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Sensor laboratory, Micro- and nanotechnology
Laboratory program

Measurement guide

Study of the switching parameters of diodes

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1 Overview

The goal of the exercise to measure those physical and electrical parameters of diodes which mainly define the application field of the investigated device.

The parameters to be measured are:

1. The capacitance and inductance of the reverse biased diode.
2. The recovery time.
3. The life time of the minority carriers.
4. The minority carrier stored by the diffusion capacitance.

In the course of the exercise the material parameters and applicability of Si and Ge based pn diodes including the Varicap type will be seen, but the Schottky diodes due to their low capacitance will be mainly avoided.

2 The theoretical background

2.1 The capacitance of the reverse-biased diode

The basic part of the diode is the so-called depleted layer. The depleted layer does not contain movable carriers and it is formed at the interface of the material layers having different parameters (e.g., different charge type of the semiconductor layers or metal – semiconductor layer structure).

The depletion capacitance (C_j) is defined by the first derivative of the stored charge of the depleted layer (Q_j) on the applied reverse bias (V_R):

$$C_j = \frac{dQ_j}{dV_R}$$

The depletion capacitance depends on the material parameters (concentration profile, material permittivity) and on the geometry of the depleted layer. In the case of a planar structure – where the effect of the perimeter is negligible – the depletion capacitance can be expressed as:

$$C_j = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

where ε_0 is the vacuum permittivity (8.85×10^{-12} As/Vm),
ε_r is the relative permittivity of the material (in the case of Si: 11.2),
A is the surface of the junction (m^2),
d is the thickness of the depleted layer (m).

The thickness of the depleted layer depends on the applied voltage and on the spatial distribution of the dopants.

The most common case is that the dopant concentration on the two side of a p-n junction differs with some order of magnitude resulting the depleted layer mostly being in the lightly doped side. This type of the p-n junction is called to be one-sided version. If the lightly doped part has a constant dopant concentration, then a step-wise junction is present. In this case, the depletion capacitance depends on the reverse bias according to the following expression:

$$C_j = A\sqrt{\frac{q\varepsilon_0\varepsilon_r N_B}{2}}\left(V_{bi} + V_R - \frac{2kT}{q}\right)^{-\frac{1}{2}}$$

where q is the elementary charge (1.6×10^{-19} As),
N_B is the doping concentration of the less-doped side (m^{-3}),

V_{bi} is the built-in potential of the junction (V),

k is the Boltzmann's constant (1.38×10^{-23} VAs/K),

T is the junction's temperature (K),

Another usual case is, if the doping profile had a linear change, i.e. constant gradient across the metallurgical junction. In this case the depletion capacitance depends on the reverse bias as follows:

$$C_j = A\left[\frac{qa(\varepsilon_0\varepsilon_r)^2}{12}\right]^{\frac{1}{3}}\left(V_g + V_R\right)^{-\frac{1}{3}}$$

where a is the concentration gradient of the doping (m^{-4}),

V_g is the gradient bias:

$$V_g = \frac{2}{3}\frac{kT}{q}\ln\left[\frac{a^2\varepsilon_0\varepsilon_r\frac{kT}{q}}{8qn_i^3}\right]$$

where n_i is the intrinsic concentration of the material (m^{-3}).

(In the case of Si it is 1.5×10^{16} m^{-3})

2.2 The recovery time

The depletion-layer capacitance discussed in 2.1 accounts for most of the junction capacitance when the junction is reverse-biased. When the diode is forward-biased there is in addition a significant contribution to junction capacitance from the rearrangement of minority carrier density, the so-called diffusion capacitance.

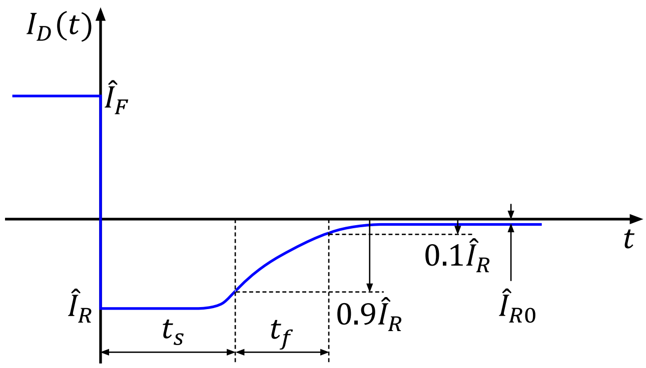

Figure 1: Diode's current in the course of forward-to-reverse switching

As a diode structure is turned-off, i.e. switched from forward bias to reverse bias, its current will change according to the Figure 1. This behaviour shows how the reverse current will deplete the carriers accumulated in the diffusion capacitance.

