A Survey of DC - Methods for Determining the Series Resistances of Bipolar Transistors including the new DI_{Sub} - Method[1]

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Abstract - A survey of the most important DC - methods for determining the series resistances of integrated npn - bipolar transistors is presented. The principles, advantages and disadvantages are discussed. Some methods are compared based on measurement results. Furthermore, a new simple method for determining the collector series resistance, the ΔI_{Sub} - method, is proposed. This method is based on the use of the substrate current, caused by the parasitic pnp - transistor, if the npn - transistor is in the state of saturation.

1. Introduction

This paper deals with methods for determining the parasitic series resistances of integrated bipolar transistors. These methods can be divided into two classes: AC - methods and DC - methods. A well known AC - method for determining the base resistance, for example, is the input impedance cycle diagram method by Sansen and Meyer /1/. Other AC - methods, using the transistor input impedance at low frequency or the cross modulation behaviour, are proposed by Neugroschel /2/ and De Graaf /3/. This paper is restricted only to DC - methods. The main advantages of DC - methods are: they are easy and fast to use and no special and expensive equipment is necessary.

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[1] Presented at the European IC-CAP / HP 4062 User Meeting, October 1994 in Hourbourg - Wihr, Rev. 10/94

2. Methods

2.1. Method by Kulke - Miller (1957)

The method by Kulke - Miller /4/ is an often used way for determining the emitter resistance. It is based on the measurement of the open collector floating voltage vs. base current in emitter grounded circuit. That's why it is also called the floating voltage method[2].The collector - emitter voltage can be expressed from Fig. 1 as:

$$U_{CE} = U_{ce} + I_B\ R_E \tag{1}$$

The inner collector - emitter voltage can be written as:

$$U_{ce} = U_T \ln\left(1 + \frac{1}{B_R}\right) \tag{2}$$

For a fixed value of B_R the inner collector - emitter voltage is constant, and the slope of the characteristic $U_{CE} = f(I_B)$ is proportional to the emitter resistance:

$$R_E = \frac{\Delta U_{CE}}{\Delta I_B} \tag{3}$$

This method is easy to use. However a high base current is necessary to attain the linear range of the characteristic $U_{CE} = f(I_B)$. This can possibly cause thermal problems.

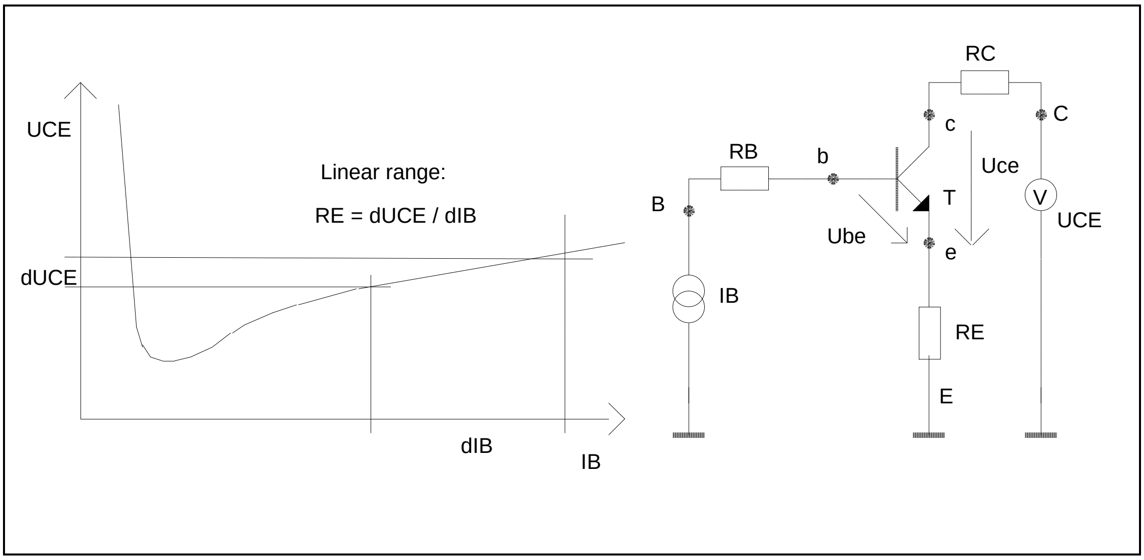

Fig. 1: Floating voltage method by Kulke and Miller /4/

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[2] The method, described by Giacoletto in 1972 /6/, is identical to the Kulke - Miller method. Giacoletto has also used this method for determining the collector resistance, but that is not recommended for integrated transistors.
The method, proposed by Filensky and Beneking /10/, is a slight variation of the floating voltage method too. It is based on observations of the output characteristic near the origin. For different base currents the value of the collector - emitter voltage is measured, at which the collector current deviates from zero. The result is an U_{CE} vs. I_B - characteristic, and eqn (3) is valid again.

2.2. Method by Logan (1971)

Logan /5/ described a method for determining R_C using the saturation voltage, often called the forced - beta method. With a constant collector - base current ratio $B_{FB} = I_C / I_B$ the collector - emitter voltage can be expressed as[3]:

$$U_{CEsat} = I_C R_C + I_E R_E + U_T \ln \frac{1+\frac{1}{B_R}\left[1+\frac{I_C}{I_B}\right]}{1+\frac{1}{B_F}\frac{I_C}{I_B}} \tag{4}$$

Assuming nearly constant current gains B_F and B_R in the current range of interest, the inner saturation voltage is constant. Rearranging eqn (4), we have:

$$U_{CEsat} = I_C\left[R_C + \left(1+\frac{1}{B_{FB}}\right)R_E\right] + U_{ce}$$

(5)

