2 Theoretical basics

2.1 Bipolar transistor

The transistor is an element with three terminals: C - collector, B - base and E - emitter. The bipolar transistor comes in two types: npn and pnp. The following considerations are valid for npn transistors. When considering pnp transistors, all voltages and currents change sign.

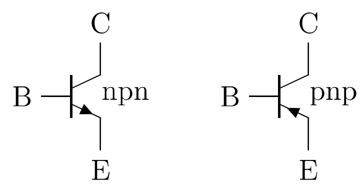


Figure 1: Symbol of npn and pnp transistor

For the transistor **npn** the following rules apply:

- the collector potential must be greater than the emitter potential ,
- base-emitter and base-collector circuits behave like diodes, in normal operation the base-emitter junction is forward biased, and the base-collector junction is reverse biased,

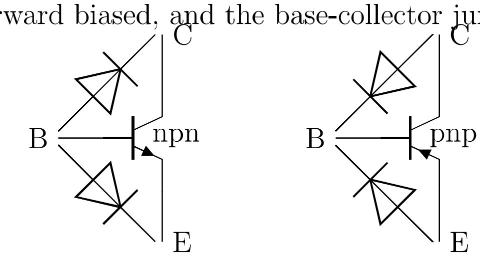


Figure 2: Interpretation of the base-emitter junction and the collector base of the npn and pnp transistor

- each transistor is characterized by the maximum values of currents and voltages I_{Cmax}, I_{Bmax}, U_{CEmax}, exceeding which leads to damage. The limitation is also the power losses on the transistor P_{max}, the junction temperature and the voltage U_{BEmax}.
- if the above conditions are met, the base current controls the collector current and approximately the collector current is proportional to the base current:

$$I_C = \beta I_B = h_{FE} I_B,$$

where β or h_{FE} are called current gain, typical low power transistors have a gain of more than 100.

When the base current I_B in the layout shown in the picture 3 equals to 0, then the transistor is in **clogged state**. Then the collector current does not flow ($I_C = 0$), voltage $U_{CE} = U$.

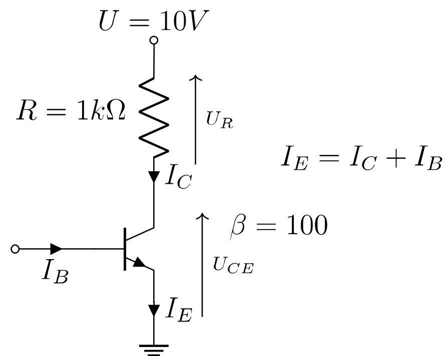


Figure 3

When in the circuit in the drawing **??** the base current increases to the value $I_B = 10\mu A$, then:
- collector current: $I_C = \beta I_B = 100 \cdot 10 \cdot 10^{-6} = 10^{-3}A = 1mA$,
- voltage across the R resistor: $U_R = I_C R = 10^{-3} \cdot 10^3 = 1V$,
- collector-emitter voltage: $U_{CE} = U - U_R = 10 - 1 = 9$V.

For the base current $I_B = 50\mu A$ we get the following values:
- collector current: $I_C = \beta I_B = 100 \cdot 50 \cdot 10^{-6} = 5 \cdot 10^{-3}A = 5mA$,
- voltage across the R resistor: $U_R = I_C R = 5 \cdot 10^{-3} \cdot 10^3 = 5V$,
- collector-emitter voltage: $U_{CE} = U - U_R = 10 - 5 = 5$V.

For the base current $I_B = 90\mu A$ we get the following values:
- collector current: $I_C = \beta I_B = 100 \cdot 90 \cdot 10^{-6} = 9 \cdot 10^{-3}A = 9mA$,
- voltage across the R resistor: $U_R = I_C R = 9\ cdot 10^{-3} \cdot 10^3 = 9V$,
- collector-emitter voltage: $U_{CE} = U - U_R = 10 - 9 = 1$V.

Assuming the current $I_B = 100\mu A$ theoretically we will get the following values: $I_C = 10$mA, $U_R = 10V$ and $U_{CE} = 0V$. The transistor will be fully open. Practically, when the transistor conducts the collector-emitter voltage, it cannot reach zero. The minimum collector-emitter voltage is $U_{CE\ sat} \approx 0.2V$. So for the system from the drawing 3 when the current $I_B \geq 10\mu A$ is $U_{CE} = U_{C\ sat} \approx 0.2V$, $U_R = U - U_{CE} = 10 - 0.2 = 9.8$V and $I_C = I_R = \frac{U_R}{R} = \frac{9.8}{10^3} = 9.8$mA. A further increase in the base current will not increase the collector current since the maximum collector current is limited by the R resistor.