The parameters shown in Figure 1 are:

$\hat{I}_F$ the peak value of the forward current, (A)

$\hat{I}_R$ the peak value of the reverse current, (A)

$\hat{I}_{R0}$ the residual (minimum) value of the reverse current, (A)

t_s the storage time, (s)

t_f the decay time, (s).

The recovery time of the diode is the sum of the storage and the decay time:

$$t_r = t_s + t_f$$

2.3 The life time of the minority carriers

As it was mentioned in the section 2.1. the in the case of forward-biased diode the majority carriers crossing the depleted layer will be accumulated at the boundary of the depleted layer as a minority carrier. The accumulated minority carriers drifting towards the neutral zones will recombine with the local majority carriers. Switching off the forward bias and cutting the current's path the accumulated carriers could disappear only by recombination. According to this, the voltage waveform should be as in Figure 2.

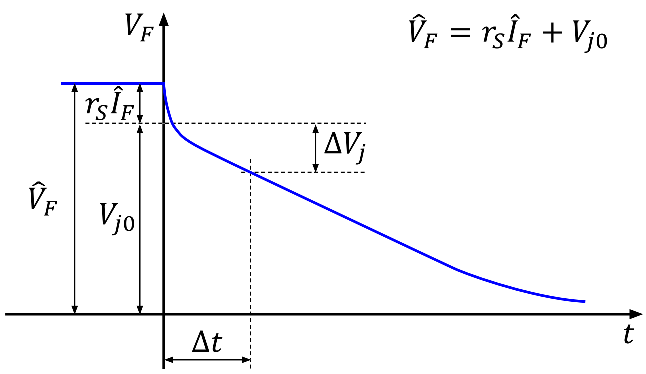

Figure 2: The diode's voltage in the course of carrier recombination

The parameters in Figure 2 are:

$\hat{I}_F$ the peak value of the forward current, (A)

$\hat{V}_F$ the peak value of the forward bias, (V)

r_S the series resistance of the diode, (Ω)

V_{j0} the voltage of the junction at the moment of turning off, (V)

Δt time difference, (s)

ΔV_j the voltage drop during Δt, (V).

Cancelling the forward current, the voltage drop on the series resistance ($r_S \hat{I}_F$) will be diminished immediately, as well.

Supposing a p⁺n diode the holes (*p*) in the n-type region will be the overwhelming minority contributor. The hole's concentration decreases exponentially by the time at the depletion layer boundary:

$$p_0(t) = p_{00} e^{\left(-\frac{t}{\tau_p}\right)} + p_{n0}$$

where p_{00} is the hole's concentration at the junction at the moment of switch-off, at *t*=0,

p_{n0} is the hole's equilibrium concentration in the n-type side,

τ_p is the life time of the holes in the n-type layer.

As we know by the theory, the bias dependence of the injected concentration is:

$$p_0 = p_{n0} e^{\left(\frac{V_j}{V_T}\right)}$$

where $V_T = \frac{kT}{q}$ is the thermal voltage, 25.85 mV (26 mV) at the room temperature, and

V_j the junction voltage.

Combining and rearranging the previous two equations, the time dependence of the junction voltage will be:

$$V_j(t) = V_T ln\left(1 + \frac{p_{00}}{p_{n0}} e^{\left(-\frac{t}{\tau_p}\right)}\right).$$

At the very beginning, e.g. shortly after the forward voltage switch-off the second part in the logarithmic expression will be much larger than unity, so the previous equation could be simplified to:

$$V_j(t) \cong V_{j0} - V_T \frac{t}{\tau_p}$$

Based on the parameters given in Figure 2 the life time of the holes can be expressed as:

$$\tau_p = V_T \frac{\Delta t}{\Delta V_j}$$

2.4 The minority carrier stored by the diffusion capacitance

In the case of forward biasing the majority carriers crossed the depletion layer will accumulate at the boundary of the depleted layer. Later as minority carriers of the oppositely doped region moving towards the neutral regions, they will be recombined with the local majority carriers. This minority carriers' packages on the two side of the depletion layer will act as the charge of the diffusion capacitance.

