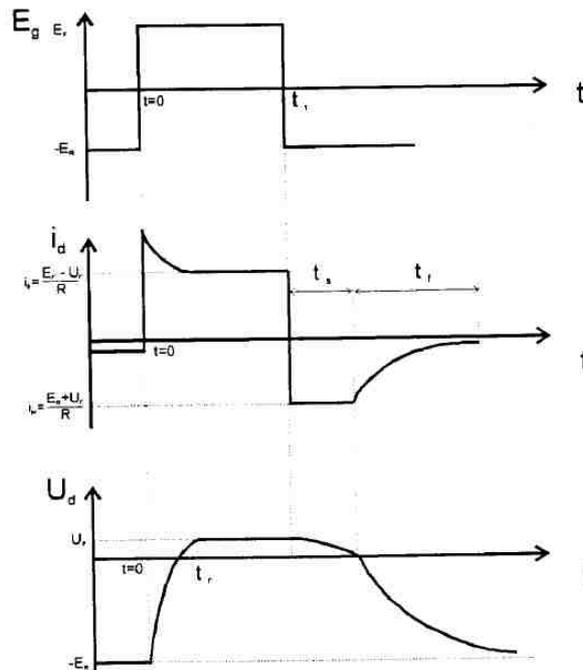


Fig. 10. Switching –changes of voltage and current

The switching process begins in $t = 0$ (E_g changes from E_R up to E_F). Till moment $t = 0$ the diode is reversely biased and the reverse current I_S flows through the diode. The change of supplying voltage starts the reloading process. The C_j capacity is reloaded as the first one and the reverse bias voltage lowers. When the sign of supplying voltage the C_d loading comes in prominence. The voltage rise time t_r during switching on, when E_F is much higher than U_0 can be calculated with the aid of following formula:

$$t_r = 0.7RC \quad (5)$$

where $C = C_j$.

The reverse switching starts when E_g changes from E_F to E_R and has two stages. During the first stage (lasting for time t_s) the diffusive capacity is discharged. The diode is in a forward bias condition and the reverse current, which flows through it, is limited only by the outer resistance. When the capacity is discharged, the reverse voltage appears and the second stage begins. The C_j is being reloaded. The switching off time of the diode is defined as the sum of t_s and t_r .

Exercise

Static characteristics

Laboratory set-up consists of measurement panel presented in Fig. 11, PC with installed Parametric Measurement Manager Pro software, measurement device Keithley 2722A, VirtualBench apparatus that assures functions of a generator, a digital multimeter, an oscilloscope and a supply. First, you should switch on the power strip to assure that all the laboratory set-up devices and the PC are supplied. Next you should switch on the PC and follow the measurement procedure.

1) Run Parametric Measurement Manager Pro. The window shown in Fig. 12 should be displayed. Then choose „File” and „New Project”. Enter arbitrary name and save.



Fig.11. Front of the measurement panel with marked sockets no.1 – DC characteristics, no.2 – switching, no. 3 – Junction capacitance

