CHARACTERISTICS OF BIPOLAR JUNCTION TRANSISTOR

In addition to this instructions, please read the following chapters in the book 'Basic electronics for scientists and engineers' by D. L. Eggleston:

4.2. Bipolar transistor fundamentals,
4.3. DC and switching applications,
4.4. Amplifiers:
    4.4.1. The universal DC bias circuits
    4.4.3. AC equivalents for bipolar junction transistor
    4.4.8. Distortion

Additional resources:
https://www.electronics-tutorials.ws/transistor/tran_1.html
https://www.electronics-tutorials.ws/transistor/tran_2.html
https://www.electronics-tutorials.ws/transistor/tran_8.html (only BJT transistor)

Transistor is a semiconductor electronic element with two PN junctions. For comparison, semiconductor diode has only one PN junction. In unipolar transistor (field effect transistor, FET), the current is carried only by one type of charge: positive (holes) or negative (electrons), so FET transistor can be n-FET or p-FET. In FET, the current is determined by majority charge carriers. Both types of charge (electrons and holes) contribute to the current through the bipolar transistor (bipolar junction transistor, BJT), so the current consists of both majority and minority charge carriers.

Bipolar transistor has three electrodes: emitter (E), base (B) and collector (C). Unipolar transistor also has three electrodes: source (S), gate (G) and drain (D). Depending on the types of the extrinsic semiconductors present in the emitter, base and collector, two types of bipolar transistors are possible: PNP and NPN. In PNP bipolar transistor, emitter and collector are made of p-type semiconductor and base is made of n-type semiconductor. Consequently, holes are majority charge carriers in emitter and collector, while electrons are majority charge carriers in base. The opposite is true for NPN bipolar transistor: electrons are majority charge carriers in emitter and collector, while holes are majority charge carriers in base.

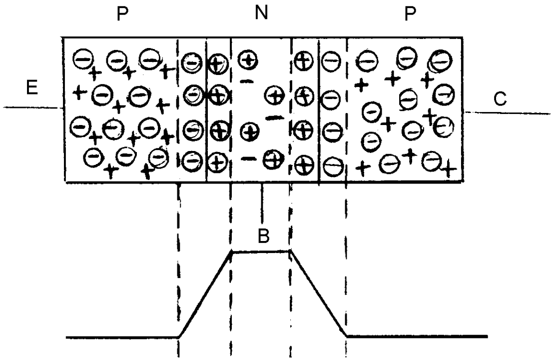


Figure 1. *Unbiased bipolar PNP transistor*

Similar to the semiconductor diode where potential barriers and depletion region are formed at the PN junction of the two types of the semiconductors, in transistor two such potential barriers and depletion regions are present, each at the two PN junctions (fig. 1). If collector and emitter are connected with the battery (power supply) so that the voltage (difference of electric potentials) between collector and emitter is U_{CE}, one PN junction will be forward biased, and one reverse biased regardless the polarity of U_{CE} voltage. If the barrier between emitter and base is increased so that the PN junction is reverse biased, the current will not flow through the transistor regardless of the forward bias of the second PN junction. If the barrier between emitter and base is lowered so that the PN junction is forward biased, the second PN junction between base and collector must be reverse-biased in order for transistor to operate. Active operating transistor must be biased as shown on figure 2.

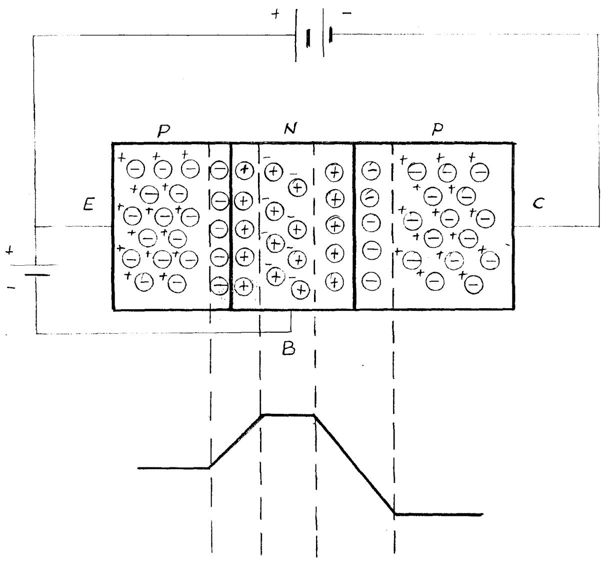


Figure 2. *Correctly biased PN junctions in a bipolar transistor connected to the external power supply (battery)*