3 The test setup

Figure 3 shows the applied text fixtures. The marked boundaries and numbering refer to the serial number of the measuring tasks. In all measurement cases the proper polarity of the DUT (device under test – diodes) is shown.

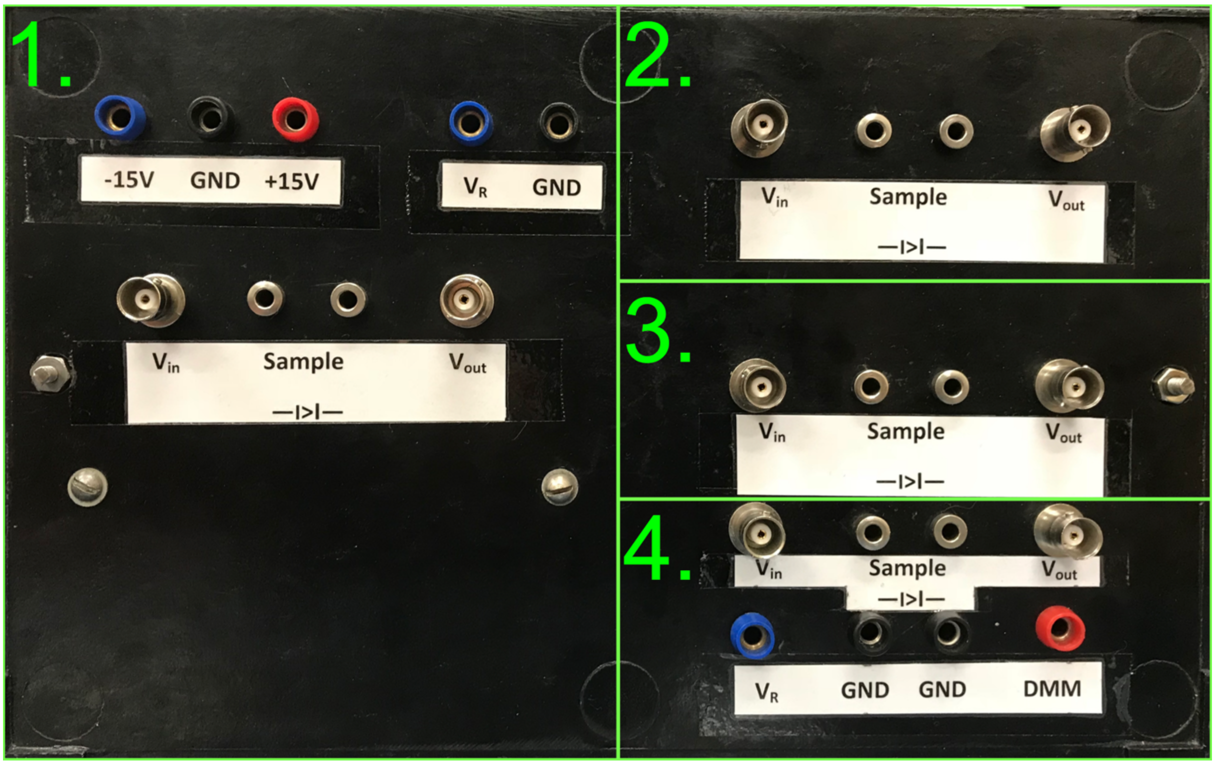

Figure 3: The applied test fixtures

The **test circuit 1** of the fixtures is devoted to the measurement of the diode impedance and capacitance. The built-in measuring circuit requires dual polarity supply namely ±15 V. The diode to be measured requires reverse bias consequently the positive output of the HAMEG power supply to the GND point, its negative output to the V_R point will be connected.

The **test circuit 2** of the fixtures is dedicated to the measurement of the recovery time, while the **test circuit 3** is devoted to the minority carrier's life time measurement. In both cases the Rigol function generator has to be connected to the V_{in} connector and an oscilloscope should be connected to the V_{out} connector applying BNC-BNC cables.