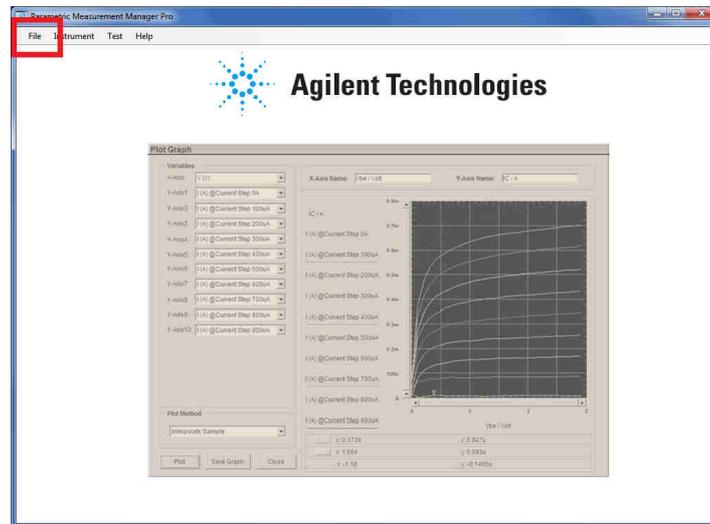


Fig.12. Main window of Parametric Measurement Manager Pro software

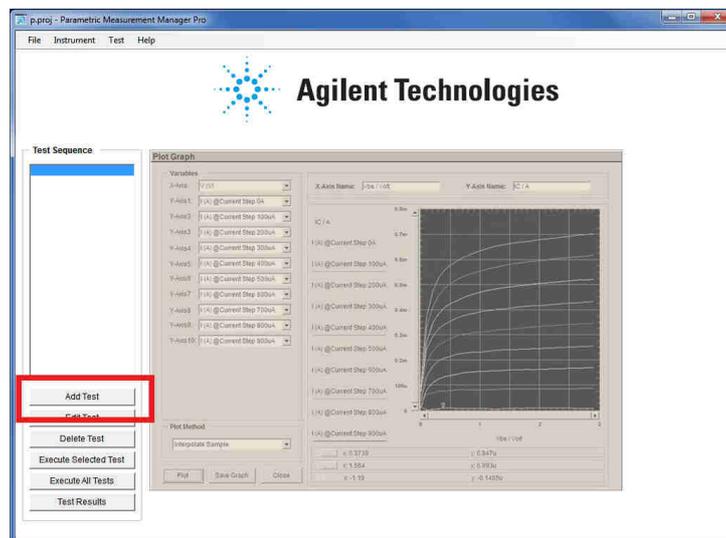


Fig.13. Main window of Parametric Measurement Manager Pro software with context menu

2) From the context menu on the left side, choose "Add test". The window that is displayed is presented in Fig. 14. Next, choose "Diode test".

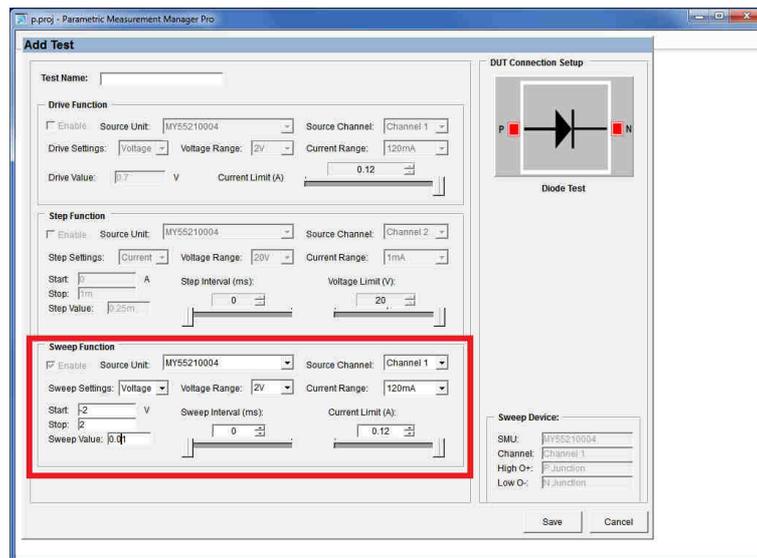


Fig.14. "Add test" window

3) Initial parameters that you enter in the "Diode test" should follow the scheme:

- Test name → enter arbitrary name;
- Sweep Function - Source channel → Channel 1;
- Sweep Function - Sweep settings → Voltage;
- Sweep Function - Voltage range → 2 [V];
- Sweep Function - Start → -2 [V];
- Sweep Function - Stop → 2 [V];
- Sweep Function - Current range → 120 [mA];
- Sweep Function - Sweep value → 0,01;
- Sweep Function - Sweep Interval → 10 [ms];
- Sweep Function - Current Limit → 0,12 [A];

REMARK: The initial settings depends on the diode type and its ratings. Please, verify the above data with the values in the datasheet!