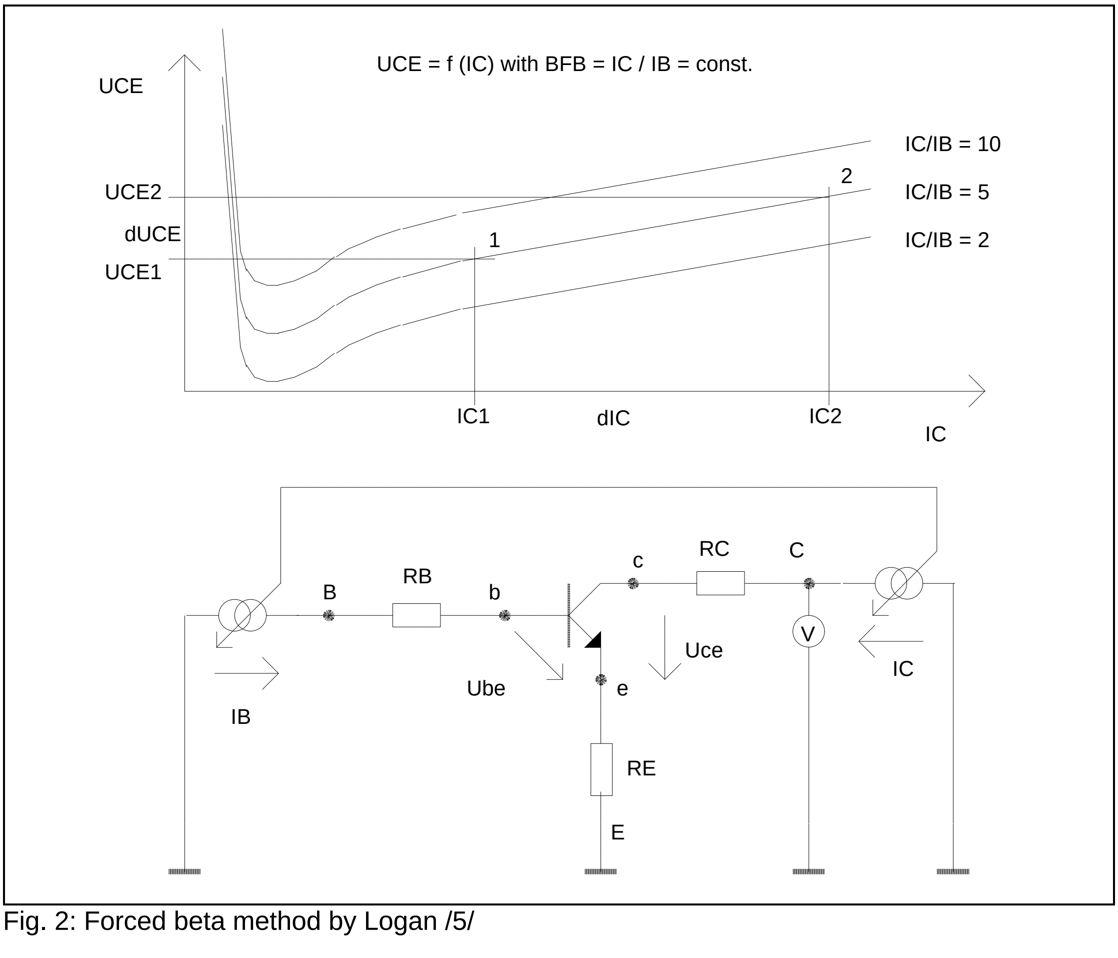

Fig. 2: Forced beta method by Logan /5/

Using two measurement points, the collector resistance can be calculated from eqn (5) as:

$$R_C = \frac{U_{CE2} - U_{CE1}}{I_{C2} - I_{C1}} - \left[1+\frac{1}{B_{FB}}\right]R_E \tag{6}$$

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[3] Logan neglected originally the emitter resistance voltage drop, but it is useful to take this resistance into account.

Consequently we need the value of the emitter resistance R_E (e.g. measured by the floating voltage method) for the determination of the collector resistance. According to eqn (6) we expect a constant R_C value, despite of different values of forced beta. But in practice there is a slight dependence on the forced beta value B_{FB}. This dependence is based on the current dependence of the current gains B_F and B_R and the collector resistance.

2.3. Method by Getreu (1978)

Getreu /8/ used a method for collector resistance determination similar to the forced beta method. The main condition for the measurement arrangement (Fig. 3) is a constant collector current instead of a constant collector - base current ratio.
The calculation of R_C is based on the choice of two measurement points, both indicated by the same value of collector to base current ratio at different collector currents:

$$\frac{I_{C1}}{I_{B1}} = \frac{I_{C2}}{I_{B2}} \tag{7}$$

This condition is identical with a constant forced beta B_{FB}. The calculation of R_C is then possible using eqn (6) again. From this point of view, the method is a variation of the forced beta method.