The **test circuit 4** of the fixtures is devoted to measure the diffusion charge of the forward biased diode structure. The V_R, GND points accept the negative bias for the DUT, the GND and DMM points are for the DC millivolt meter. V_{in} connector accepts the function generator, V_{out} is for an oscilloscope.

3.1 The operation of test circuit 1

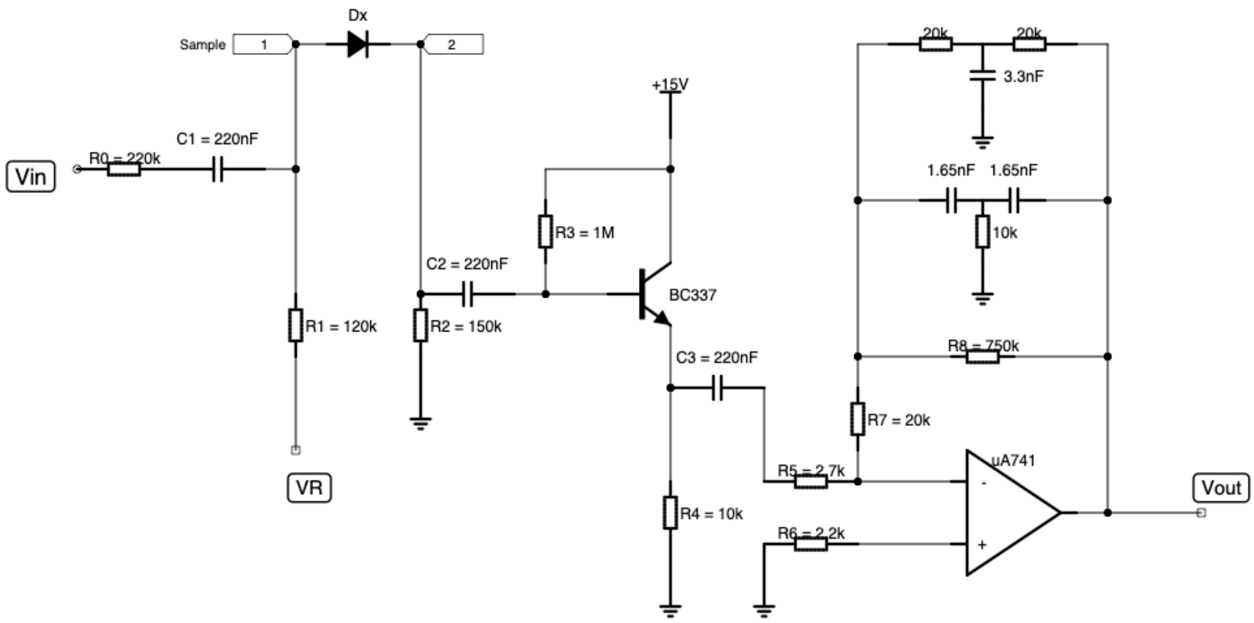

Figure 4: The test circuit of diode capacitance measurement

Figure 2 shows the applied test circuit for diode capacitance measurement. It contains three parts; the measuring circuit, the voltage follower, and the selective amplifier. To the input of the measuring circuit (V_{in}) a mV_{eff} range sine signal, while to the V_R connector the reverse bias of D_x — diodes to be measured — should be connected. The serial capacitance of C_1, C_2, and D_x will be measured by the measuring circuit. The diode capacitance will dominate the result since its value is in the pF range overwhelming the 220 nF values of C_1 and C_2. The voltage follower is a common collector amplifier ensuring high input impedance ($r_{in} = R_3 \times (\beta R_4)$). Its voltage gain is nearly unity. The third stage is the selective amplifier having R_5 input resistance only. The feedback loop contains a TT-filter, its purpose is to filter out the unnecessary frequency components (noises). In accordance with this arrangement, the measurement should be performed at the frequency of TT-filter (R = 20 kΩ, C = 1.65 nF):