In PNP transistor, holes are majority charge carriers in emitter. If the potential barrier between emitter and base is lowered by external power supply (battery), PN junction between emitter and base becomes forward-biased and more holes can flow from emitter to the base. Electrons are majority charge carriers in the base. Therefore, holes that flow from emitter to the base become minority charge carriers in the base. Holes, which are minority charge carriers in the base, encounter electrons while travelling through the base. Consequently, holes recombine in the base and a lower number of holes reach PN junction between base and collector than the number of the holes that entered base from the emitter. In order for holes to pass through the potential barrier of the second PN junction between base and collector, the PN junction has to be reverse biased as the holes are minority charge carriers in the base. As it was shown in a reverse-biased diode, only minority charge carriers can flow through the reverse biased PN junction, while the majority charge carriers are stopped due to the potential barrier.

To summarize, the current that flows through the bipolar transistor is a current of the reverse-biased PN junction between base and collector, as shown on figure 2 for a PNP transistor. Transistor is mainly used as an amplifier, so the goal is to increase this reverse-bias current. This reverse-bias current can be increased by lowering the potential barrier between emitter and base, i.e. by increasing the voltage U_{BE} of the forward-biased PN junction between emitter and base (fig. 2). This can be achieved by connecting emitter and base to the external power supply (battery) that will provide the voltage U_{BE}. In forward-biased emitter-base junction, the number of holes in the base (minority charge carriers) is increased as they flow from the emitter (majority charge carriers) by diffusion through the barrier. More holes will reach collector and increase the current through the transistor if their recombination with the electrons in the base is lowered. This can be achieved by decreasing the width of the base and by lowering the impurity concentration in the base. If the base is less doped with less impurity, the concentration of majority charge carriers (electrons) will be lower, reducing the recombination processes. This also reduces the electron component of the current from the emitter as it does not contribute to the transistor amplification (remember, only hole component of the current from the emitter is important). The width of the base can be also reduced by increasing the size of the depletion region, which can be achieved by increasing the reverse-bias voltage between base and collector. This reverse-bias voltage is increased if the voltage between collector and emitter is increased. Consequently, the current through the transistor, i.e. the current through the collector will increase if the voltage U_{CE} between collector and emitter is increased.

Electrons lost in the recombination with the holes in the base must be replaced from an external source that has the required voltage U_{BE}, and such electrons form the base current I_B. The number of recombinations is very small, so the base current is also expected to be very small, much smaller than the current I_E through the emitter and current I_C through the collector. The base current can be considered as the current 'lost' in the transistor, so that the emitter current is decreased to the value of the collector current by the amount of the base current:

$$I_E = I_C + I_B$$

As the base current is much smaller than the collector current, it follows:

$$I_E \approx I_C$$

If the number of holes (minority charge carriers in the base) is increased in the base as the emitter current I_E increases, the number of recombinations in the base will increase and the base current I_B also increases. Consequently, the collector current I_C through the reverse-biased base-collector junction will also increase.

For a transistor to function properly, base-collector junction must always be reverse biased, so $|U_{CE}| > |U_{BE}|$ for a transistor in **active** working conditions. If $|U_{CE}| < |U_{BE}|$, both PN junctions, collector-base and base-emitter junctions, are forward-biased and the transistor is in **saturation** and not in the active working conditions. If both PN junctions are reverse-biased, the transistor is in **cutoff** conditions.

Circuit configurations with a bipolar transistor

Transistor should be connected into a circuit in a specific configuration in order to use it as a voltage or current amplifier. Configuration depends on the intended use of the transistor and of the circuit. Electrodes of the bipolar transistor can be connected in three different configurations:

a) common base (amplifier),
b) common emitter (amplifier),
c) common collector (amplifier).

One of the three electrodes is connected to the input signal, the second electrode is connected to the output signal, while the third electrode is usually grounded, belongs to both the input and output circuit and is called common electrode. Therefore, a simplest circuit with the bipolar transistor has in two electric circuits: input and output circuit. The direction of the current flow is represented by the arrow on the symbol of the transistor (fig. 3) and is considered to be positive. Voltages between electrodes are differences between electric potentials of the each of the two non-grounded electrode and of the grounded electrode. So, in a common emitter amplifier, we will measure voltage U_{BE} between base and grounded emitter, and voltage U_{CE} between collector and grounded emitter (fig. 3). If PNP transistor is connected in common emitter circuit, base and collector currents are negative as their directions are opposite from the defined ones (fig. 3).