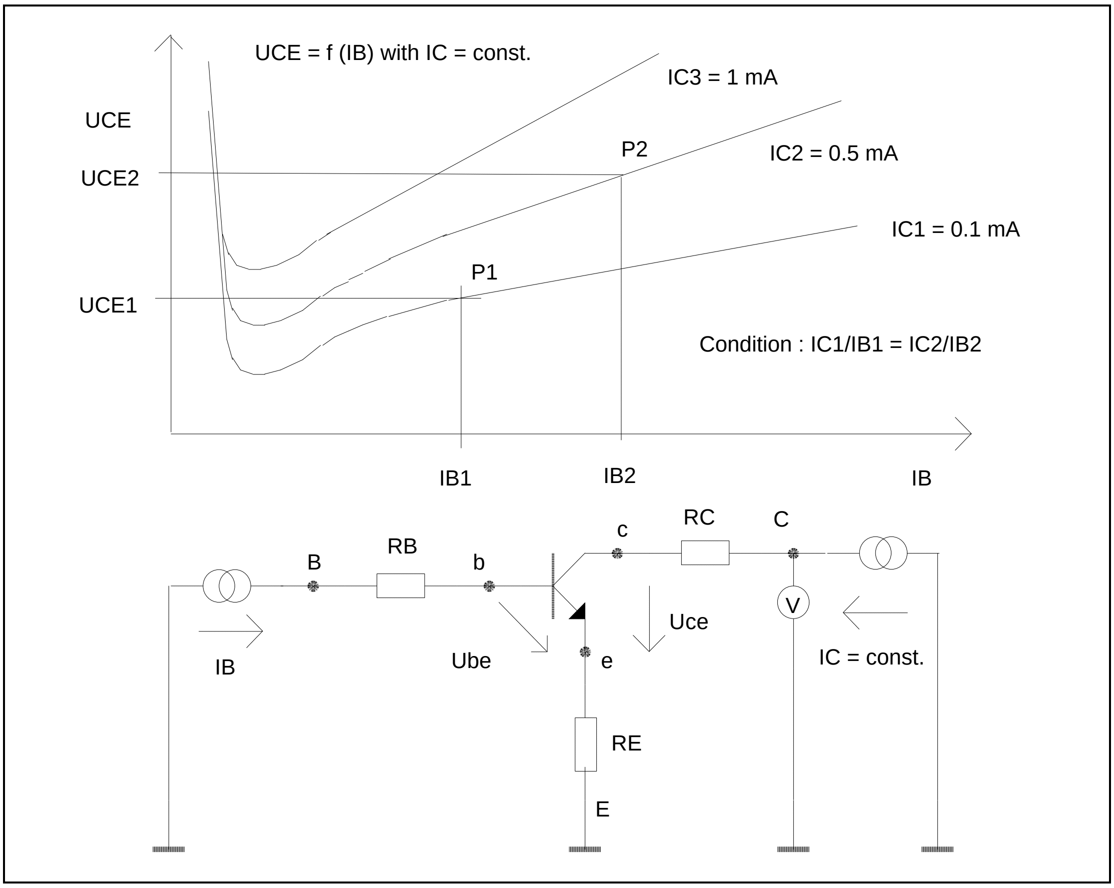


Fig. 3: Determination of R_C according to Getreu /8/

2.4. Method by Incecik (1979)

Incecik /9/ used the floating voltage method and the forced beta method in a modified manner.
His method is based on the calculation of the inner collector emitter voltage using the Gummel - Poon equations. The emitter resistance, e.g., is than determined by the difference between the calculated inner and the measured outer collector emitter voltage in the open collector circuit (see Fig. 1) :

$$R_E = \frac{U_{CE} - U_{ce}}{I_B} \tag{8}$$

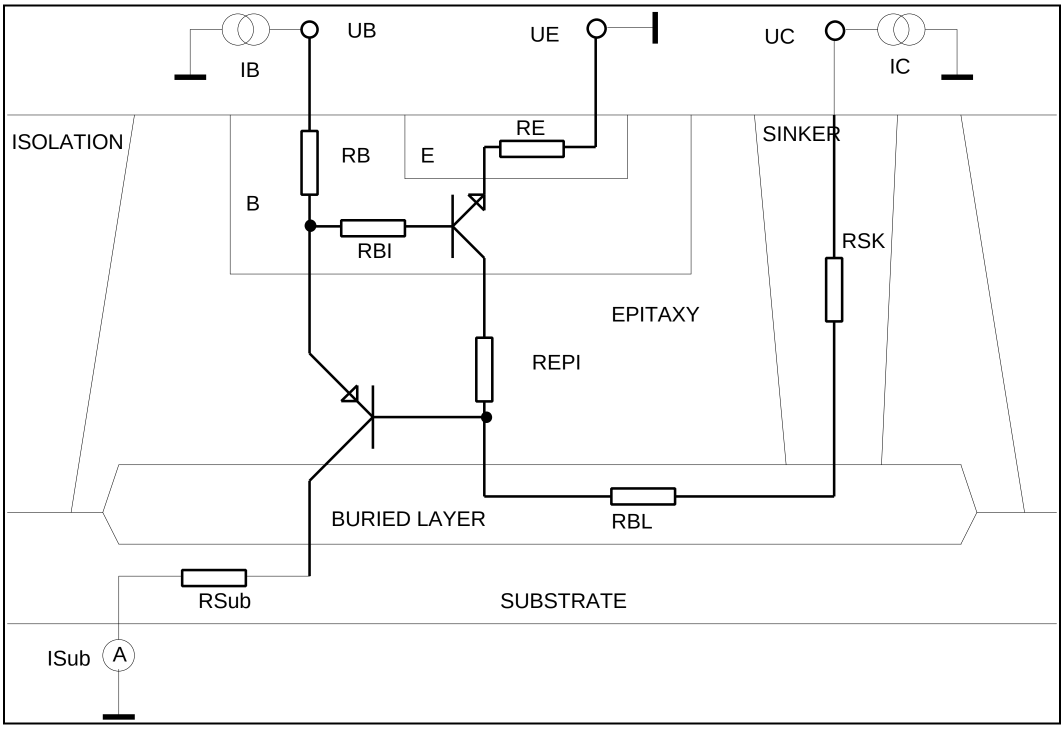
The same principle is used for collector resistance determination, according to the forced beta method (see Fig. 2). Then R_C is given by:

$$R_C = \frac{U_{CE} - U_{ce} - I_E\ R_E}{I_C} \tag{9}$$

The main problem of this method is due to the fact that the high current parameters IKF and IKR are necessary for the calculation of the inner collector - emitter voltage. Incecik has derived these two parameters with a graphical method or by an iteration process, respectively, from the high current deviations of the transfer characteristics. This non ideal behaviour of the transfer characteristics in the high current range, however, is caused by both series resistances and high current effects.[4]

2.5. Method by Mack and Horowitz (1982)

Mack's method /11/ takes into account the three different portions of the collector resistance: the epitaxial layer resistance R_{EPI}, the buried layer resistance R_{BL} and the sinker resistance R_{SK}: While R_{EPI} is current dependent, R_{BL} and R_{SK} are constant. To evaluate these components Mack used a combination of two methods: the ΔI_E - method for the entire collector resistance R_C and a substrate current method for the constant part $R_{BL} + R_{SK}$.
The substrate current method is based on the observation that a substrate current flows, if the npn - transistor is in saturation or in quasi - saturation, respectively. In this case the parasitic pnp - transistor (base - epitaxial layer - substrate) is in the active forward mode. This means that a transfer current is injected from the base region through the epitaxial layer to the substrate. Fig. 4 shows the cross section of a npn - transistor and the appropriate equivalent circuit.



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[4] Similar to this method is the method from Yang /13/. The series resistances will be extracted from the difference of measured transfer characteristics and calculated inner voltages. The high current parameters are determined by an iteration.

Fig 4: Determination of $R_{BL} + R_{SK}$ according to Mack[5] /11/

From Fig. 4 for the base - emitter voltage of the pnp - transistor we can write:

$$U_{eb\,(pnp)} = U_B - U_C - U_{RB} + U_{RBL} + U_{SK} \tag{10}$$

At this step it should be pointed out, that the unknown base - emitter voltage of the pnp - transistor $U_{eb(pnp)}$ is constant if the substrate current is hold at a constant value. Then, for two operating points IC_1 and IC_2 eqn (10) can be rewritten as:

$$R_{BL} + R_{SK} = \frac{U_{BC1} - U_{BC2}}{I_{C1} - I_{C2}} \tag{11}$$

One assumption was used in eqn (11): the base resistance voltage drop is negligible. Note, that Mack has connected the base terminal of the pnp - transistor to the lower end of the epitaxial layer resistance. This fact is important for the derivation of eqn (11).
For determination of the total collector resistance Mack used the ΔI_E - method: the transistor is driven by decreasing the collector - emitter voltage from the active forward mode into the saturation, until a fixed value of ΔI_E is reached. The appropriate value of U_{CE} is recorded . This is made for different base - emitter voltages. According to Mack, the slope of the U_{CE} vs. I_E will yield the sum of collector and emitter resistance:

$$R_{EPI} + R_{BL} + R_{SK} + R_E = \frac{\Delta U_{CE}}{\Delta I_E} \tag{12}$$

2.6. Method by Ning and Tang (1984)

Ning /12/ described a method for determining the base and the emitter resistance by evaluating the transfer characteristics I_C, $I_B = f(U_{BE})$ with $U_{CB} = 0V$.

