Exercise 8.

Active electronic components

Aim of the measurement

The aim of the measurements is to study different discrete semiconductor diodes and bipolar transistors: their characteristics, parameters and dynamic properties. In addition to the physical properties of the devices to be measured, an important objective is to introduce and practice the measurement procedures, measurement set-ups and instruments used to perform the measurements.

Required knowledge

- Description of the pn junction
- DC characteristic of diodes
- Transients in diodes
- DC and AC models of transistors
- Transistors in switching mode.

Instruments

Digital multimeter (6½ digit)	Agilent 34401A
Power supply	Agilent E3630A
Oscilloscope	Agilent 54622A
Function generator	Agilent 332220A

Test panel

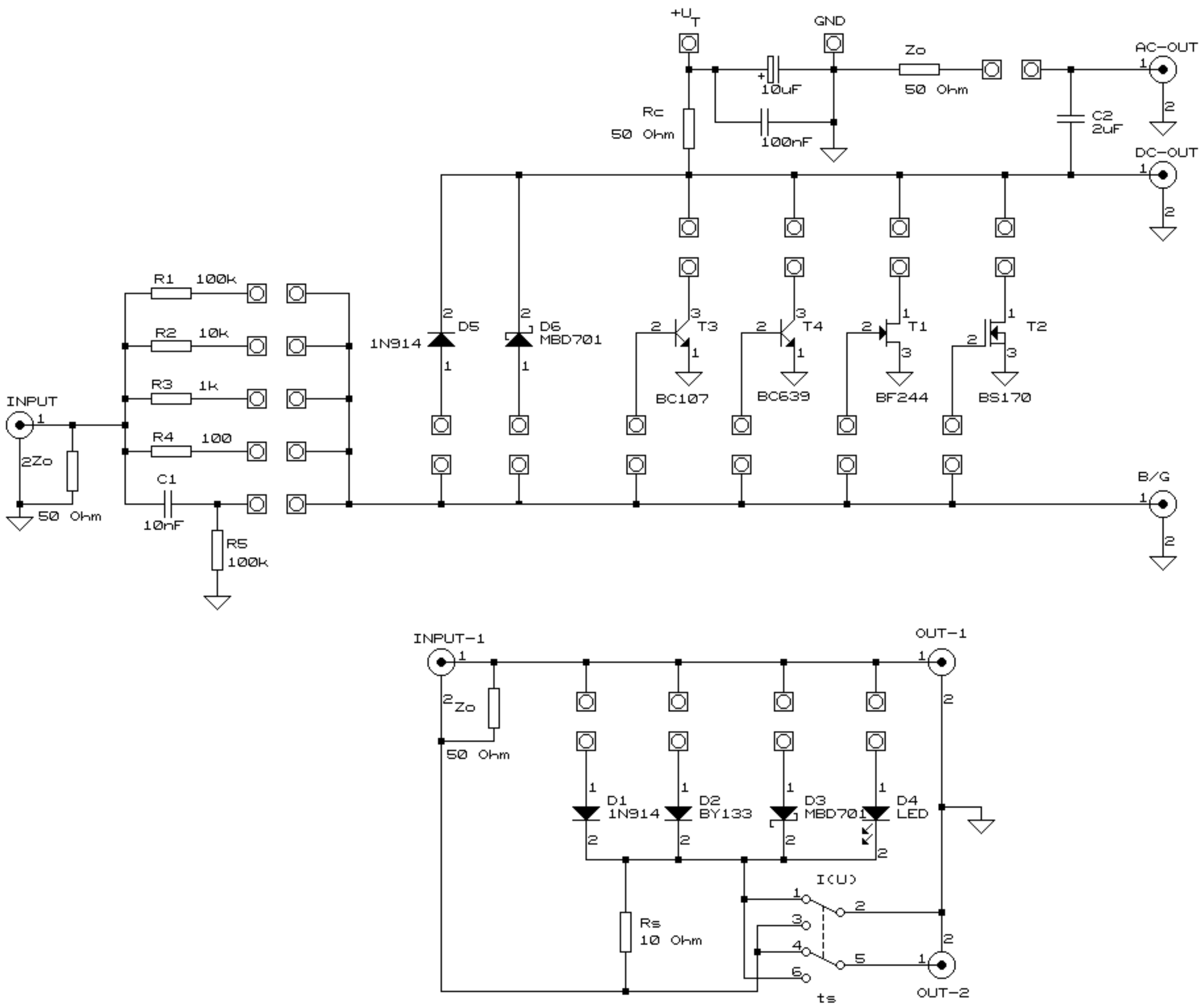


Figure 8–1. Schematic diagram of test panel

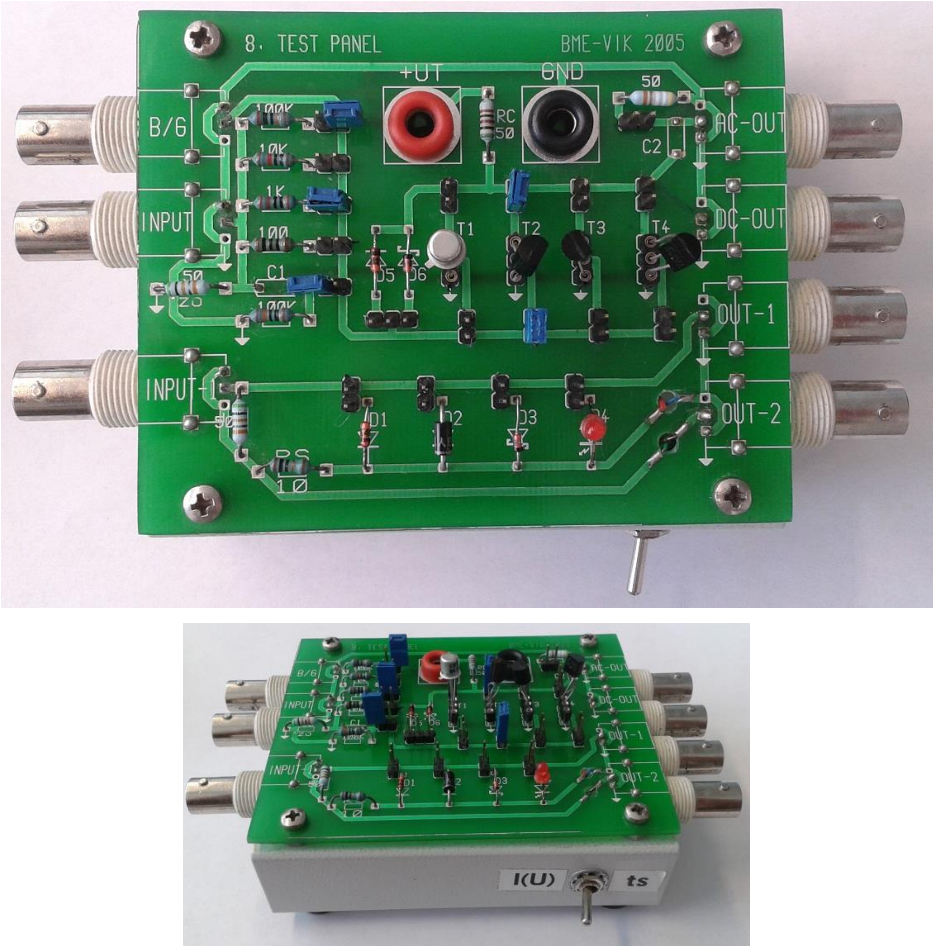


Figure 8–2. Photo of the test panel

Operation of a diode

Static characteristics

The static characteristic of the ideal diode is exponential as described by the following equation:

$$I(U) = I_{S0}\left(\exp\left(\frac{U}{U_T}\right) - 1\right) \qquad (8\text{-}1)$$

where:

- I_{S0}: saturation current
- U_T: thermal voltage

The thermal voltage is:

$$U_T = \frac{kT}{q} \qquad (8\text{-}2)$$

where k is the Boltzmann-constant, T is the temperature in Kelvin, q is the charge of the electron. The value of U_T is approximately 26 mV at room temperature (it is worth to memorize this constant).

The saturation current changes in a wide range, it is in the order of magnitude of 10^{-10}.