4) Confirm the chosen settings with the button "Save" and plug the diode into the socket no. 1 marked in Fig. 11.

5) The program returns to the window from Fig. 13. From the context menu choose an option "execute selected test" and „run mode: single mode“.

6) After the test is ended, the window shown in Fig.15 is displayed. To plot the characteristic and verify the data choose an option "plot graph", next "2 inputs" and "proceed". To export the data to the file, you must choose an option "export to csv". The file is saved in the chosen directory.

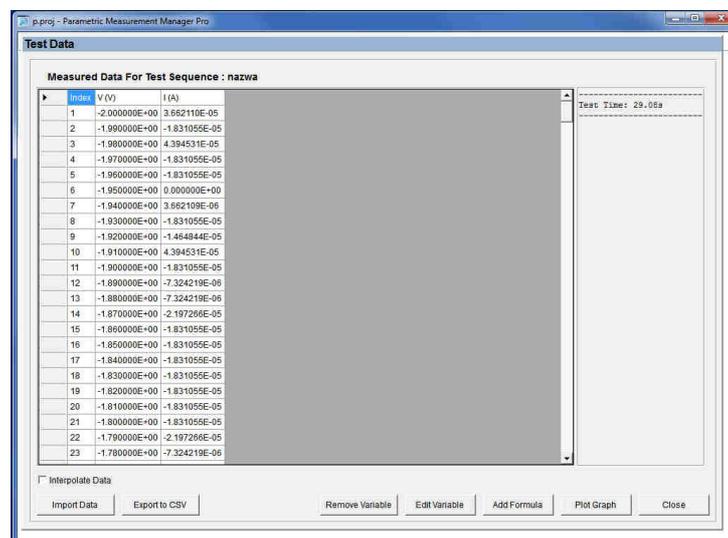


Fig.15. "Test data" window

7) Repeat the procedure step 3 to step 6 with "Edit test" option chosen from the context menu visible in Fig. 13. You can change the Voltage range (**do not exceed 15 V**), Start value (**do not decrease below -15 V**), Stop value (**do not exceed 3V**) and Sweep value, so the measurement procedure is not too time consuming and the expected characteristic is accurate. Please, consult the changes with the instructor.

8) Repeat the measurement for at least eight diodes (two rectifying diodes, two switching diodes, two LEDs and two Zener diodes). Consult your choice with the instructor.

Switching characteristics

To examine the switching capabilities of different diodes, follow the procedure below:

1) Make sure that the BNC connectors are plugged in the sockets of the measurement panel according to the scheme presented in Fig. 16.

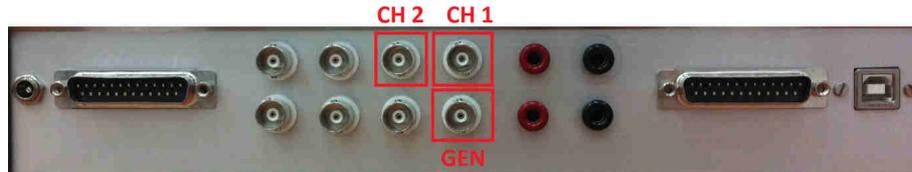


Fig.16. Back side of a measurement panel

2) Run the VirtualBench program (accessible from "My computer" ("Mój komputer")). The window shown in Fig. 17 should appear.

3) Initial settings should be as follows:

- 1 - Generator **(A)** set frequency to 100 kHz;
(B) set amplitude to +/- 5V;
(C) set duty cycle to 20%;
(D) choose rectangular wave;

2 - Oscilloscope

- (E)** turn on both channels. Channel 1 (red trace) represents the voltage of the generator, while channel 2 (yellow trace) represents the voltage on the tested diode.
- (F)** turn on the mathematical function and set it to (A-B) and subtract channel 2 from channel 1. The function (blue trace) represents the current flowing through the diode.
- (G)** set the triggering to rising edge from channel 1 and place the traces so they are readable.