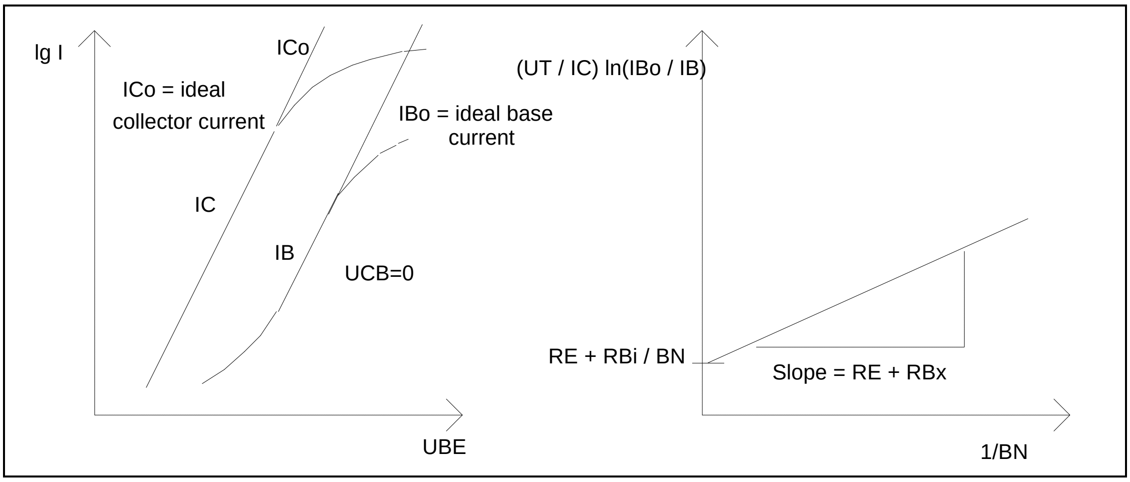

Fig. 5: Determination of R_E and R_{Bx} according to Ning /12/

This method is based on the following considerations. The deviation of the collector current from the ideal behaviour[6] is caused by two reasons: base conductivity modulation and emitter and base resistance. In contrast to the collector current, the base current is only affected by the series resistances[7].

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[5] Mack has'nt clear defined the measurement conditions. We assume here current sources at the base and the collector terminal.

[6] An ideal current is proportional to exp (U_{BE} / U_T).

[7] The method is based on the validity of this assumption.

Dividing the base resistance in the inner (R_{BI}) and the external (R_{Bx}) part, the base current is given as:

$$I_B = \frac{I_S}{B_F} \exp \frac{U_{BE} - U_{RE} - U_{RBi} - U_{RBx}}{U_T} \tag{13}$$

With the ideal base current

$$I_{Bo} = \frac{I_S}{B_F} \exp \frac{U_{BE}}{U_T} \tag{14}$$

the ratio of ideal and non - ideal base current I_{Bo} / I_B can be expressed as:

$$\frac{I_{Bo}}{I_B} = \exp \frac{I_E R_E + I_B R_{Bi} + I_B R_{Bx}}{U_T} = \exp \frac{I_C \left[R_E + \frac{R_E}{B_N} + \frac{R_{Bi}}{B_N} + \frac{R_{Bx}}{B_N} \right]}{U_T} \tag{15}$$

Rearranging eqn (15) we have:

$$\frac{U_T}{I_C} \ln \frac{I_{Bo}}{I_B} = (R_{Bx} + R_E) \frac{1}{B_N} + \frac{R_{Bi}}{B_N} + R_E \tag{16}$$

Assuming a constant ratio R_{BI} / B_N, the slope of an $(U_T/I_C) * \ln(I_{Bo}/I_B)$ vs. $1/B_N$ plot gives $R_E + R_{Bx}$ and the y - axis intercept gives $R_E + R_{BI}/B_N$. That means, for determining R_E it is necessary to know R_{BI} . This value can be calculated as $R_{BI} = (W / L)(\rho_B / 12)$ for a rectangular emitter, $R_{BI} = \rho_B / 32$ for a square emitter and $R_{BI} = \rho_B / 8\Pi$ for a round emitter.
Thus accuracy of the method is affected by two facts:

- the accuracy of I_{Bo} calculation; a sufficient linear part of the base current transfer characteristic is necessary, but this is unfortunately not the case for each bipolar transistor
- the accuracy of R_{BI} calculation, based on technological data

In practice, according to /12/, the method is convenient for transistors with sufficient high R_E- and R_{Bx} - values.

2.7. Method by Park et.al. (1991)

Park /14/ used similar to Mack and Horowitz the substrate current for determining the collector resistance. Two measurement circuits are used: the upward mode for determining the constant part of the collector resistance and the downward mode[8] for the total collector resistance. The resistance determination for both the upward and the downward is based on the same idea: for a constant substrate current the base - emitter voltage of the pnp - transistor is constant too.

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[8] "Upward" and "Downward" denotes the mode of the parasitic pnp - transistor.