The static characteristic when the output value is the voltage:

$$U(I) = U_T\left[\ln\left(\frac{I}{I_{S0}} + 1\right)\right] \qquad (8\text{-}3)$$

In practice, the ideal diode equation should be extended in several ways, for example:

$$I(U) = I_{S0}\left(\exp\left(\frac{U}{mU_T}\right) - 1\right) \qquad (8\text{-}4)$$

Where *m* is the so-called ideality factor, it is in the range of approximately 1-2.

Figure 8–3. illustrates the forward bias characteristics of an ideal diode. It can be seen that above a given voltage level the diode current increases rapidly. This voltage is called the forward opening voltage of the diode. The opening voltage is of course associated with a current value, the value of which may depend on the diode's datasheet and its application (typically a few mA or more).

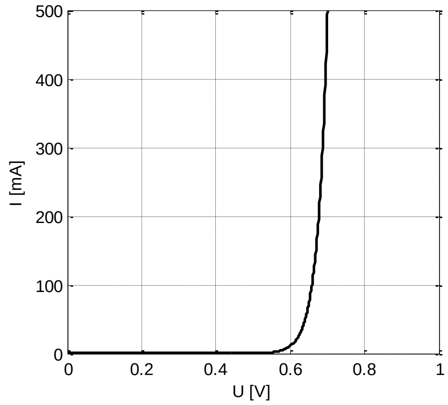


Figure 8–3. Characteristic of an ideal diode

The forward opening voltage of the Si diode is usually in the range 0.6 V - 0.7 V depending on the diode parameters. For other types of diodes, the opening voltages may vary. For Schottky diodes the opening voltage is lower, in the range 100 mV – 400 mV. For LEDs the opening voltage is higher: about 1.5 V or (especially for high brightness LEDs) much higher. Importantly, however, there can be variations of up to a few 100 mV due to temperature or manufacturing parameters.

Secondary effects

The ideal characteristics of a diode are influenced by several secondary phenomena. Among these we can highlight the following:

- series resistance,
- increased reverse leakage current,
- reverse breakdown.

One of the phenomena is the series resistance of the diode, which can be most simply described mathematically as:

$$U(I) = mU_T\left[\ln\left(\frac{I}{I_{S0}} + 1\right)\right] + R_s I \qquad (8\text{-}5)$$

The series resistance of the diode causes a larger voltage drop across the diode for a given current, so the characteristic is shifted to the right. The effect of series resistance is particularly significant for higher currents.

It is also part of the real characteristic that the current starts to increase suddenly at high negative voltages. This sudden drop is usually out of the normal operating range (except for Zener diodes, for example), and can cause the diode to fail.

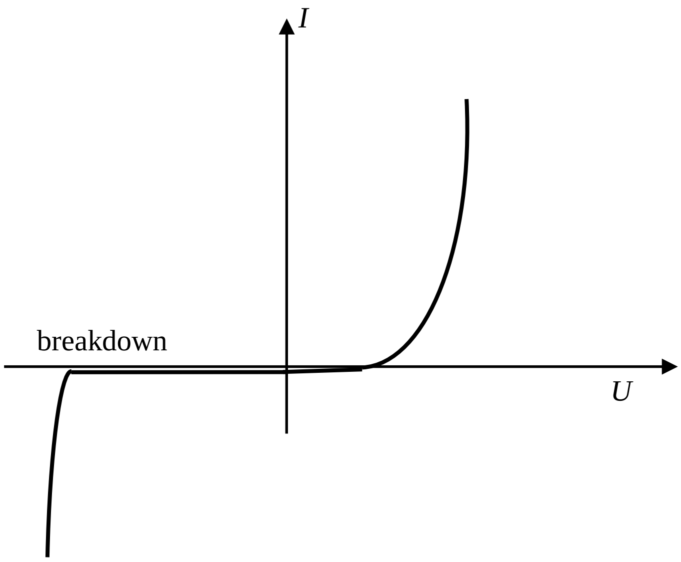


Figure 8–4. Characteristics of a real diode

Transient behavior of a diode

The transient behavior of the diode is investigated in the following theoretical setup:

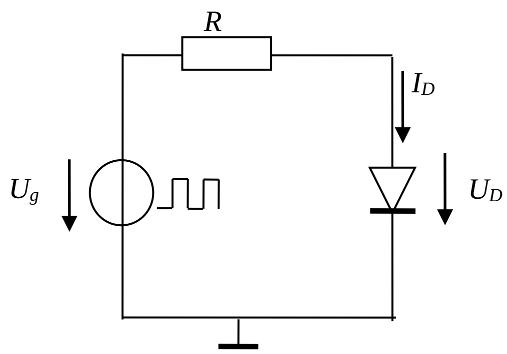
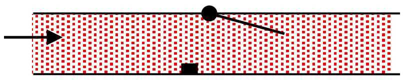


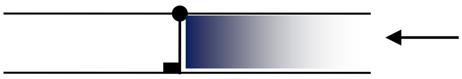
Figure 8–5. Simplified schematic diagram for diode transient test

In the following part, an illustrative explanation is shown for the transient behavior. Let's note that this simplified model doesn't describe the phenomena correctly.

Let's see Figure 8–6.! Here, the diode is modeled as a pipeline with a trap door in the middle to allow the medium (e.g. a compressible gas) to flow in one direction. The particles of the gas correspond to charge carriers (electrons or holes), their flow to electric current, and the pressure to voltage in electrical terms.



Diffusion charge: the carriers found in the diode during the diode is forward biased



space charge: in reverse biased mode, the charge which is found at the pn junction

Figure 8–6. Simple pipe model of diode for explanation of transient behavior.

Different types of charges accumulate in the device when the diode is forward or reverse biased. These charges cannot be ignored during fast switching, as they take time to accumulate and remove, which slows down the switching process. Two types of charge are distinguished

- *diffusion charge*: this charge essentially corresponds to the charge found in the diode during conduction, which embodies the current flow. The greater the current flowing in the forward direction, the greater the amount of diffusion charge. (You can think of these charges as if the diode were an open pipeline and the diffusion charge is the amount of gas flowing through it; see the left side of Figure 8–6. The greater the amount of gas flowing at a given time, the greater the amount of gas in the pipe section at a given time)
- *space charge:* this charge is dominant when the diode is closed. In the closed state of the diode, the p-n junction essentially acts as an insulating layer separating two conductive layers, essentially forming a capacitor. Thus, as the reverse voltage is increased, more and more charge is accumulated at the pn junction, called space charge. The higher the reverse bias voltage, the greater the space charge. (You can think of these charges as if the diode were a pipeline closed in the middle and the space charge were a gas that accumulates more and more as the pressure in the closed pipeline increases, see the right side of Figure 8–6).

The above charge accumulation (charge storage) phenomena are modelled with a capacitor connected in parallel with the diode, i.e. with components capable of charge storage. Note that this capacitance is largely nonlinear function of the voltage.

The switching cycle is illustrated in Figure 8–7. using the pipeline model shown. Initially, the pipeline is under negative pressure (reverse bias), so the trap door is closed and charge builds up at the pn junction (space charge). The pressure then becomes positive (forward bias) and the accumulated space charge is first removed, after which the trap door (diode) opens and the pipe fills with gas (diffusion charge is formed). At the end of the conductive state, the pressure direction is reversed and the accumulated gas (diffusion charge) in the tube is removed by the negative pressure (reverse voltage). All gas is removed from the pipeline and the trap door closes, and the accumulation of space charge begins again, so the cycle starts from the beginning. The above model does not describe the diode operation with complete accuracy, but it illustrates the main stages.