The state where the collector current is proportional to the base current is called **active state** (the collector current is β times the base current). **When active, a small base current controls a much higher collector current**.

The state in which the base current is so large that the collector circuit is unable to deliver β times the base current is **saturation state**. The value of the saturation voltage ($U_{CE\ sat}$) is about $0.2V$, the collector current is limited by the R resistor.

In addition, we can also distinguish **inverse active state**, in which the base-emitter junction is biased in the reverse direction and the base-collector junction in the forward direction.

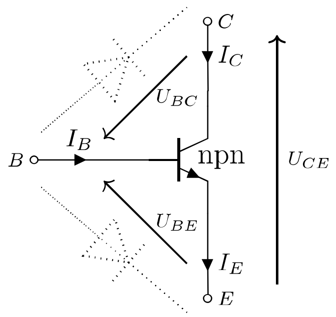


Figure 4: Marking the directions of currents and voltages of the NPN transistor

Summary, a bipolar transistor can be in one of four states:

- **clogged state** (cut-off) - BE and BC connectors are polarized in the reverse direction, i.e. $U_{BE} \leq 0$, $U_{BC} < 0$, $I_B = 0$, $I_C = 0$,
- **saturation state** - BE and CB junctions are forward biased, i.e. $U_{BE} > 0$, $U_{BC} > 0$, $I_B \neq 0$, $I_C \neq 0$,
- **active state** - forward biased BE connector, reverse biased BC connector, i.e. $U_{BE} > 0$, $U_{BC} < 0$, $I_C = \beta I_B$,
- **inverse active state** - reverse biased BE connector, forward biased BC connector, ie $U_{BE} < 0$, $U_{BC} > 0$.

The use of a bipolar transistor in electronic circuits:

- **active state** - is the basic operating state of the transistor used in amplifiers,
- **saturation and cut-off state** - are used in pulse technology and digital circuits,
- **inverse active state** is rarely used because the transistor has worse parameters than in the active state.

2.1.1 Static characteristics of the NPN transistor

We distinguish the following static characteristics of a bipolar transistor:

- **input characteristic** - $I_B = f(U_{BE})$ while $U_{CE} = const$,
- **transient characteristic** - $I_C = f(I_B)$ while $U_{CE} = const$,
- **output characteristics** - $I_C = f(U_{CE})$ while $I_B = const$.

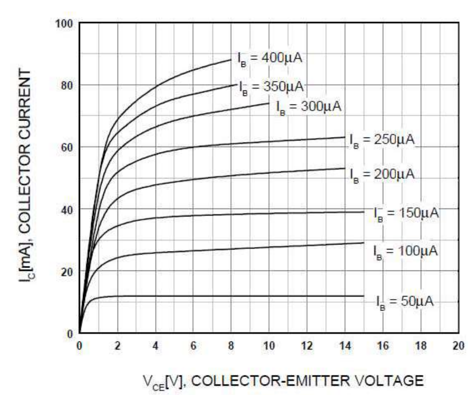


Figure 5: Transistor output characteristics BC546

3 The course of the exercise

3.1 Determination of the static characteristics of a bipolar transistor

Use the plate for measurements **E3 with BC546 transistor**.

3.1.1 Input characteristics

Connect the circuit as shown in the picture **??**. On the first channel of the power supply (CH1), set the current limit to $\boldsymbol{I_{CH1max} = 150mA}$ and the supply voltage $\boldsymbol{U_{CH1} = 12V}$.

CAUTION! - before switching on the system: set the maximum resistance in the collector circuit - potentiometer VR2 (upper terminals) turn right and set the minimum base current - source potentiometers $\boldsymbol{J}$ turn left.

By changing the base current $\boldsymbol{I_B \in (15\mu A; 300\mu A)}$ determine the input characteristics $\boldsymbol{U_{BE} = f(I_B)}$ at $\boldsymbol{U_{CE} = 3.5V = const}$.

To perform a single measurement point, set the I_B current, then, by changing the resistance with the VR1 potentiometer, set the $U_{CE} = 3.5V$ voltage and save the I_B and U_{BE} measurements.