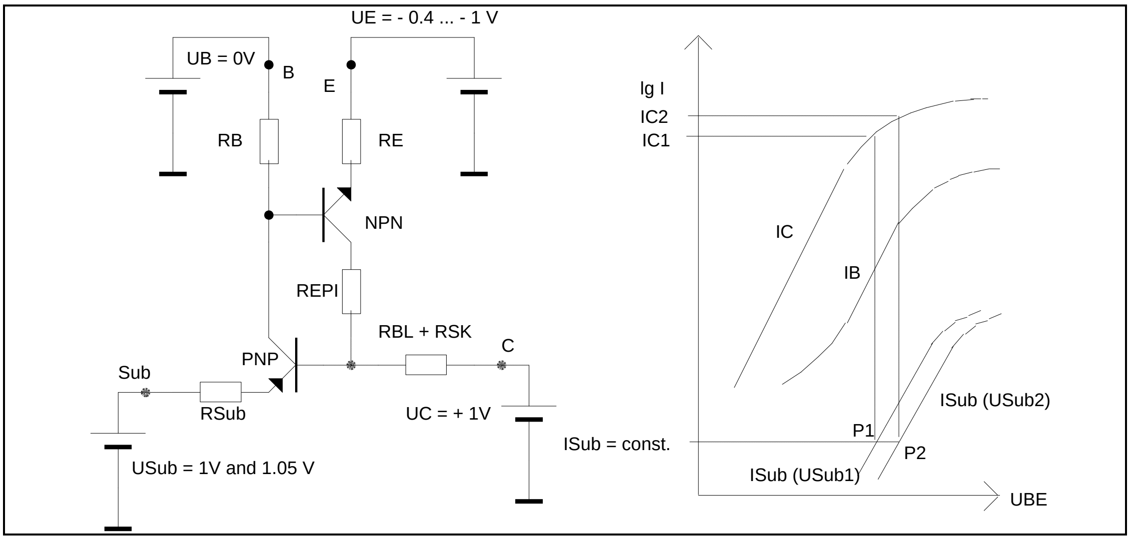

Fig. 6: Upward mode according to Park /14/ : npn - transistor = active normal, pnp - transistor = active inverse

Fig. 6 shows the measurement circuit for the upward mode. The substrate acts as the emitter of the parasitic pnp - transistor. It's base emitter voltage is given by:

$$U_{eb\,(pnp)} = U_{Sub} - I_{Sub}\ R_{Sub} + I_C\left[R_{BL} + R_{SK}\right] - U_C \tag{17}$$

Two measurements with a slight variation (30 ... 50 mV) of the substrate potential resulting in two substrate transfer characteristics, as shown in Fig. 6. Now the collector resistance can be calculated, using two measurement points P1 and P2 with the same substrate current values (see Fig. 6):

$$R_{BL} + R_{SK} = \frac{U_{Sub2} - U_{Sub1}}{I_{C2} - I_{C1}} \tag{18}$$

Fig. 7 shows the downward mode. As may be seen from this circuit, the base emitter voltage of the pnp -transistor is now given by:

$$U_{eb\,(pnp)} = U_B - I_B R_B + I_C (R_{EPI} + R_{BL} + R_{SK}) - U_C \tag{19}$$

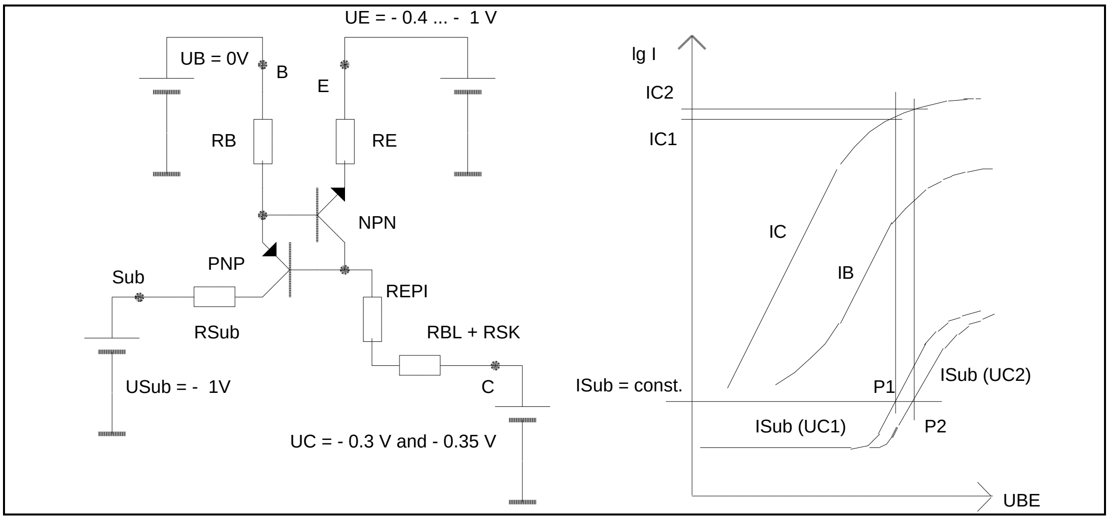

Fig. 7: Downward mode according to Park /14/ : npn - transistor = saturation, pnp - transistor = active normal

From eqn (19), using two measurement points P1 and P2 again and for a slight variation of the collector potential (U_{C1} and U_{C2}), the relationship for the total collector resistance can be expressed as:

$$R_C = \frac{U_{C2} - U_{C1}}{I_{C2} - I_{C1}} \qquad (20)$$

Two assumptions were made in eqn (20):

- the base resistance voltage drop is nearly constant for the two operating points ($I_{B1} * R_B = I_{B2} * R_B$)
- the deviation of R_{EPI} caused by the variation of the collector potential $\Delta U_C = U_{C2} - U_{C1}$ is negligible

Note, that in the downward mode equivalent circuit the base terminal is connected to the upper end of the epitaxial layer resistance R_{EPI} . Based on this fact Park proposed to use the downward mode for determination of the total collector resistance and its dependence from collector current[9]. But in practice it is difficult to find out the sharp increase of the collector resistance for low currents, as decribed by Park.

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[9] This is in contrast to Mack and Horowitz. They used the downward mode only for the calculation of the constant collector resistance part.

2.8. Method by Verzellesi et.al. (1993)

Verzellesi et.al. /15/ proposed a method, using an impact ionization effect. At a collector - base voltage U_{BCZ} the base current is reduced to zero, caused by a base current reversal. Using circuit 1 in Fig. 9 we can measure the characteristics I_B = f(U_{CB}) and U_{BE} = f(U_{CB}). In this way curves as given in Fig. 8 with the emitter current as a parameter were obtained. As can be seen, the base current reduces to zero at collector - base voltages of about 21 ... 22.5 V, depending on the emitter current. The appropriate base - emitter voltage increases slightly, caused by the Early effect.