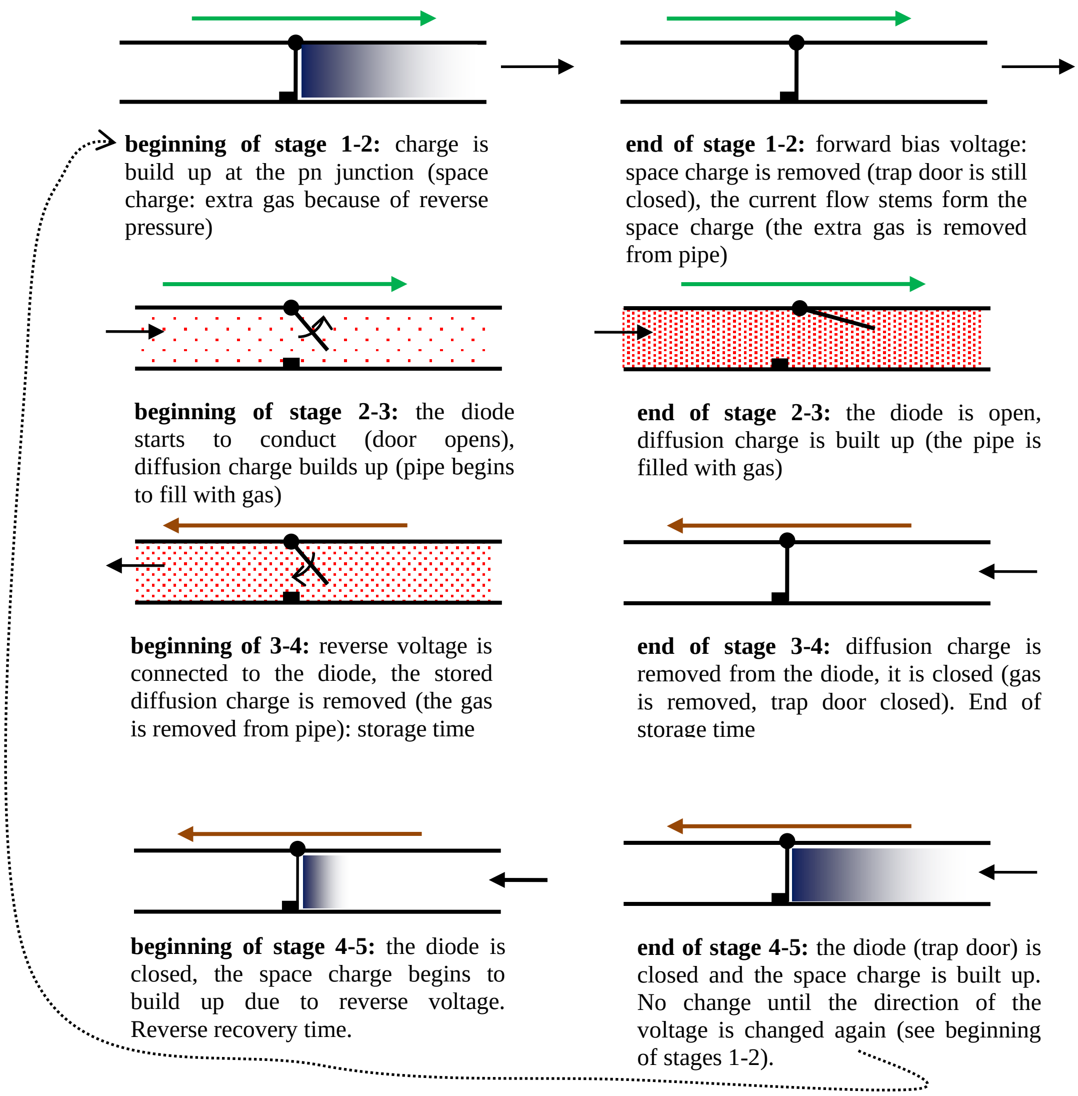


Figure 8–7. Illustration of transient behavior of diode

In the following, we will examine the switching transients of the diode, the voltage and current waveforms that are generated during switching. The circuit shown in Figure 8–5 is excited using a square wave signal and the diode current and voltage are observed. The typical signal shapes are shown in Figure 8–8 (for each stage, it is also worth observing Figure 8–7 simultaneously).

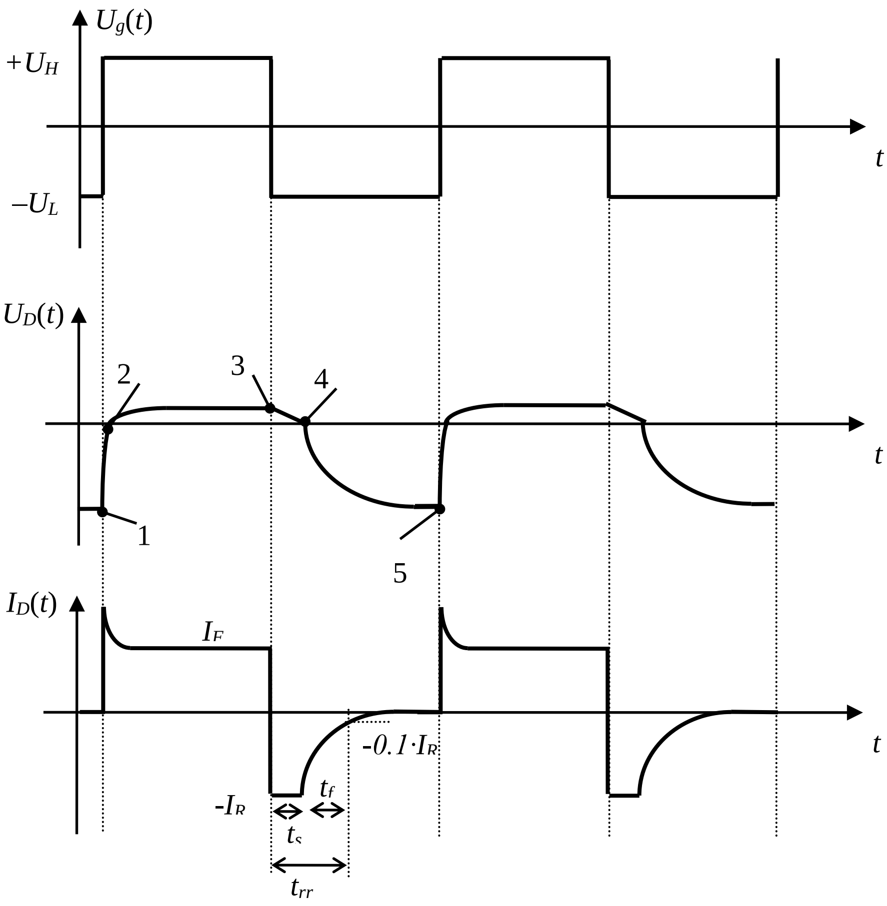


Figure 8–8. Waveforms belonging to dynamic measurements

It is assumed that the diode is initially connected to a voltage in the negative terminating direction. At each stage of the switching transient, the following processes take place:

stage 1-2: When the diode is closed, a positive opening voltage is suddenly applied. First, the space charge accumulated in the closed state must be removed, i.e. the space charge capacitance must be charged from negative voltage to zero voltage.

The voltage of the diode at the beginning of the phase (space charge capacitance charged to negative voltage):

$$U_{D1} = -U_L \tag{8-6}$$

And at the end of the stage (the space charge capacity is charged to 0 voltage):

$$U_{D2} = 0 \tag{8-7}$$

The currents are as follows:

$$I_{D1} = \frac{U_H-(-U_L)}{R} = \frac{U_H+U_L}{R} \tag{8-8}$$

$$I_{D2} = \frac{U_H}{R} \tag{8-9}$$

stage 2-3: The diode starts from the zero-voltage state at the beginning of the stage and reaches the steady-state opening voltage at the end of the stage, i.e:

$$U_{D3} = U_F \tag{8-10}$$

where U_F denotes the forward voltage. At this stage, the diffusion charge must be established (the empty pipeline is filled with gas).