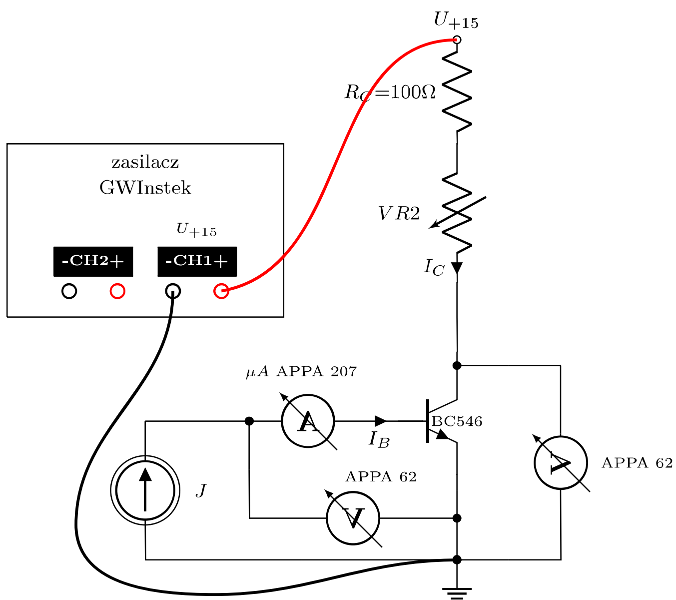


Figure 6

Save the results in the table 1 and mark in the picture 10a.

3.1.2 Transient characteristics

Connect the circuit as shown in the picture **??**. On the first channel of the power supply (CH1), set the current limit to $\boldsymbol{I_{CH1max} = 150mA}$ and the supply voltage $\boldsymbol{U_{CH1} = 12V}$.

ATTENTION! - before switching on the system: set the maximum resistance in the collector circuit - potentiometer VR2 (upper terminals) turn right and set the minimum base current - source potentiometers $\boldsymbol{J}$ turn left.

By changing the base current $\boldsymbol{I_B \in (15\mu A; 300\mu A)}$ determine the transition characteristic $\boldsymbol{I_C = f(I_B)}$ at $\boldsymbol{U_{CE} = 3.5V = const}$.

To perform a single measurement point, set the I_B current, then by changing the resistance with the VR1 potentiometer, set the $U_{CE} = 3.5V$ voltage and save the I_B and I_C measurements.

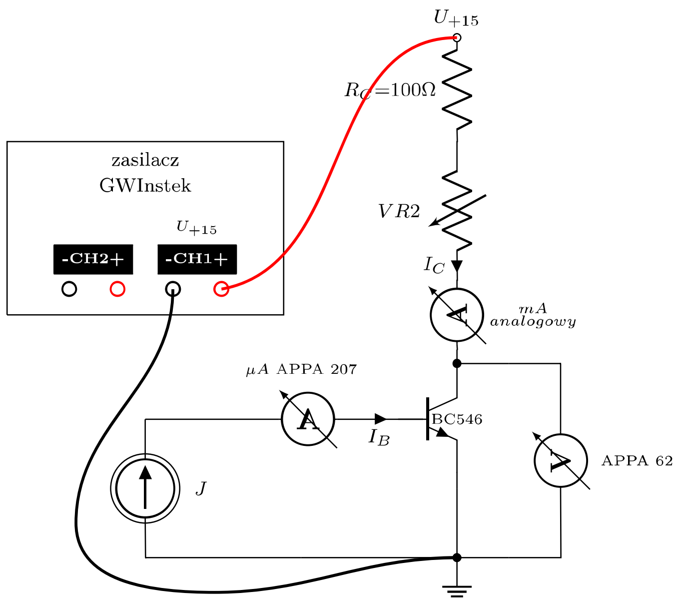


Figure 7

Save the results in the table 1 and mark in the picture 10b.

3.1.3 Output characteristics

Connect the circuit as shown in the picture ??. On the first channel of the power supply (CH1), set the supply voltage $\boldsymbol{U_{+15} = 15V}$ and the current limit to $\boldsymbol{I_{CH1max} = 100mA}$.

ATTENTION! - before switching on the system: set the maximum resistance in the collector circuit - potentiometer VR2 (upper terminals) turn right and set the minimum base current - source potentiometers $\boldsymbol{J}$ turn left.

For a constant base current, by reducing the collector resistance with a potentiometer, measure the collector current $\boldsymbol{I_C}$ and the voltage $\boldsymbol{U_{CE}}$. Make 3 curves for the following base currents:

- $\boldsymbol{I_{B1} = 25\mu A}$,
- $\boldsymbol{I_{B2} = 50\mu A}$,
- $\boldsymbol{I_{B3} = 75\mu A}$.