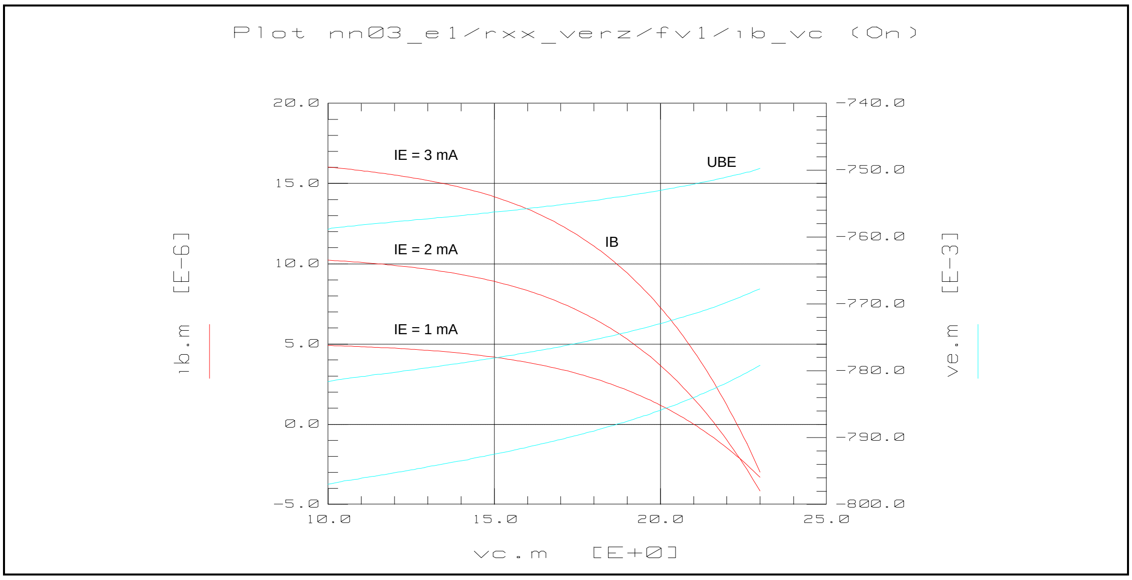


Fig. 8: I_B = f(U_{CB}) and U_{BE} = f(U_{CB}), measured by circuit 1

As can be seen from Fig. 9, the base - emitter voltage can be written as:

$$U_{BE} = R_B\, I_B + U_{be} + R_E\, I_E \tag{21}$$

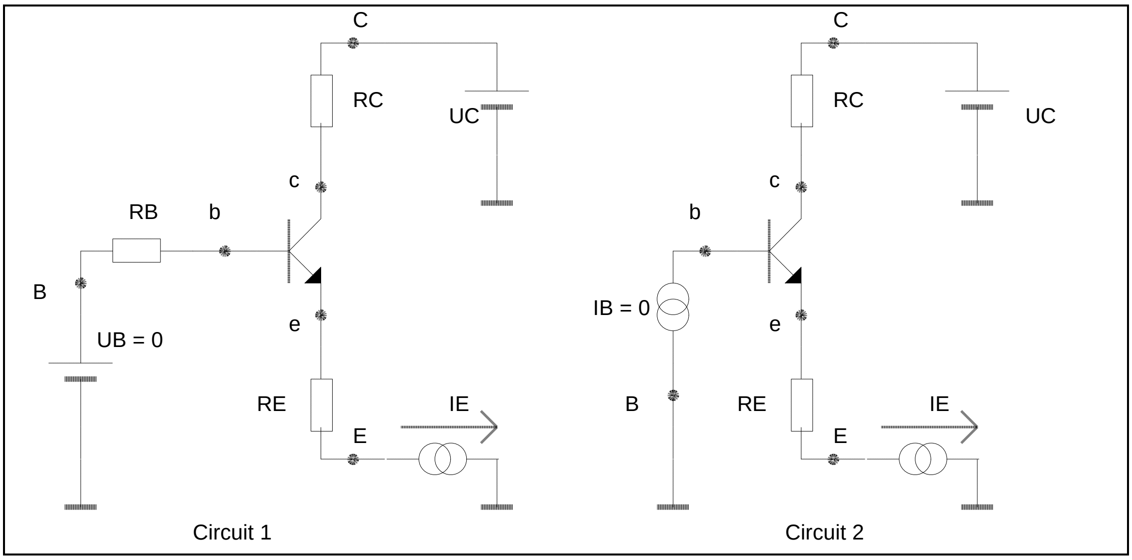


Fig. 9: Measurement circuits according to Verzellesi et.al. /15/

and for the case $U_{CB} = U_{CBz}$, respectively:

$$U_{BEz} = U_{bez} + R_E \; I_E \tag{22}$$

with

U_{BEz} - base - emitter voltage at the terminals for $U_{CB} = U_{CBz}$
U_{bez} - inner base - emitter voltage for $U_{CB} = U_{CBz}$

The base - emitter voltage decreases with increasing voltage U_{CB} and a constant emitter current, caused by the early effect. The relationship between these quantities can be given as:

$$U_{be} = U_T \ln \frac{I_E}{I_{ES}} \frac{1}{\left(1 + \frac{U_{CB}}{U_{AF}}\right)} \tag{23}$$

and

$$U_{bez} = U_T \ln \frac{I_E}{I_{ES}} \frac{1}{\left(1 + \frac{U_{CBz}}{U_{AF}}\right)} \tag{24}$$

with

I_{ES} - emitter saturation current
U_{AF} - forward early voltage

Combining eqn (22) and (24) gives for the emitter resistance:

$$R_E = \frac{U_{BEz} - U_T \ln \frac{I_E}{I_{ES}} \frac{1}{\left(1 + \frac{U_{CBz}}{U_{AF}}\right)}}{I_E} \tag{25}$$

Rearranging eqn (25) gives:

$$U_{BEz} - U_T \ln \frac{I_E}{I_{ES}} \frac{1}{\left(1 + \frac{U_{CBz}}{U_{AF}}\right)} = R_E I_E \tag{26}$$

From eqn (26), the slope of the left hand side term vs. emitter current gives the emitter resistance. From Fig. 9 the base - collector voltage is given by:

$$U_{CB} = U_{cb} + R_C \; I_C - R_B \; I_B \tag{27}$$

and for the case $U_{CB} = U_{CBz}$, respectively:

$$U_{CBz} = U_{cbz} + R_C \; I_E \tag{28}$$

The slope of the plot $U_{CBz} = f(I_E)$ gives now the collector resistance.

2.9. The DIsub - method (1994)

I developed this ΔI_{Sub} - method /16/ for collector resistance determination based on the observation that the substrate current, caused by the parasitic pnp - transistor if the npn - transistor in saturation or in quasi - saturation, shows a distinct increase with increasing voltage drop across the collector resistance. We can observe a linear range in the substrate current characteristic, where the current is ideal. This range is useful for determination of the collector resistance. Fig. 10 shows the measurement circuit, used for this method.