If it is true for the generator voltage $U_H \gg U_F$, then the current is nearly constant (slightly decreasing towards the end of the phase)::

$$I_{D2,3} \approx \frac{U_H}{R} \tag{8-11}$$

Exactly:

$$I_{D3} = \frac{U_H - U_F}{R} \tag{8-12}$$

stage 3-4: The duration of this interval is called **storage time (t_s)**. A negative (reverse) voltage of $-U_L$ is suddenly applied to the diode when it is open. The diode voltage drops from the voltage U_F to 0 V:

$$U_{D4} = 0V \tag{8-13}$$

In the case of sufficiently high generator voltage ($U_L \gg U_F$) the current is:

$$I_{D3,4} = I_R \approx \frac{U_L}{R} \tag{8-14}$$

I_R denotes the maximum reverse current (which removes the stored charge). The reverse current is approximately constant at this stage, since the diode still contains the diffusion charge needed for opening.

stage 4-5: The diode is closed and its voltage approaches the negative U_L voltage:

$$U_{D5} = -U_L \tag{8-15}$$

The reverse current also decreases, and is used to remove the remaining diffusion charge, and to charge the space charge capacitance (the depletion layer of the pn junction) to the negative voltage of the generator. Finally, the current becomes zero (more precisely, it is equal to the negligible reverse leakage current):

$$I_{D4} = I_R \approx \frac{U_L}{R}$$

$$I_{D5} \approx 0$$

The time interval from the beginning of stage 3-4 until the reverse current disappears (or decreases to approx. 10% of the maximum reverse current) is called **reverse recovery time (t_{rr})**.

The switching process is summarized as follows. The diffusion and state charge must be built up in the on and off phases. On power-up, the space charge of the depletion layer shall be charged and the diffusion charge shall be built up. On power-down, the diffusion charge shall be removed and the charges shall be removed from the depletion layer. During these processes, the diode acts as a capacitive device and the current supplied by the generator is used to remove these charges during the turn-on and turn-off phases.

Important conclusions about the switching process:

- The accumulated diffusion charge is proportional to the forward current, so the higher the forward current (positive generator voltage), the higher the stored diffusion charge.
- The higher the reverse current (generator voltage in the reverse direction), the faster the stored diffusion charge can be removed from the diode, so the faster the diode can be forced to a closed state.

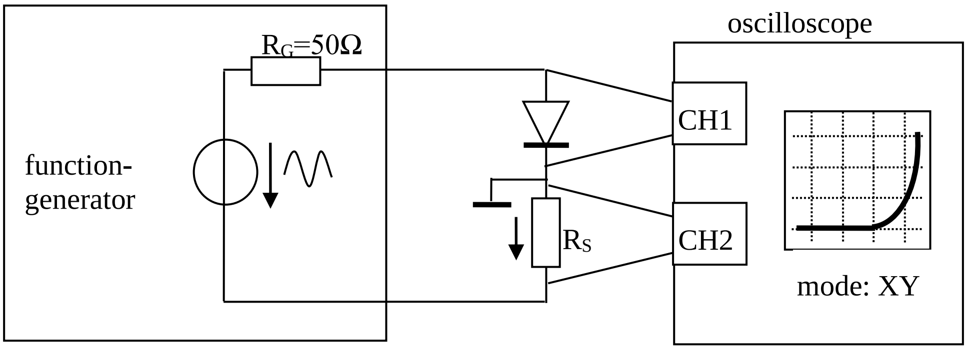
According to the above two statements, the ratio $\frac{I_F}{I_R}$ of the forward and reverse currents determines the length of the turn-off transient. The higher this ratio, the longer the storage time. In many cases, the forward current is given by design, so the turn-off time can be reduced by increasing the reverse current. Thus:

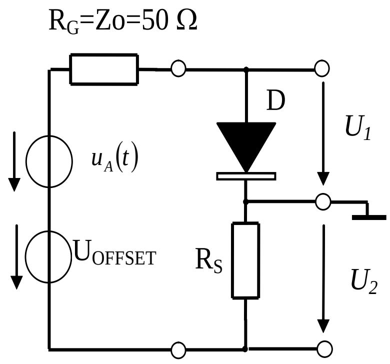
- A larger forward current creates a larger diffusion charge. So at a given reverse current: the larger the forward current, the larger the reverse recovery time.
- A higher reverse current at a given forward current removes the stored diffusion charge more quickly, so the reverse recovery time is reduced.

Measurement the static characteristics of a diode

The measurement setup is shown in Figure 8–9, and the test panel setup is given in Figure 8–10. Since the characteristics are to be displayed on an oscilloscope, which basically allows voltage measurements, the diode current measurement is reduced to a voltage measurement: the voltage across a diode in series with a resistor R_S=10 Ω is measured and the current flowing through it is calculated as follows:

$$I_D = \frac{U_2}{R_S} = \frac{U_2}{10\Omega} \quad (8\text{-}16)$$





$$u_A(t) = U_A \sin(\omega t)$$
$$0 \le U_{OFFSET} \le 5V$$

Figure 8–9. Measurement setup and schematic belonging to the measurement of static characteristics of a diode

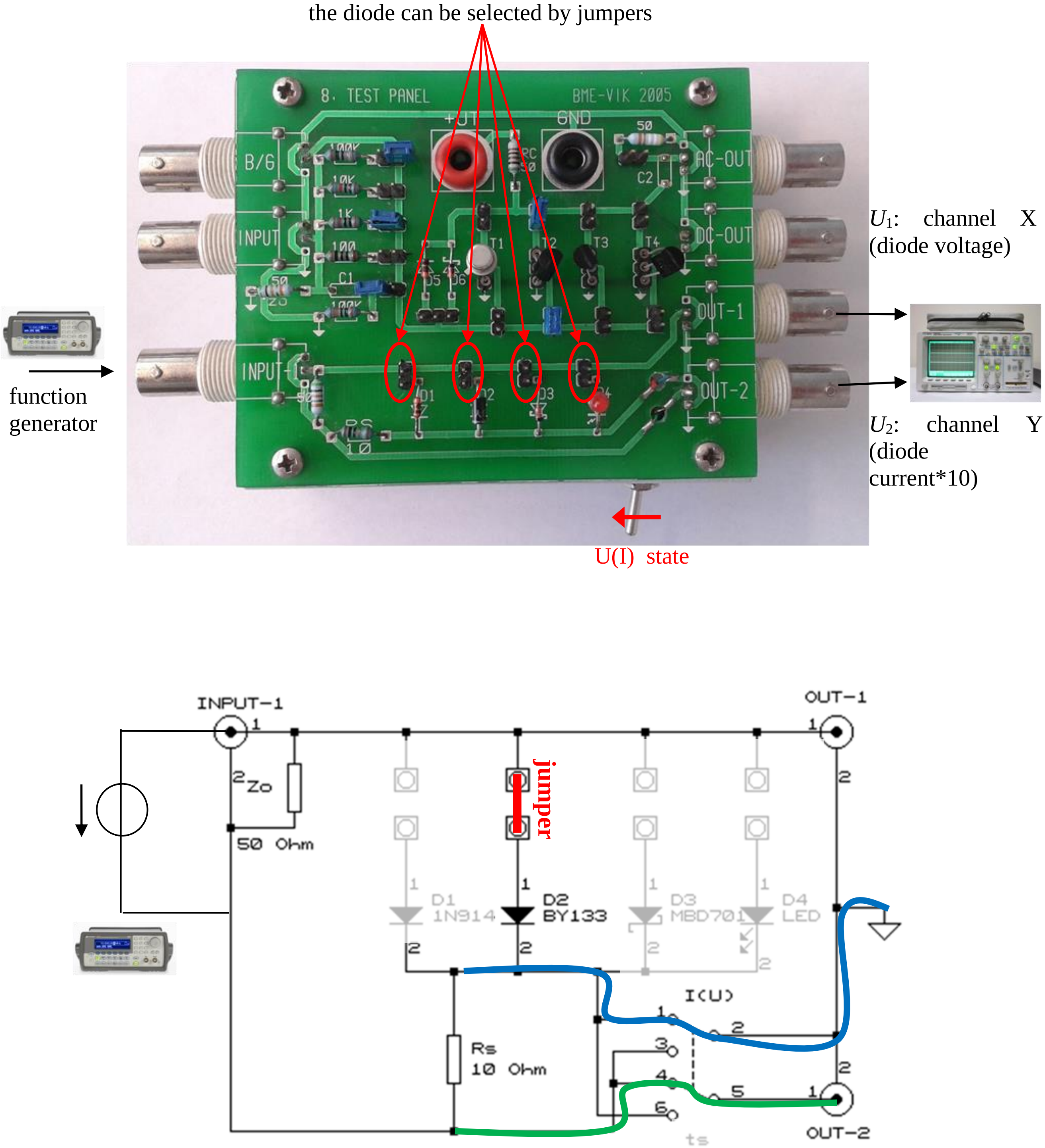


Figure 8–10. Use of a test panel during static characteristics measurement.
Bottom figure: marking of current paths at switch position U(I), diode BY133 selected with jumper, unused parts greyed out.