ATTENTION! - before increasing the base current: set the maximum resistance in the collector circuit - VR2 (upper terminals) turn right.

ATTENTION! - do not exceed: on the collector do not exceed the voltage [i] .:

- $\boldsymbol{U_{CEmax} = 15V}$ dla $\boldsymbol{I_{B1} = 25\mu A}$,
- $\boldsymbol{U_{CEmax} = 10V}$ dla $\boldsymbol{I_{B2} = 50\mu A}$,
- $\boldsymbol{U_{CEmax} = 5V}$ dla $\boldsymbol{I_{B3} = 75\mu A}$.

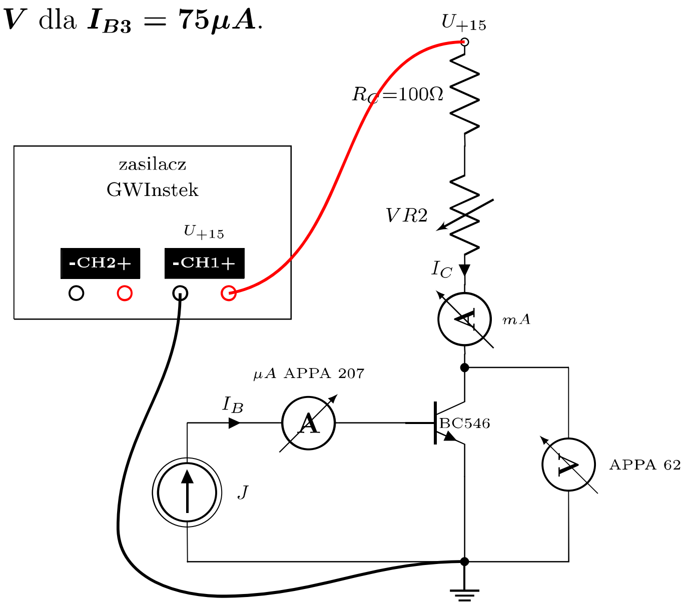


Figure 8

Save the results in the table 2 and mark in the picture 11.

[i]Limits result from the maximum permissible power of losses on the transistor, **exceeding this value causes damage to the transistor.**

3.2 Determination of the static characteristics of the field effect transistor

Use the board for measurements **E3 with transistor BS170**.

3.2.1 Transient characteristics

Connect the circuit as shown in the picture ??. On the first channel, set the current limit to $\boldsymbol{I_{CH1max} = 200mA}$ and on the second channel $\boldsymbol{I_{CH2max} = 100mA}$. On the first channel of the power supply set the voltage $\boldsymbol{U_{CH1} = 0V}$ and on the second channel the voltage $\boldsymbol{U_{CH2} = 3.5V}$.
By changing the voltage $\boldsymbol{U_{GS} \in (2V; 3V)}$ determine two transition characteristics $\boldsymbol{I_D = f(U_{GS})}$ with

- $\boldsymbol{U_{DS1} = 2V = const}$,
- $\boldsymbol{U_{DS2} = 3V = const}$,

In order to perform a single measurement point, set the U_{GS} voltage and then, by changing the voltage on the first channel of the power supply, set the U_{DS} voltage at the selected constant value. **ATTENTION! - do not exceed:** while taking measurements, do not exceed the current $\boldsymbol{I_{Dmax} = 75mA}$.