$$f_0 = \frac{1}{2\pi RC} = 4823 \text{ [Hz]}$$

3.2 The operation of test circuit 2

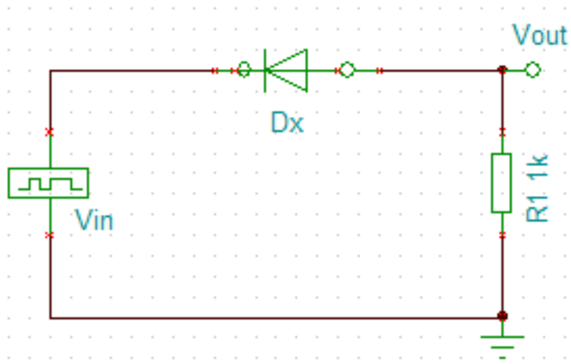

Figure 5: The test circuit of recovery time

The pulse generator shown in Figure 5 has two tasks, on the one hand it gives the reverse bias pulses to the D_x diode which will be measured, on the other hand it supports the forward bias (the offset voltage).

Since the output voltage (V_{out}) is generated by the diode's current flowing through the R_1 resistor its wave-form will be the same as the wave-form of D_x's current.

The measuring devices cannot measure in the nanosecond range, that is why the high-speed switching diodes (the Schottky diodes) will not be studied with this circuit (and the related measurement task). The studied diodes belong to the slow, rectifying types, which has respectively thick junction width.

The time constants given in Figure 1 can be expressed as:

$t_s = 0.23\tau_p$ $\quad$ $t_f = 1.1(\tau_p + R_1 C_j)$ $\quad$ supposing, that $\quad$ $|\hat{I}_F| = |\hat{I}_R|$

Where R_1 the resistor's value of in Figure 5, C_j is the average junction capacitance calculated based on the values obtained in task 4.1.5, τ_p is the life time of holes will be obtained in task 4.3.4.

3.3 The operation of test circuit 3

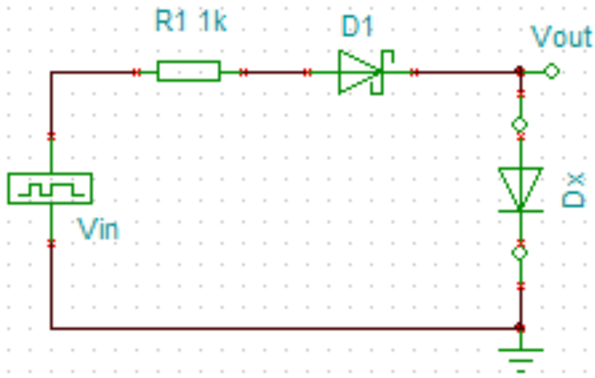

Figure 6: The test circuit of the life time of the minority carriers

The function generator supplies positive, forward voltage pulses to the D_x. Since the input impedance of the oscilloscope connected to the V_{out} is 1 MΩ, and at the end of the positive pulses the D_1 Schottky diode is closing much faster than the D_x, the charge accumulated in D_x will disappear by recombination only.

Setting the proper square-wave signal on the function-generator the wave-form measured at V_{out} connector will be like as shown in Figure 2.

3.4 The operation of test circuit 4

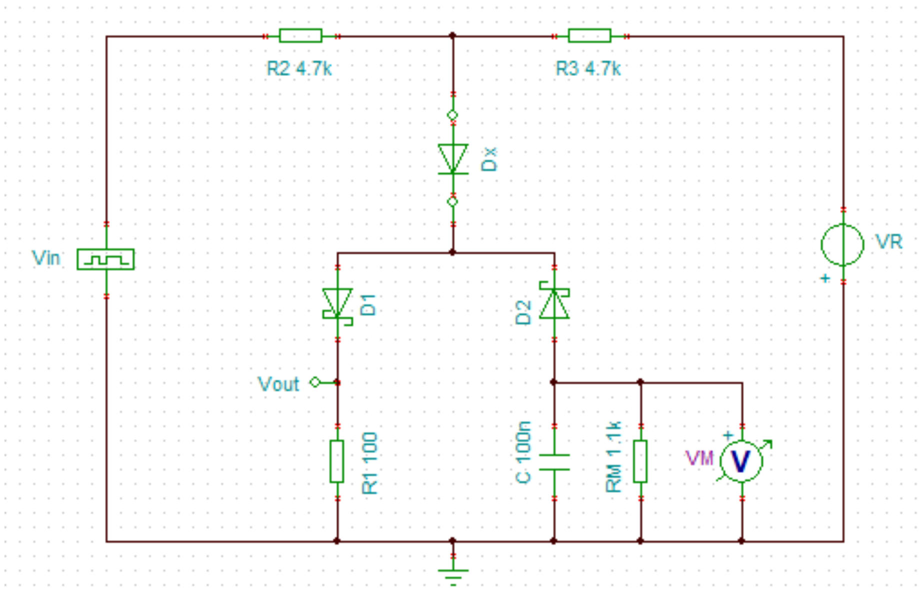

Figure 7: The test circuit of the minority carrier stored by the diffusion capacitance