The characteristics are plotted using an oscilloscope in the X-Y display mode (the X axis of the display is the CH1 channel, the Y axis is the CH2 channel). To make the X axis the voltage and the Y axis the diode current, the appropriate setup must be established as shown in the diagram.

Attention! In the design of the connection, we have taken advantage of the fact that the available generators are capable of providing a low-frequency output independent of ground (*floating output*). This may not be true for all instruments in general. This makes it possible to ground the common point of the diode and the RS resistor in the measurement arrangement, so that both current and voltage can be measured separately. The ground point on the panel cannot be selected by simply connecting the cables, but by setting the switch on the side of the panel to the appropriate position (see Figure 8–1 and Figure 8–2). The bottom of Figure 8–10. shows that the ground point is connected to the common point of the diode and the current sensing resistor (blue line) when the switch is set to U(I) and the output OUT-2 is connected to the negative point of the current sensing resistor (green line).

The oscilloscope allows the scaling of the individual channels, accordingly channel CH2 should be set to display 1/10 part of the measured voltage and the dimension should be set to current [A]. It is also important to note that since channel CH2 measures a voltage with the opposite sign to the reference voltage, the inverting function should be enabled during measurement.

As an excitation signal, you can choose any signal that is continuous, does not contain large jumps, and can sweep through the appropriate input voltage range (e.g. triangle or sine wave is fine, but saw or square wave is not!). In this measurement, sine excitation is used for this purpose. It could be a little misleading that a sinusoidal signal is usually used to measure the transfer function of linear systems, in this case we are measuring static transfer characteristics.

The low and high levels of the excitation signal must be chosen to be able to scan the voltage range we need, so the high level must reach the diode's opening voltage and the low voltage must drive the diode to a closed state. There is also a 50 Ω input termination resistor on the test panel, so it is a good idea to fit the generator to a 50 Ω input resistor (Utility → Output setup → 50 Ω load).

When measuring static characteristics, the frequency of the excitation signal should be chosen so that the transient properties do not yet appear in the characteristics. If the frequency is too high, the capacitive components of the diode are already detectable. During the falling edge, even negative-direction currents of measurable magnitude may then flow, leading to the looping of the characteristic as shown in Figure 8–11.

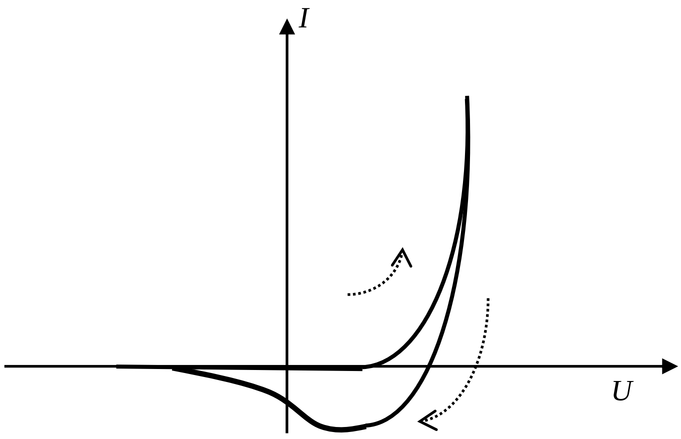


Figure 8–11. Diode characteristic looping for an excitation signal with too high frequency.

Four different diode characteristics are measured: high current Si diode, low current Si diode, Schottky diode, LED. The diode to be measured is selected using the jumpers on the panel (see Figure 8–1 and Figure 8–2).

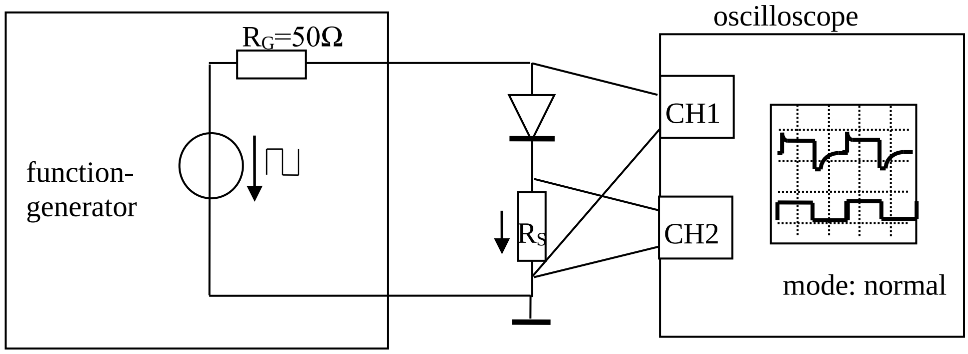
Measurement of transient times of a diode

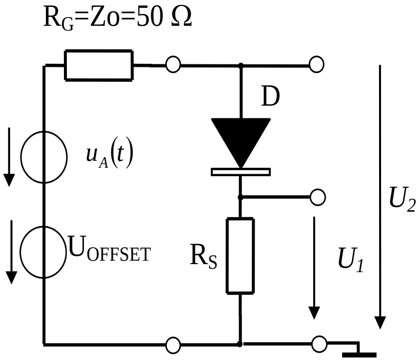
The arrangement used to measure the transient behavior of the diode is identical to that used to measure the static characteristics, except for the ground point, see Figure 8–12. and Figure 8–13. Since at the frequencies of the excitation signal used for the measurement, the generator cannot be considered as a floating supply, both the negative output of the generator and the ground point of the oscilloscope inputs must be connected to the same point.

To measure the static and transient characteristics, the test setup does not need to be modified, but *the switch on the side of the test panel must be set to the appropriate position to swap the ground points* (Figure 8–2). On the oscilloscope, the inversion of channel 2 must be switched off. As shown in the lower part of Figure Figure 8–13, with the switch at the bottom of the panel in position ts, the lower point of the current sensing resistor Rs is grounded (blue line) and the common point of the diode and resistor is brought out to the OUT-2 output (compare with Figure 8–10.).

Attention! In this case, the voltage on channel CH1 is not the diode voltage, but the sum of the diode voltage and the current sensing resistor voltage! During the measurement, we are mainly looking at the current waveform, so this is not a problem. To plot the diode voltage, the difference between channels 1 and 2 must be displayed in MATH mode.

During the measurement, the rising edge of the excitation signal is limited to 100 ns to avoid interference due to the steep edge change and transients caused by the parasitic inductance/capacitance of the leads. Accordingly, the signal generator should be used in pulse mode (not square wave), because only the rising edge slope can be limited here.





$$u_A(t) = U_A \, \mathrm{sqr}(\omega t)$$
$$0 \le U_{OFFSET} \le 5V$$

Figure 8–12. Measurement setup and schematic belonging to the measurement of dynamic characteristics of a diode