Fig.17. VirtualBench main window

- 4) Plug the test diode in the socket no. 2 marked in Fig. 11.
- 5) Read and write the type of the tested diode.
- 6) Switch on the generator and set the timebase settings so that you can see the whole time period.
- 7) Save the obtained results.
- 8) **Switch off the generator.**
- 9) Remove the tested diode from the socket.
- 10) Repeat steps 4 to 9 for all the chosen diodes (consult your choice with the instructor).

Small signal parameters - capacitance

To examine the junction capacitance of the diode, the intrinsic capacitance of the measurement circuit must be found. To achieve it, you need to measure the natural frequency of the circuit and use the formula:

$$C_{\text{circuit}} = \frac{1}{(2\pi \cdot f_{\text{circuit}})^2 \cdot L} \quad (6)$$

where: f_{circuit} is natural frequency of the circuit [Hz] and L is an inductance (take 50 μH for calculations).

To measure f_{circuit} , follow the procedure:

- 1) Reconnect the BNC connectors according to the scheme presented in Fig. 18 (ONLY CH 1 and CH 2).

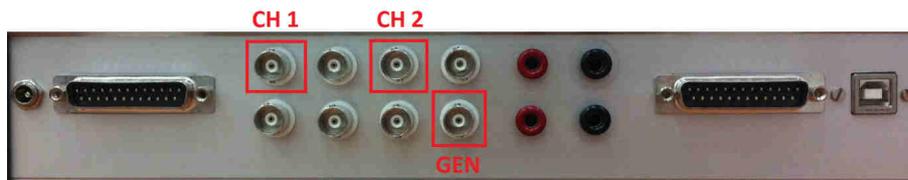


Fig.18. Back side of a measurement panel

- 2) Run the VirtualBench program (accessible from "My computer" ("Mój komputer")). The window shown in Fig. 19 should appear.
- 3) Initial settings should be as follows:
 - 1 - Supply (A) section one, set to 6 V and limit the current to 0,5 A;
 - (B) section two and three, set to 0 V and limit the current to 0,5 A;
- 4) Switch on the supply



Fig.19. VirtualBench main window

- 5) Set the initial settings of the virtual oscilloscope:

2 – Oscilloscope

(C) turn on both channels. Channel 1 (red trace) represents the voltage in the point of resonance. of the generator, while channel 2 (yellow trace) represents the voltage on the tested diode.

(D) set the triggering to rising edge from channel 1.

(E) set the timebase so you can see 3 to 4 periods of the signal.

- 6) Read and note down the frequency ($f_{circuit}$) of the generated signal.
- 7) Switch off the supply.
- 8) Calculate $C_{circuit}$ with the aid of formula (6).
- 9) Plug the test diode in the socket no. 3 shown in Fig.11.
- 10) Switch on the supply and set the timebase so you can see 3 to 4 periods of the signal.
- 11) Note down the measured frequency f .

To calculate the junction capacitance of the diode, use the formula:

$$C_{\text{measured}} = \frac{1}{(2\pi \cdot f)^2 \cdot L} \quad (7)$$

$$C_j = C_{\text{measured}} - C_{\text{circuit}} \quad (8)$$

- 12) Change the voltage in section two by 1 V.
- 13) Note down the measured frequency f and calculate the junction capacitance according to formula (7) and (8)
- 14) Repeat the steps 12 and 13 up to 25 V (**supply - section two**).
- 15) Switch off the supply.
- 16) Remove the tested diode from the socket.
- 17) Repeat the steps 9 to 16 for all the chosen diodes (consult your choice with the instructor).

Report

The report from the laboratory exercise should contain:

- Characteristics of the diodes (REMARKS: gather the characteristic of the diodes of the same type e.g. Zener diodes, rectifying diodes etc. on one graph).
- Perform piecewise linear approximation for each diode (graphs should be included).
- Calculate parameters such as: U_P , U_Z , R_R , R_F , R_B of all examined diodes and gather them in the table.
- Switching characteristics of tested diodes (switching times t_r , t_s and t_f should be gathered in the table).
- Junction capacitance characteristics.
- Remarks, observations and conclusions.