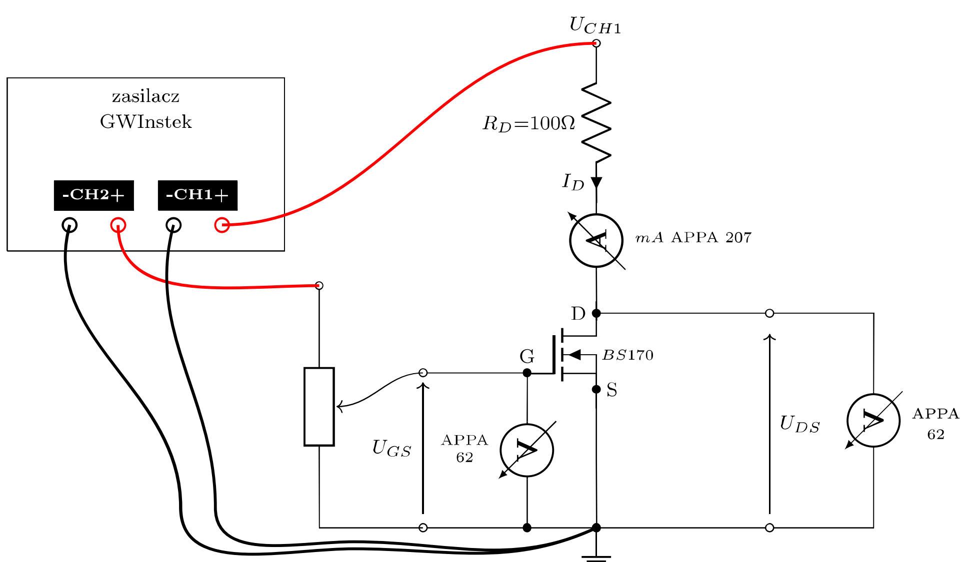


Figure 9: Układ pomiarowy

Record the results in the table 3 and mark it in the picture 12.

3.2.2 Output characteristics

In the system from the previous point (figure 9) determine the output characteristic. On the first channel, set the current limit to $\boldsymbol{I_{CH1max} = 200mA}$ and on the second channel $\boldsymbol{I_{CH2max} = 100mA}$. On the first channel of the power supply, set the voltage $\boldsymbol{U_{CH1} = 0V}$ and on the second channel the voltage $\boldsymbol{U_{CH2} = 4V}$. For the constant voltage U_{GS}, by changing the voltage on the first channel, measure the drain current I_D and the drain-source voltage U_{DS}. Make 3 characteristics for the following voltages U_{GS}:

- $\boldsymbol{U_{GS1} = 2,5V}$,
- $\boldsymbol{U_{GS2} = 2,75V}$,
- $\boldsymbol{U_{GS3} = 3V}$,

ATTENTION! - before increasing the U_{GS} voltage, set the $U_{CH1} = 0V$ voltage on the first channel. **ATTENTION! - do not exceed:** on the drain do not exceed the voltage [ii]:

- $\boldsymbol{U_{DSmax} = 15V}$ dla $\boldsymbol{U_{GS1} = 2,5V}$,
- $\boldsymbol{U_{DSmax} = 6V}$ dla $\boldsymbol{U_{GS2} = 2,75V}$,
- $\boldsymbol{U_{DSmax} = 3,5V}$ dla $\boldsymbol{U_{GS3} = 3V}$.

Record the results in the table 4 and mark it in the picture 13.

[ii] Limits result from the maximum permissible power of losses on the transistor, **exceeding this value causes damage to the transistor.**