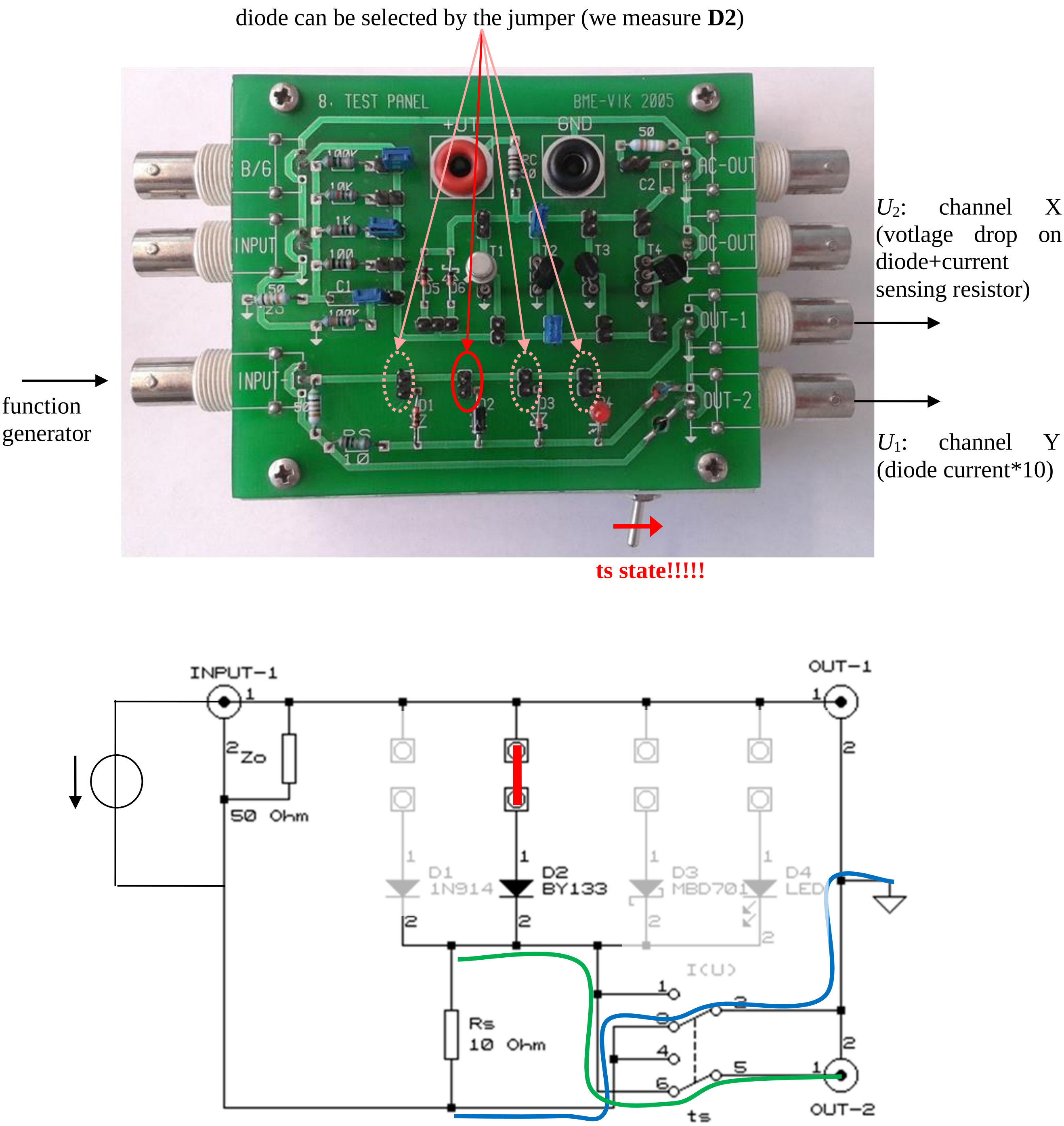


Figure 8–13. Using a test panel to measure dynamic behaviour.
Bottom figure: marking of current paths in position ts of switch, diode BY133 selected with jumper, unused parts greyed out.

Measurement of bipolar transistor parameter

Equations and characteristics describing the large-signal behaviour of a transistor

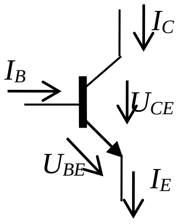


Figure 8–14. Schematic symbol of transistor

The large-signal operation of ideal transistor is given by Ebers–Moll-model:

$$I_E(U_{BE}) = I_{S0}\left(\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right) \tag{8-17}$$

As described for the diode, the base-emitter voltage for a Si transistor can be considered constant for high-signal operation to a first approximation: $U_{BE}\approx 0.7$ V.

The collector current follows the value of the base current in a manner proportional to the so-called current amplification factor (B):

$$I_C = B \cdot I_B \tag{8-18}$$

The emitter current is the sum of the base and collector currents:

$$I_E = I_C + I_B \tag{8-19}$$

Putting together the above equations:

$$I_E = (B + 1)I_B \tag{8-20}$$

The above equations are true as long as the transistor operates in the so-called *normal active* region, i.e. the base-collector pn junction is not open.

The region when the base-collector pn junction is biased in the opening direction ($U_{BC} > 0$) is called the *saturation region*. At this point the base current is already contributed by the base-collector transition current.

One of the most common ways to characterize transistors is to define their output characteristics (see Figure 8–15.).). The output characteristic is a curve of the collector current versus collector-emitter voltage: $I_C(U_{CE})$. The curves are usually parameterized according to the base current ($I_{B1}, I_{B2} \ldots$).

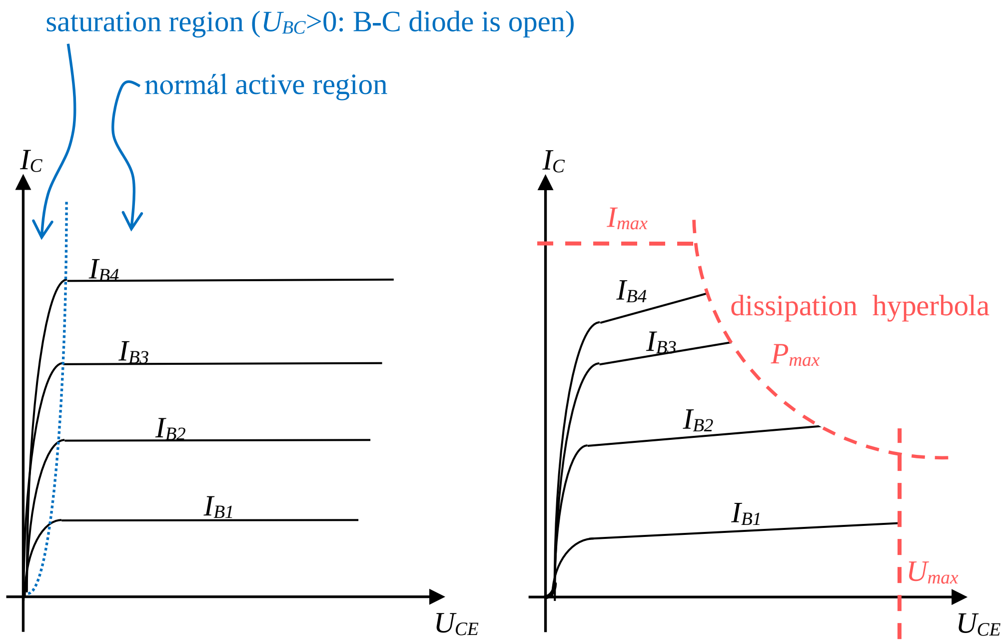


Figure 8–15. Transistor output characteristics: left: ideal, right: real

The blue dotted line on the characteristics shows the saturation limit.

Although not part of the characteristics, the red dashed line also indicates the so-called dissipation hyperbola and the maximum allowed voltage and current, which are typical limits for transistors. The dissipation hyperbola, I_{max} és U_{max} delimit the range within which the device can be operated without failure (e.g. overheating due to dissipation, breakdown). This safe area is called the Safe Operating Area (SOA). The maximum current and voltage designations are relatively straightforward, with little explanation required for the dissipation hyperbola. Let the maximum dissipation be P_{max}. The dissipation of the transistor due to the minimum base current is mainly given by the power dissipated at the collector-emitter junction, which must be true:

$$U_{CE} \cdot I_C \leq P_{max} \rightarrow I_C \leq \frac{P_{max}}{U_{CE}} \qquad (8\text{-}21)$$

It can be seen that the area where the dissipation of the device is less than the allowed one is indeed a hyperbola, i.e., $\frac{1}{x}$ nature.

In addition to the maximum dissipation, the limiting data usually include I_{Cmax}, U_{CEmax}, base-emitter maximum reverse voltage, maximum/minimum temperature ...

The real characteristics differ from the ideal in the following main points:

- The output curves are not horizontal in the normal active region. This is because the output conductance is not zero, and the output current increases with increasing voltage. The slope of the characteristic gives the output conductance. The output conductance is usually at least tens or hundreds of kΩ (a few μS).

- Even if the base currents given as parameters vary uniformly, the spacing of the characteristics is not uniform. This is because the current gain *B* depends on the collector current.

Operation point setting

The tests for setting the working point are carried out as shown in Figure 8–16. The large-signal model is used for calculation. The base-emitter junction is modeled with a voltage generator U_{BE} (the voltage is approximately 0.7 V at room temperature), and the collector current is *B*-times of the base current.