As previously stated, the forward biased pn-junction is capable of storing charges in the form of diffusion capacitance. The amount of these charges can be measured with the circuit shown in

Figure 3. The V_R supply provides a reverse bias voltage for the D_x diode (sample). The V_{in} function generator provides short, forward biased current impulses for the diode; as a result, charges will be accumulated on the D_x diode.

The forward biased current impulses are transferred via D_1 diode to R_1 resistor, while the reverse current (caused by the diffusion capacitance) is suppressed by D_2 diode. This measurement will work as it is intended, if D_1 and D_2 diodes are way faster than the measured D_x diode. The forward current impulses can be measured on R_1 = 100 Ω resistor with oscilloscope (note that the signal will be a few to a few ten mV-s of magnitude). The peak current value can be determined from $\hat{V}_{out}$ peak value using the following equation:

$$\hat{I}_F = \frac{\hat{V}_{out}}{R_1}$$

Note that the equation gives a correct result only, if the oscilloscope's input impedance is a lot larger than R_1; in this case, the oscilloscope's R_{in} = 1 MΩ value is considered way larger than the 100 Ω value. The diode current (that is caused by the stored charges) is integrated by the C = 100 nF and R_M = 1.1 kΩ resistor. The mean value of this current can be determined after measuring the voltage on R_M resistor using a digital multimeter. For this purpose, the DMM must be set to DCmV setting. Knowing the V_M voltage, the amount of accumulated charges can be calculated:

$$Q = \frac{V_M}{R_M} t_i$$

where t_i is the cycle time of the pulses provided by the function generator.

If V_M is given in volts, R_M in ohms, t_i in seconds, then, as the result we will get the amount of charges in coulombs. The amount of charges in a diode is also determined by the accumulation time constant, τ_{DF}, and by the peak value of the forward current, $\hat{I}_F$:

$$Q = \tau_{DF} \hat{I}_F$$

As a conclusion, if $\hat{I}_F$ increases, so will Q. It is also important to mention that there is a strong connection between the amount of stored charges, and the recovery time of the diode.

4 Measurement tasks

4.1 Obtaining the bias dependence of depletion capacitance and impedance

4.1.1 Switch ±15 V bias to the circuit using FOK-GYEM TR9175/A power supply! Beforehand the current limit must be set low both sides. Connect one adjustable output (0 - 20 V) of HM8040 power supply to the V_R, GND points this will be the reverse bias of the diodes. The output of the DG1022 function generator together (through a T connector) with the input of a HM8012 multimeter set to AC mV will be connected to the V_{in} BNC connector. The T connector is used to diminish the noise level. The V_{out} will be connected to the other HM8012 multimeter.

4.1.2 Set 150 mVpp sine signal on the function generator, the voltage value should be measured by a multimeter. One of the supplied capacitors should be connected to the sample points. (During this step of the measurement process the V_R value is not important.) Adjust the input signal's frequency nearby the TT-filter's frequency (f_0) to reach the maximal reading on V_{out}. Record the final frequency value, it should be kept constant during the following steps.

4.1.3 Remove the applied capacitor and record the output signal value. This will be the offset value of the circuit. It has to be used to correct all voltage reading later.

4.1.4 Measure the V_{out} voltage connecting the known capacitors C_x piece by piece, into the system! Define the linear region of the measurement setup! This is that part of the $C_x(V_{out})$ function where the squared correlation coefficient of the best fit line is higher than 0.9995. The equation of the best fit line will be used to convert the voltage readout to measured capacitance value.

4.1.5 Connect the studied diodes to the circuit. Mind the proper polarity! Set V_R in between 1 - 15 V range with 1 V step. Measure V_{out}! Perform the measurement at V_R = 0.5 V, as well. Calculate and draw the $C_j(V_R)$ and $Zj(V_R)$ functions for all supplied diodes!