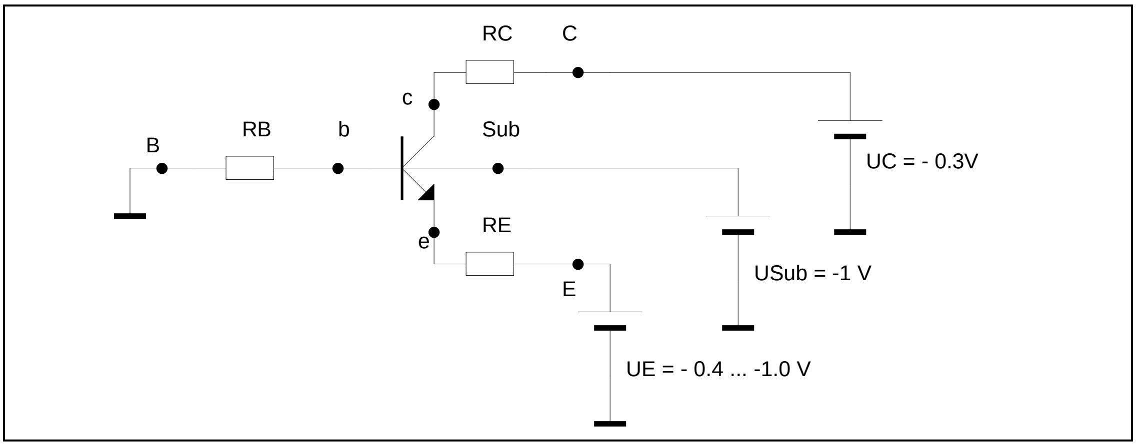


Fig. 10: Measurement circuit for the Δ Isub - method

This circuit is appropriate to the circuit usual used for measurements of the forward active transfer characteristics, except the negative collector potential. That's why the npn - transistor is for low base - emitter voltages in weak saturation. With increasing base emitter voltage the collector current, the voltage drop across R_C and the substrate current increases, and the transistor will attain hard saturation. Fig.11 shows this circuit together with the cross section of the transistor.

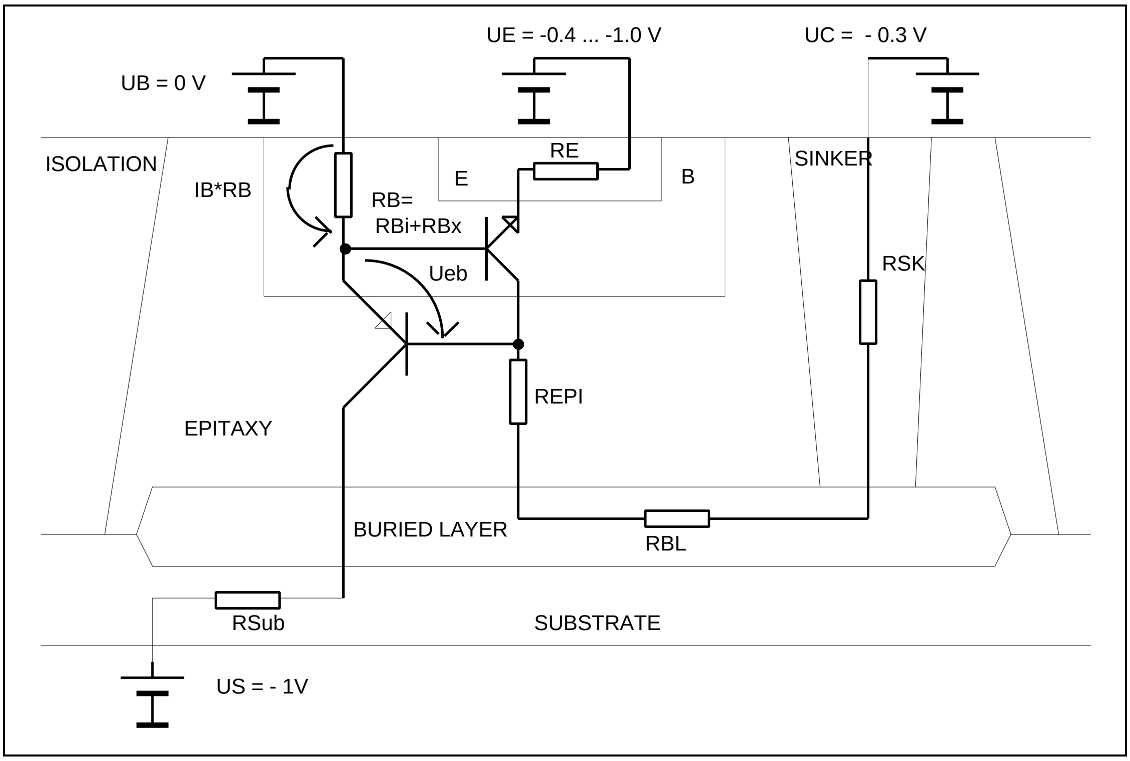


Fig. 11: Cross section of the npn - and the parasitic pnp - transistor

Considering the transfer characteristics of the npn - transistor nn03 (Fig. 12) shows: the substrate current is nearly constant with 5 E-11 A if the base - emitter voltage of the pnp - transistor is lower than 0.7 V. This current is the transfer current of the pnp - transistor. With increasing npn - base - emitter voltage we can observe a transition range, a linear range and than a high current range for the substrate current characteristic. In the linear range the substrate current is ideal. In that range it is now possible to determine the unknown base - emitter voltage of the pnp - transistor using the ratio of two substrate current values (P1 and P2 in Fig. 12).