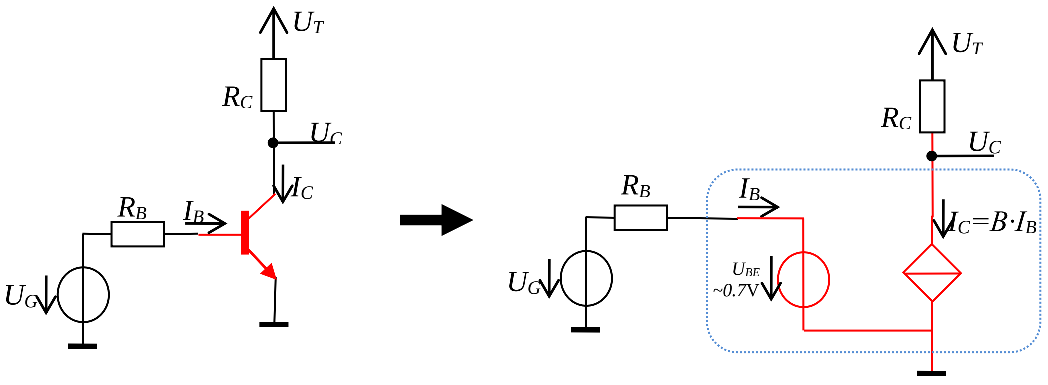


Figure 8–16. Operation point setting and large-signal model

System equations:

$$I_B = \frac{U_G - U_{BE}}{R_B} \tag{8-22}$$

$$I_C = B \cdot I_B \tag{8-23}$$

$$U_C = U_T - R_C \cdot I_C \tag{8-24}$$

The transistor operates in the normal active range as long as the collector potential is greater than the base potential. Accordingly, at the saturation limit $U_C = U_{BE}$, so:

$$I_{C,lim} = \frac{U_T - U_{BE}}{R_C} < \frac{U_T}{R_C} \tag{8-25}$$

The corresponding base current and generator voltage:

$$I_{B,lim} = \frac{I_{C,lim}}{B} \tag{8-26}$$

$$U_{G,lim} = I_{B,lim} R_B + U_{BE} \tag{8-27}$$

In linear mode (normal active region), the generator voltage can usually be separated into two components:

$$U_G(t) = U_{G0} + u_G(t) \tag{8-28}$$

where U_{G0} is the DC component responsible for operation point setting, and $u_G(t)$ is the AC component.

Measurement of transistor operating point setting and saturation point

The schematic circuit diagram for the measurement and the layout of the measurement panel are shown in Figure 8–17. and Figure 8–18 .

In this case, the panel requires an external power supply. The supply voltage to be set is 5 V, supplied by the external lab power supply. The measurement of the collector current is also necessary, which is done with a digital multimeter connected in series with the power supply.

The excitation signal is connected to the top input marked INPUT on the left side of the panel. Attention! The input of the panel has a 50 Ω termination, so the signal generator connected to the input must be configured for a 50 Ω load (Ulitlity → Output setup → 50Ω load), otherwise you have to manually multiply the specified voltages by two. The input voltage can be measured using a T-connector. The panel provides the possibility to measure back the base-emitter voltage at the B/G output.

On the panel, the transistors can be selected using jumpers (two jumpers). The base resistance can also be configured using a jumper in the range 100 Ω ... 100 kΩ (1 kΩ is used for the measurement). The transistor collector voltage can be measured with DC and AC coupling at the DC-OUT and AC-OUT outputs.

Measurement of current gain

In the first part of the measurement, the current gain B is determined. The measurement is carried out with a BC639 transistor, because this type is able to switch the correct current without noticeable degradation of its parameters. During the measurement, the DC voltage on the signal generator connected to the input of the panel is switched to a voltage level where the transistor is not yet driven into saturation (1 V…1.5 V). The base current is then calculated using the following formula:

$$I_B = \frac{U_{in} - U_{BE}}{R_B} \tag{8-29}$$

The voltage U_{BE} can be measured at output B/G or can be estimated as 0.7 V. The collector current I_C can be measured with a multimeter, and the current gain is:

$$B = \frac{I_C}{I_B} \tag{8-30}$$

Unfortunately, the AC component of the signal generator cannot be disabled completely. For this measurement, enter 0 V and it will automatically set to the lowest value, but this will not interfere with the measurement.

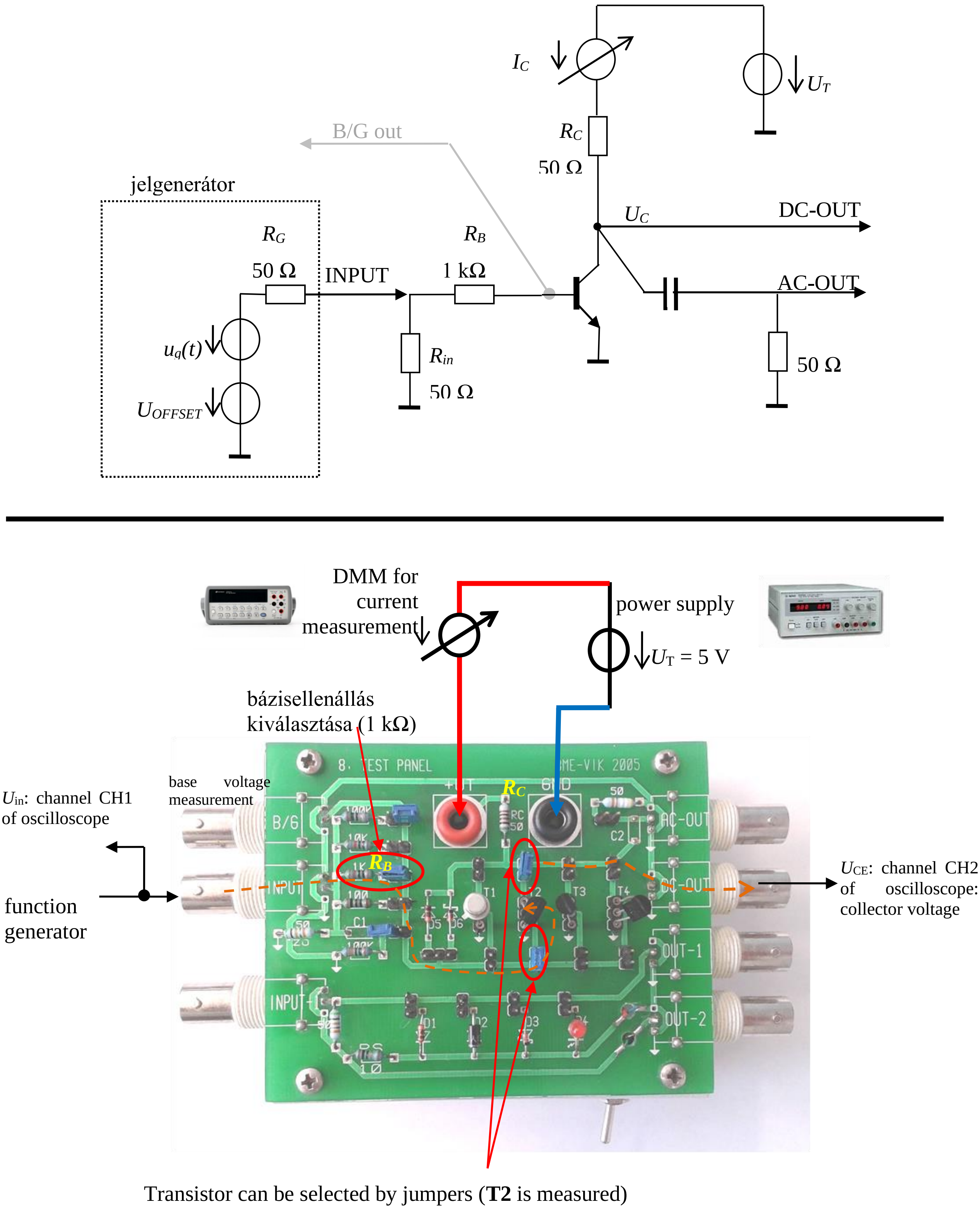


Figure 8–17. Using a test panel while measuring a transistor. Top: schematic diagram, bottom: drawing of test panel showing the connection points