4.2 Obtaining the recovery time

4.2.1 Assemble the measurement setup as shown on Figure 5. Connect the Rigol function generator's output to V_{in}, and Rigol DS1052 digital oscilloscope to the V_{out}.

4.2.2 Connect a diode to be measured according to Figure 5 and 3.

4.2.3 Set up a 50 kHz (20 µs period time), 50 % duty cycle (symmetrical) square wave signal on the function generator, with 10 V amplitude. Adjust the settings of the function generator to get an output wave-form similar to Figure 1.

4.2.4 Obtain the storage time (t_s) and the decay time (t_f) in case of three different input wave-form (amplitude and bias) using diode's bias voltage less than 10 V.

4.2.5 Perform the measurement for all the supplied diodes.

4.3 Obtaining the life time

4.3.1 Assemble the measurement setup as shown on Figure 6. Connect the Rigol function generator's output to V_{in}, and Rigol DS1052 digital oscilloscope to the V_{out}.

4.3.2 Connect a diode to be measured according to Figure 6 and 3.

4.3.3 Set up a 1 kHz (20 µs period time), 50 % duty cycle (symmetrical) square wave signal on the function generator, with 10 V amplitude. Adjust the settings of the function generator to get an output wave-form similar to Figure 2.

4.3.4 Obtain the minority carrier life time for each supplied Si diodes.

4.3.5 Check the validity of the equations of 3.2 for the measured values.

4.4 Obtaining the minority carrier stored by the diffusion capacitance

4.4.1 Assemble the measurement setup as shown on Figure 7. Connect the Rigol function generator's output to V_{in}, and one output of the FOK-GYEM TR9175A to V_R connectors (only after setting a low value of current limit). Connect an oscilloscope on V_{out}, and a Hameg multimeter between the DMM connections (DC mV setting is required). Set up a 50 kHz (20 µs period time), 50 % duty cycle (symmetrical) square wave signal on the function generator, with 10 V amplitude, and +5 V offset voltage. The value of V_R reverse voltage should be -30 V. After putting in a sample diode, make sure that the forward current pulses appear on the oscilloscope screen. *In case of a noisy waveform, the usage of analogue oscilloscope is recommended.

4.4.2 Measure and determine the charge storing time constant (τ_{DF}), the peak value of forward current ($\hat{I}_F$), and the amount of accumulated charges for each sample diodes supplied for the measurement!

5 Equipment to be used

- Test fixture,
- Hameg HM8012 digital multimeter, 2 pcs,
- FOK-GYEM TR9175/A dual power supply,
- Hameg HM8040 dual power supply (for diode biasing),
- Rigol DS1052 digital oscilloscope,
- Rigol DG1022 function generator.

6 Review questions

1. What is the reason of depletion region formation?
2. Let's define the depletion capacitance!
3. What does it mean the one-sided, abrupt junction?
4. Draw the doping profile around the crystalline interface for linear junction!
5. What is the $C_j(V_R)$ function of the one-sided, abrupt junction?
6. Why should we measure the $C_x(V_{out})$ function?
7. How could be the C_j value calculated?
8. Why do we have capacitance in the case of forward-biased pn junction?
9. What causes to decrease the accumulated charge if there is no any current in the diode's circuit?
10. What is the origin of the residual reverse current of the diode?

7 Measurement protocol

To prepare the report Excel or Numbers is strongly recommended!

Each measuring group is asked to give in one report. The report should be submitted in pdf format and not more than 5 pages, through e-mail latest after two weeks of the measurement performed.

The file name has to contain the surname of the authors and the short title of the exercise, e.g., “pap_kovacs_diodes.pdf”

The protocol has to contain:

1. The title of the measurement
2. The names of the colleagues performing the task
3. The date and location of the measurement
4. A declaration stating that the task is performed by the enumerated colleagues
5. The list of applied equipment with types and identification numbers
6. The tabulated list of the measured values (if it is feasible), the calculated values, and the requested graphs
7. In the case of calculations, the applied forms
8. Short discussion of the results for each measurement task

PLEASE do not copy previous protocols. Identical protocols will be refused.

To transport the measured and recorded data PLEASE use the internet connection instead of any USB device.