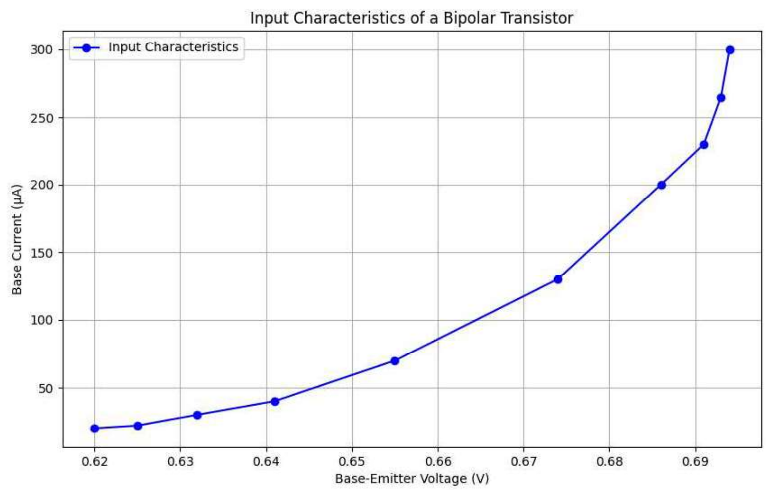
Conclusion

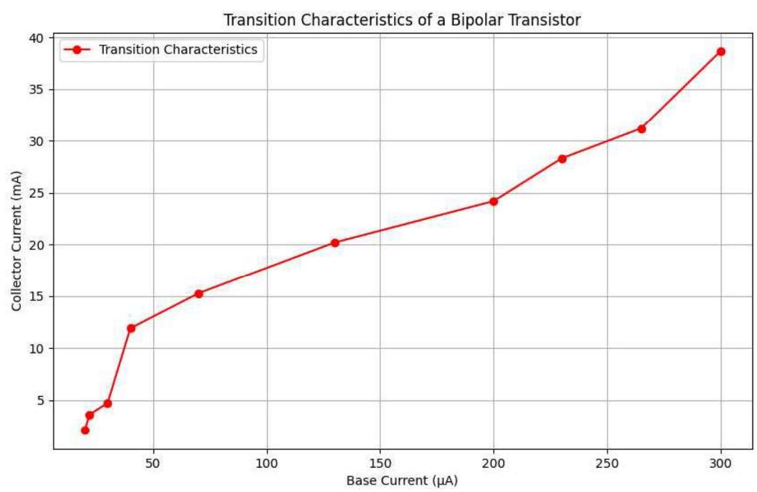
1. Input and Transition Characteristics:
- We varied the base current (IB) and measured the base-emitter voltage (UBE) at a constant collector-emitter voltage (UCE = 3.54V).
- We also measured the collector current (IC) for different base currents (IB) at the same UCE. The results showed that as IB increased, IC also increased, confirming the transistor's current amplification ability.

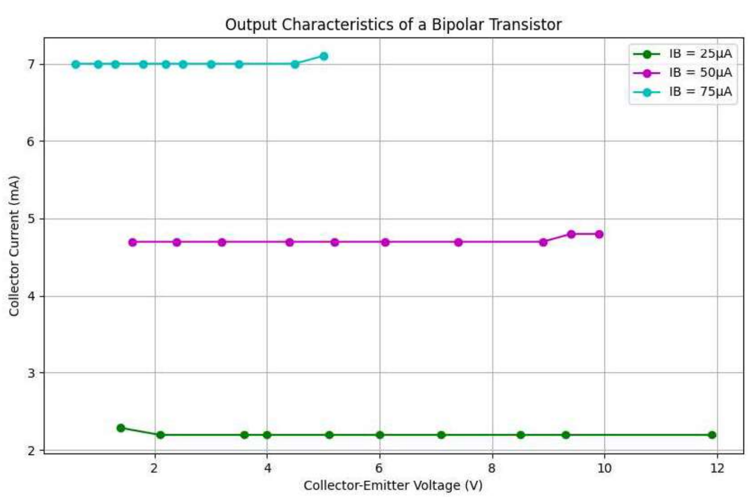
2.Output Characteristics:
- We measured the collector current (IC) for different collector-emitter voltages (UCE) at three different base currents (IB = 25µA, 50µA, and 75µA).
- The results showed that for each IB, IC stayed mostly constant as UCE increased, demonstrating the transistor's behavior in the saturation region.

These measurements show how bipolar transistors work in amplifying and switching, matching the expected behavior for these components.

Protocol					
Measurements					
Tabela 1: Input and transition characteristics of a bipolar transistor					
UCE =3.54				***UCE =3.54***	
IB[µA]	*UBE[V]*			*IB[µA]*	*IC[mA]*
20	0.62			20	2.095
22	0.625			40	3.605
30	0.632			50	4.713
40	0.641			120	11.895
70	0.655			150	15.259
130	0.674			195	20.196
200	0.686			230	24.196
230	0.691			270	28.307
265	0.693			270	31.2
300	0.694			350	38.644
IB1 = 25µA		***IB2 = 50µA***		***IB3 = 75µA***	
UCE[V]	*IC[mA]*	*UCE[V]*	*IC[mA]*	*UCE[V]*	*IC[mA]*
1.4	2.29	1.6	4.7	0.6	7
2.1	2.2	2.4	4.7	1	7
3.6	2.2	3.2	4.7	1.3	7
4	2.2	4.4	4.7	1.8	7
5.1	2.2	5.2	4.7	2.2	7
6	2.2	6.1	4.7	2.5	7
7.1	2.2	7.4	4.7	3	7
8.5	2.2	8.9	4.7	3.5	7
9.3	2.2	9.4	4.8	4.5	7
11.9	2.2	9.9	4.8	5	7.1


Input Characteristics of a Bipolar Transistor
Input Characteristics
Base Current (μA)
Base-Emitter Voltage (V)
300
250
200
150
100
50
0.62
0.63
0.64
0.65
0.66
0.67
0.68
0.69


Transition Characteristics of a Bipolar Transistor
Transition Characteristics
Collector Current (mA)
Base Current (μA)
40
35
30
25
20
15
10
5
50
100
150
200
250
300


Output Characteristics of a Bipolar Transistor
IB = 25μA
IB = 50μA
IB = 75μA
Collector Current (mA)
Collector-Emitter Voltage (V)
7
6
5
4
3
2
2
4
6
8
10
12