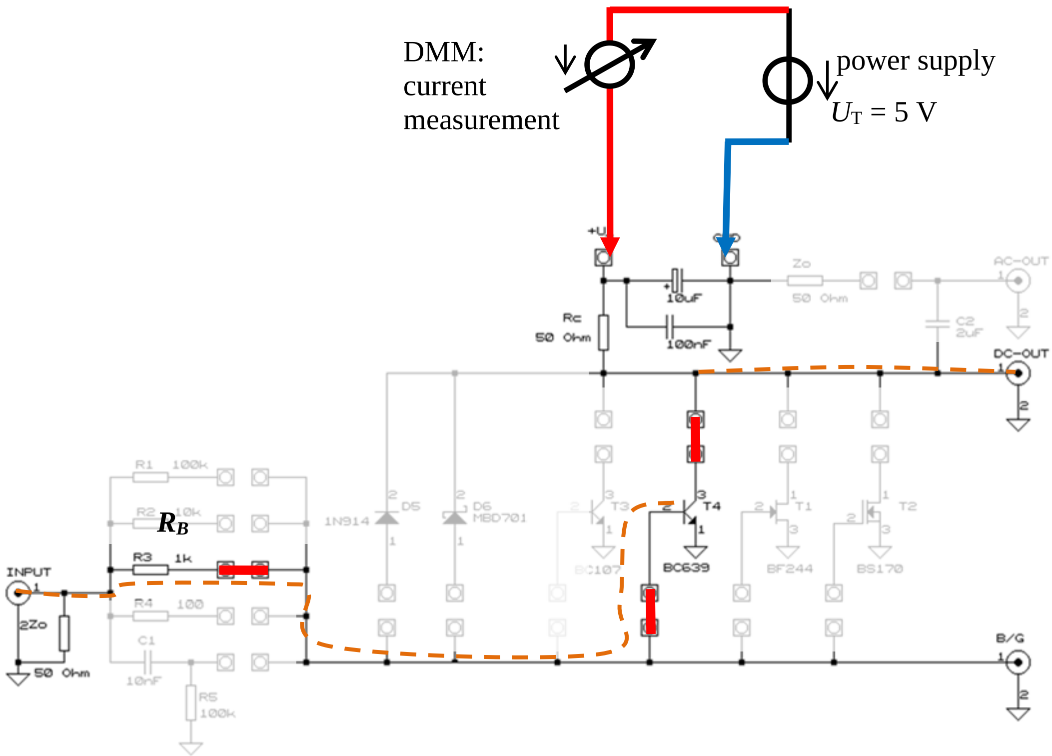


Figure 8–18. Test panel configuration (on schematic diagram). Configuration selected with jumpers: resistor RB=1 kΩ, transistor BC639. Components not used in a given configuration are greyed out. The 10 µF and 100 nF capacitors filter the supply voltage and play no active role in the measurement.

Measurement of saturation point and switching characteristics

The input voltage U_{Glim} , which drives the transistor into saturation, can be calculated from equation (8-27) and the two preceding formulas. The supply voltage is 5 V, the collector resistance is $R_C = 50\ \Omega$ and the base resistance is $R_B = 1\ k\Omega$. The base-emitter voltage can be considered as 0.7 V.

During the measurement, a triangular signal is applied to the input, which "scans" the entire input signal range (note that any continuous signal is appropriate, e.g. a sine wave). The frequency should be chosen so that transients do not have any effect; for example, in the measurement, choose 100 Hz. The low level of the excitation signal should be 0 V and the high level should be such that the transistor is driven into saturation surely (e.g. 3 V).

The voltage waveforms expected during the measurement are shown in Figure 8–19. In blue, a triangle signal connected to the input is shown, in red the collector voltage measured at the output is shown. Starting from time zero, at time t_1 the input voltage reaches the opening voltage of the transistor U_{open}. From this point current flows through the base and the collector, so the collector voltage starts to decrease due to the voltage drop on the collector resistor. The collector current increases in a roughly linear fashion (collector voltage decreases) until the transistor reaches saturation (see time instant t_2): at this point the input voltage reaches the voltage $U_{G,lim}$ given by equation (8-27). The transistor is then out of the normal active range, and the base-collector diode opens. The collector potential then continues to decrease slightly in a non-linear fashion, until the saturation voltage $U_{CE,sat}$ is achieved. The input signal starts to decrease after reaching the peak value, and at time t_3 the transistor is out of the saturation region and at time t_4 the transistor is closed.

Figure 8–20. shows a real measurement result where the phenomena described can be clearly identified.

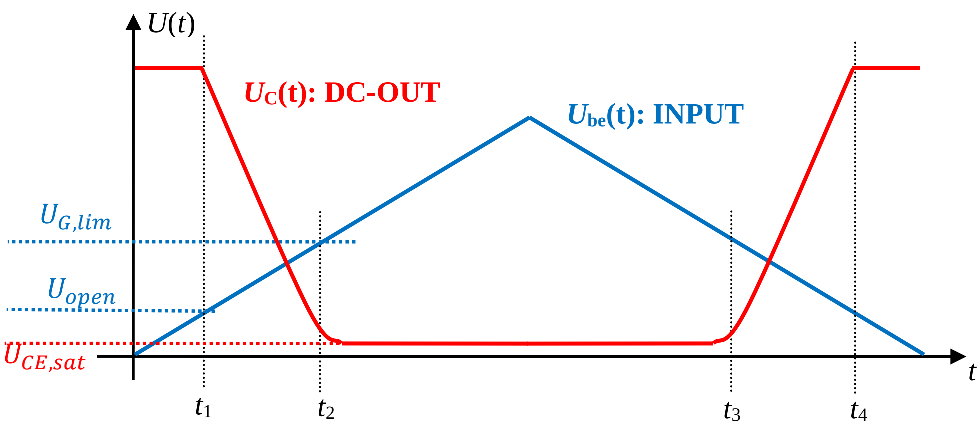


Figure 8–19. Signal waveforms during transistor switching characteristics measurement. Blue: excitation signal, red: collector voltage.

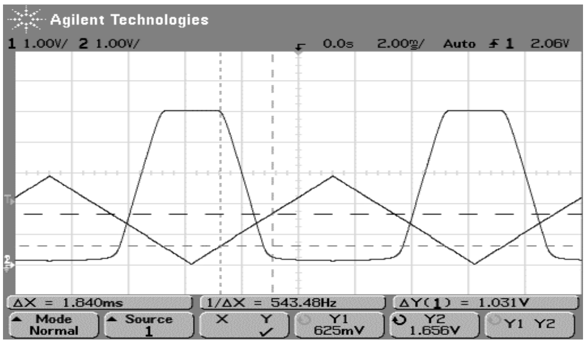


Figure 8–20. Transistor switching characteristics (real measurement).

Test questions

1. Draw the block diagram of each measurement setup!
2. Draw the $U_D(I_D)$ forward characteristic of a diode!
3. Give the characteristic equation of the “ideal diode”. What other effects shall be taken into account in case of a real diode!
4. What is experienced in the case of static characteristics measurement when excitation frequency is increased?
5. What causes the storage time of semiconductor devices?
6. Draw the time diagram of the current of a diode driven by an ideal square wave! Define in your diagram the followings: forward current (I_F), reverse current (I_R), storage time (t_s), reverse recovery time (t_{rr}).
7. If we increase the forward current of a diode, then:

   a, diffusion charge: increases / decreases / doesn’t change?

   b, space charge: increases / decreases / doesn’t change?

   c, reverse recovery time (at a given reverse current): increases / decreases / doesn’t change?
8. If the reverse current is increased (negative excitation voltage is increased at a given source resistance), then:

   a, diffusion charge: increases / decreases / doesn’t change?

   b, space charge: increases / decreases / doesn’t change?

   c, reverse recovery time (at a given reverse current): increases / decreases / doesn’t change?
9. Draw the common emitter output characteristics! Let’s denote the border between normal active and saturation region.
10. What are the most important maximum ratings of the power semiconductors?
11. What is the dissipation hyperbole?
12. What is the safe operating area (SOA)?
13. What is approximately the maximum current (I_{CMax}) of the given circuit? What is the necessary base current (I_{Blim}) to drive the transistor into saturation?