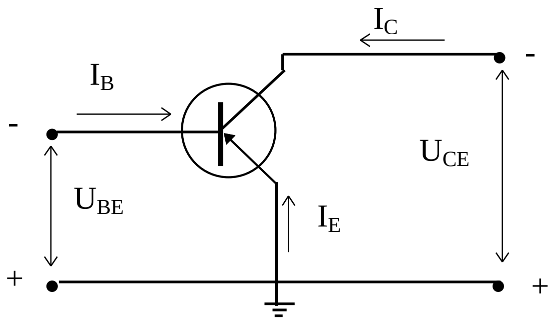


Figure 3. *Bipolar transistor of PNP type in common emitter circuit*

Common emitter amplifier

Transistor in a common emitter circuit works as a signal amplifier. Input circuit consists of the base current I_B and voltage U_{BE} between base and grounded emitter, and they represent input values. Output circuit consists of the collector current I_C and voltage U_{CE} between collector and emitter, and they represent output values. Three working conditions are possible: linear **active** region, **saturation** region and **cutoff** region. Transistor has its base-emitter junction forward biased and its base-collector junction reverse biased in the linear active conditions.

There are two types of signal amplifications, depending on the amplified quantity:

a) amplification of the current, described by the current amplification factor (β), and
b) amplification of the voltage, described by the voltage amplification factor (β_u).

Amplification factor or gain, determine the ratio between the output and input value of the corresponding quantity (current or voltage). Therefore, current amplification factor or current gain determines the ratio between output and input current, and voltage amplification factor or voltage gain determines the ratio between output and input voltage. In a common emitter amplifier, the amplification factors (gains) are:

$$\beta = \left(\frac{dI_C}{dI_B}\right)\bigg|_{U_{CE}} \qquad \beta_u = \left(\frac{dU_{CE}}{dU_{BE}}\right)\bigg|_{I_C}$$

This means that, for the current amplification, the base and collector currents varies, while the voltage between collector and emitter remains constant. Similarly, for the voltage amplification, the voltages between collector and emitter and between base and emitter are changed, while the collector current remains constant. Both amplification factors are determined only for alternate current/voltage.

We can also determine static or DC gain which is a ratio between output and input DC quantity (voltage or current). Static or DC current gain is:

$$B = \frac{I_C}{I_B}$$

For collector currents in the linear active region:

$$\beta \approx B$$

Collector current is much larger than the base current. Collector current is a large part of the emitter current that reaches the collector. Part of the emitter current is lost due to the recombination in the base, but this loss is small, $I_C \lesssim I_E$, and forms the base current. Around 95% - 99% of emitter current reaches the collector and forms collector current. Current gain usually has the value:

$$20 < \beta < 200$$

Static DC characteristics and parameters of the transistor in common-emitter amplifier

Static I-U characteristics describe the behaviour of DC input and output quantities, such as currents and voltages. Hybrid parameters can be obtained from I-U characteristics of the transistor.
Transistor connected into a circuit in all three possible configurations always has two input and two output quantities, so four different characteristic curves can be obtained for common-emitter amplifier. Each of the four characteristic curves describe the dependency of the two quantities, while the third quantity remains a constant parameter.

Characteristics of a common-emitter amplifier are:

1. input characteristic,
2. forward current gain characteristic,
3. reverse voltage gain characteristic,
4. output characteristic.

Input characteristic:

$$I_{BE} = f(U_{BE})|_{U_{CE}}$$

Input hybrid parameter determines the differential input resistance:

$$h_{11} = r_{BE} = \left(\frac{dU_{BE}}{dI_B}\right)\Big|_{U_{CE}}$$

Forward current gain characteristic:

$$I_C = f(I_B)|_{U_{CE}}$$

Corresponding hybrid parameter determines the forward current gain:

$$h_{21} = \beta = \left(\frac{dI_C}{dI_B}\right)\Big|_{U_{CE}}$$

Reverse voltage gain characteristic:

$$U_{BE} = f(U_{CE})|_{I_B}$$

Corresponding hybrid parameter determines the reverse voltage gain:

$$h_{12} = v_f = \left(\frac{dU_{BE}}{dU_{CE}}\right)\Big|_{I_B}$$

Output characteristic:

$$I_C = f(U_{CE})|_{I_B}$$

Output hybrid parameter determines differential output conductivity:

$$h_{22} = \frac{1}{r_{CE}} = \left(\frac{dI_C}{dU_{CE}}\right)\Big|_{I_B}$$

Operating point, Q-point or quiescent (silent) point is a point in transistor characteristics in which the transistor works. Variations of currents and voltages takes place around this point when input AC signal is applied.

All four characteristic curves are non-linear and the values of the hybrid parameters depend on the operating point of the transistor. Mathematically, hybrid parameters are slope coefficients of the tangent of the corresponding characteristic curve in a chosen operating point.

Hybrid parameters can be determined from such characteristics if corresponding physical quantities (voltages and currents) vary. For an adequately short interval, characteristic curve of the transistor can be linearly approximated, and mean square method can be used to determine hybrid parameter in each of the small, but finite linear segments. Hybrid parameter should be determined in a segment that contains operating point and the close neighbourhood.

As an example, differential input resistance r_{BE} which corresponds to the h_{11} hybrid parameter, can be found in the neighbourhood of the operating point Q (U_{BEQ}, I_{BQ}) for a constant U_{CE} by discrete variations of ΔU_{BE} and ΔI_B on a short, approximately linear segment of the input characteristic curve. This segment is, of course, determined by the operating point Q and its near neighbourhood.

Practically, input and output characteristics are mostly used as the other two characteristics can be obtained from them.

Input characteristics

Input characteristic curves (fig. 4) are functions $I_{BE} = f(U_{BE})|_{U_{CE}}$, which are I-U characteristics of the forward biased junction between emitter and base. Forward current through the PN junction is:

$$I_B = I_{BS}\left(e^{\frac{U_{BE}}{U_T}} - 1\right) \approx I_{BS}e^{\frac{U_{BE}}{U_T}}$$

for large forward-biased voltages U_{BE} such that $U_{BE} >> U_T$. Temperature equivalent U_T is $U_T = \frac{kT}{e}$. At a room temperature, T = 300 K, U_T is very small, only 26 mV.

Current in the base (I_B), which is a current through the PN junction between emitter and base, rises exponentially as the forward bias voltage U_{BE} is increased and the potential barrier between base and emitter lowered. Input I-U characteristic is shown on figure 4 where this rise is clearly visible. The I-U characteristic curve shifts to the right, toward higher voltages U_{BE} for a smaller absolute value of the voltage between collector and emitter, U_{CE}. This voltage, U_{CE}, provides the necessary reverse bias of the base-collector junction if $|U_{CE}| > |U_{BE}|$. The reverse bias voltage between base and collector increases if $|U_{CE}|$ increases. This means that the depletion region between base and collector will increase, mostly into the base, less doped semiconductor with less impurities. Therefore, the effective width of the base has to decrease, which also means that less holes and electrons can recombine in the base. This in turns decrease the recombination current, which corresponds to the base current. So, for a chosen U_{BE}, the base current will be lower for a larger $|U_{CE}|$ and the characteristic curve shifts to the right.

If we consider constant base current I_B, then an increase of $|U_{CE}|$ will also cause increase in U_{BE}. This means that the output voltage ($|U_{CE}|$) influences input voltage (U_{BE}), which is described by the reverse voltage gain v_r. This hybrid parameter has very small finite value in a real transistor, while it vanishes in an ideal transistor.

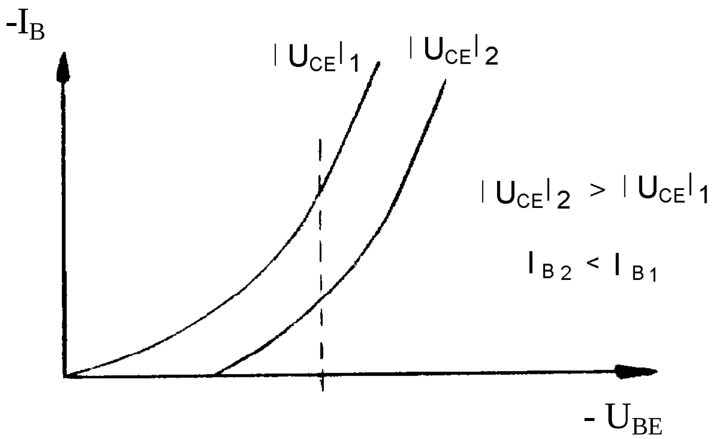


Figure 4. *Input characteristics of the PNP transistor in common emitter amplifier*

Output characteristics

Input characteristic curves (fig. 5) are functions $I_{BE} = f(U_{BE})|_{U_{CE}}$. In the saturation region (small values of $|U_{CE}|$), the collector current rises sharply as $|U_{CE}|$ increases and the base-collector junction becomes more reverse biased and emitter-collector more forward biased. When $|U_{CE}| > |U_{BE}|$ and required corresponding biases on the two PN junctions are fully achieved, transistor enters linear active region where collector current I_c is almost constant and independent of the further increase of $|U_{CE}|$. Very small increase of I_C with $|U_{CE}|$ is typical for real transistors. Collector current increases with the base current I_B, which is a constant parameter in the output characteristics.

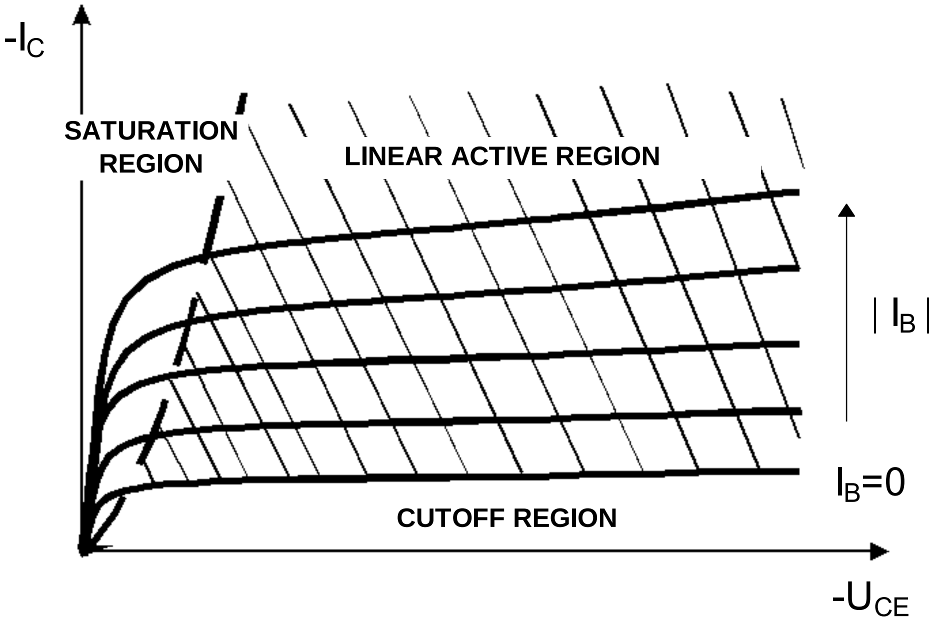
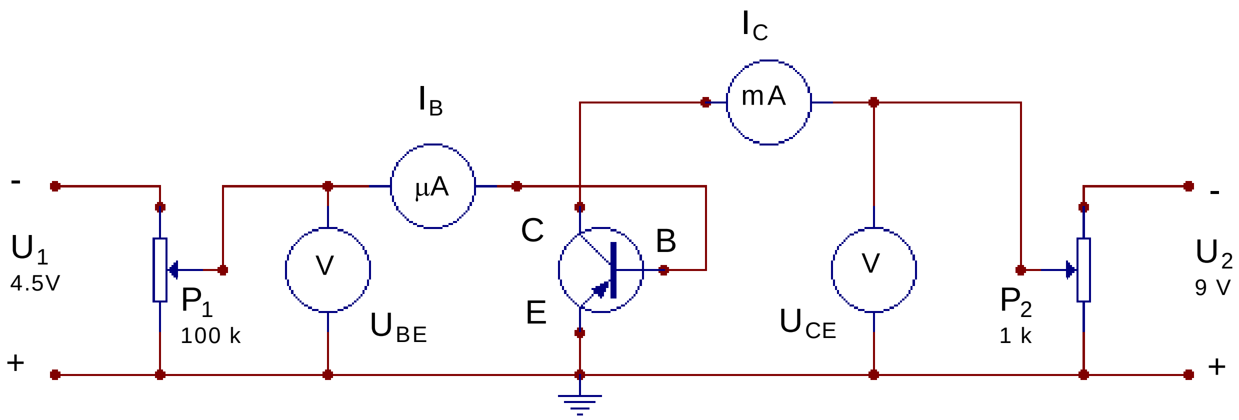


Figure 5. *Output characteristics of PNP transistor in common emitter amplifier with different operating regions*

ASSIGNMENT I:

1. Measure and determine input and output characteristics of the given bipolar germanium PNP transistor AC 550 in common emitter amplifier circuit. The electric circuit is shown below:



Notes:

- Begin measurements from the lowest values of U_{BE} and U_{CE}. Choose adequate U_{CE} by the use of potentiometer P_2 and keep it constant for each measured input characteristic. Vary U_{CE} from U_{CE} = 0.1 V up to U_{CE} = 1 V. Vary U_{BE} by the use of potentiometer P_1 and measure I_B for each U_{BE} with a constant parameter U_{CE}. **<u>Warning</u>**: Maximum base current for AC 550 transistor must not exceed I_{Bmax} = 300 µA.
- In order to determine output characteristics, chose the base current I_B by the use of potentiometer P_1 and keep it constant for each measured output characteristic. Vary U_{CE} from U_{CE} = 0.1 V up to U_{CE} = 8 V by the use of potentiometer P_2 and then measure I_C for each U_{CE} with a constant parameter I_B. Base current I_B should be varied in steps of 10 µA (10, 15, 20, 30, 40 µA) and measurements for I_B = 15 µA must be included.
- **<u>Warning</u>**: Maximum allowed power dissipation $P_C = U_{CE} I_C$ of the collector is P_{Cmax} = 120 mW.

2. Determine static DC and AC factors of current amplification (current gains) B and β in the two chosen operating points in the active region by the use of output characteristics and forward current gain characteristics ($I_C = f(I_B)|_{U_{CE}}$). Use the mean square method to determine β from forward current gain characteristic for a chosen U_{CE} of the operating point. Compare obtained B and β to each other and between the values for different operating points. Comment the results.

Notes:

- For a chosen value of U_{CE} of the operating point in the active region, find values of the pairs (I_{B1}, I_{C1}) and (I_{B2}, I_{C2}) and determine B_1 and B_2. Construct the forward current gain characteristic for that U_{CE} and determine β_{12} by the use of the mean square method. Repeat the same for a different value of U_{CE} and determine B_3 and B_4 for another two pairs. Again, determine β_{34} by the use of the mean square method from the forward current gain characteristic for the second value of U_{CE}. Compare B_1 to B_2, and B_3 to B_4, then compare β_{12} to β_{34}, and finally B_1 and B_2 to β_{12} and B_3 and B_4 to β_{34}.

ASSIGNMENT II:

1. Repeat all the measurements and procedures as described in assignment with silicon PNP transistor BC 161: measure and determine input and output characteristics of the given bipolar silicon transistor in common emitter amplifier, determine static DC and AC factors of current amplification (current gains) B and β in the two chosen operating points in the active region by the use of output characteristics and forward current gain characteristics ($I_C = f(I_B)|_{U_{CE}}$). Discuss and comment obtained results. Compare current gains B and β as in previous assignment.
2. Compare input and output characteristics of the germanium and silicon transistors. Compare factors of the current amplification (current gains) of the two transistors. Discuss the possible application of the each of the two transistors according to the differences.

Notes:

- **<u>Warning:</u>** Maximum base current I_B must not reach I_{Bmax} = 600 μA in order to avoid overheating and destruction of the transistor!
- Input characteristics should be measured for U_{CE} = 0.5, 1 and 4 V. Vary U_{BE} in steps of 0.5 V and measure I_B while keeping U_{CE} constant. U_{BE} should be varied from 0.5 to 0.75 V for U_{CE} = 0.5 and 1 V, and from U_{BE} = 0.5 V to U_{BE} = 0.65 V for U_{CE} = 4 V. Maximum base current must not reach I_B = 600 μA!
- Determine output characteristics by varying U_{CE} from U_{CE} = 0.1 V to U_{CE} = 8 V and by measuring I_C for constant I_B. Different characteristics should be obtained for I_B = 10, 30, 50, 80 and 100 μA.