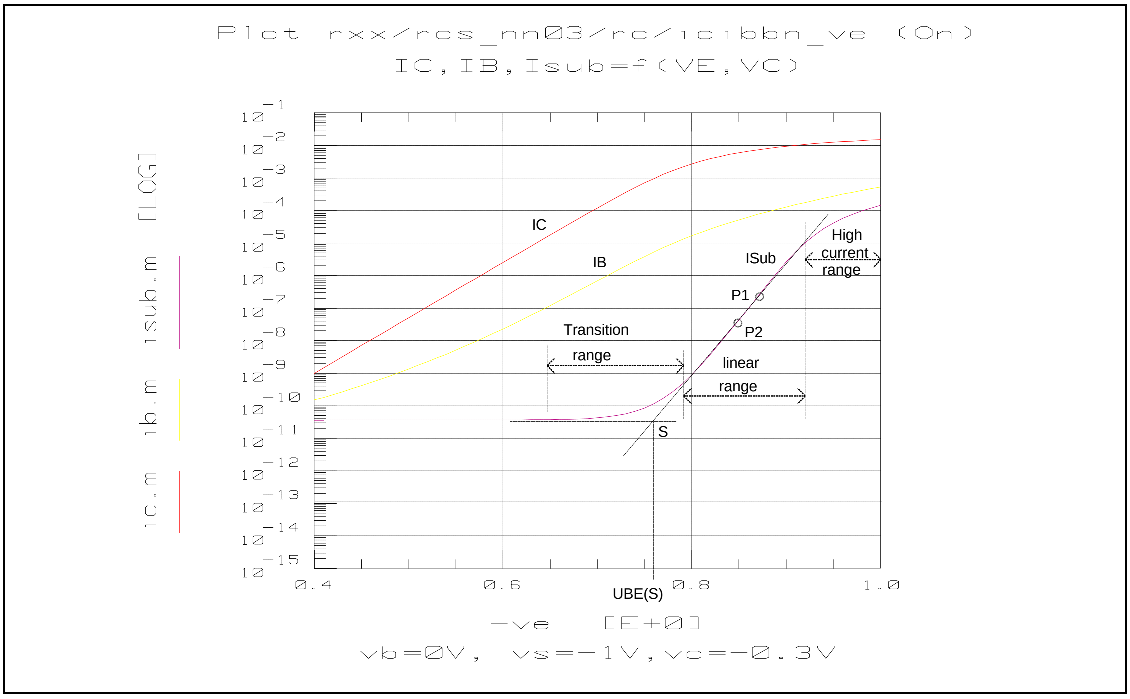


Fig. 12: Transfer characteristics I_C, I_B, I_{Sub} = f(U_{BE}), measured for the E1 - transistor nn03, U_{Sub} = - 1 V, U_C = - 0.3 V

From Fig. 11 it is clear that the base - emitter voltage of the pnp -transistor is given as:

$$U_{eb\ (pnp)} = U_B - I_B\ R_B + I_C\ (R_{EPI} + R_{BL} + R_{SK}) - U_C \tag{29}$$

Rearranging eqn (29) for two operating points P1 and P2, chosed in the linear substrate current range, we have:

$$U_{eb(pnp)1} - U_{eb(pnp)2} = [I_{C1} - I_{C2}]R_C - [I_{B1} - I_{B2}]R_B \tag{30}$$

The difference of the base - emitter voltages can be calculated now from the ratio of the two substrate current values I_{Sub1} and I_{Sub2} :

$$\frac{I_{Sub1}}{I_{Sub2}} = \exp\frac{U_{be(pnp)1} - U_{be(pnp)2}}{U_T} \tag{31}$$

Combining eqn (30) and eqn (31) gives for the collector resistance:

$$R_C = \frac{U_T \ln\frac{I_{Sub1}}{I_{Sub2}} + [I_{B1} - I_{B2}]R_B}{I_{C1} - I_{C2}} \tag{32}$$

Assuming a negligible variation of the base resistance voltage drop for the two operating points, this expression reduces to:

$$R_C = \frac{U_T \ln\frac{I_{Sub1}}{I_{Sub2}}}{I_{C1} - I_{C2}} \tag{33}$$

3. Measurements

To evaluate some of the DC - methods we used as DUT the npn - Transistor nn03. This device is made with a 18 V standard bipolar process and part of the SMI design library /17/. The emitter size is 14 µm x 16 µm. Measurements were made for the methods by Kulke and Miller (floating voltage method), Logan (forced beta method), Ning (ΔI_B - method), Park (Upward and downward method) , Verzellesi (base current reversal method) and the ΔI_{Isub} - method.

3.1. Method by Logan

The forced beta method was used for four different B_{FB} - values (B_{FB} = 2, 5, 10, 20). The collector current was varied from 0 - 20 mA and the extraction was made in the range from 5 to 20 mA. An emitter resistance of 7.33 Ohm, measured by the floating voltage method, was used in accordance to eqn (6). As expected, the R_C - value increases with B_{FB}. That means, the harder the saturation, the lower the extracted R_C - value.

B_{FB}	20	10	5	2
R_C / Ohm Extraction bounds: I_C = 5 / 15 mA	33.8	30.7	28.8	26.5

Table 1: R_C - values, extracted by the forced beta method

Moreover, the differential R_C - values were extracted between each measurement point. As we can see from Fig. 13 to 16, R_C is nearly constant vs. the collector current.

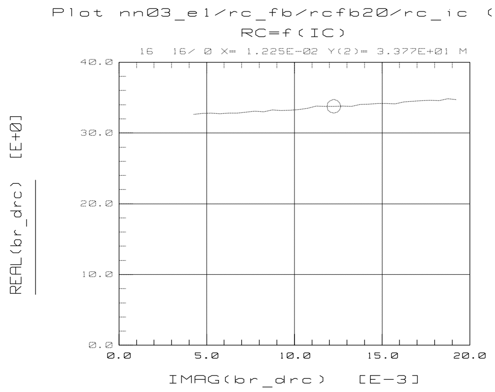


Fig. 13: R_C = f(I_C), B_{FB} = 20

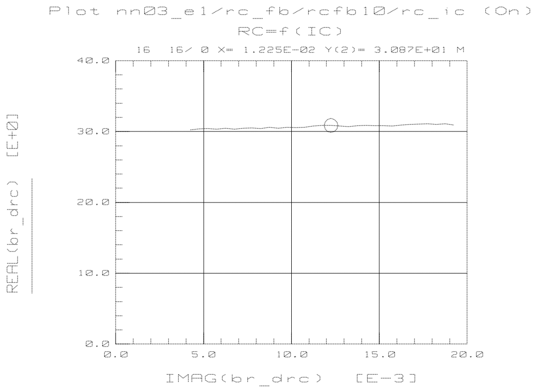


Fig. 14: R_C = f(I_C), B_{FB} = 10

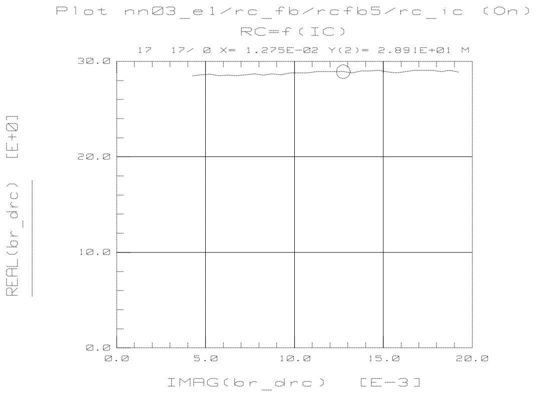


Fig. 15: R_C = f(I_C), B_{FB} = 5

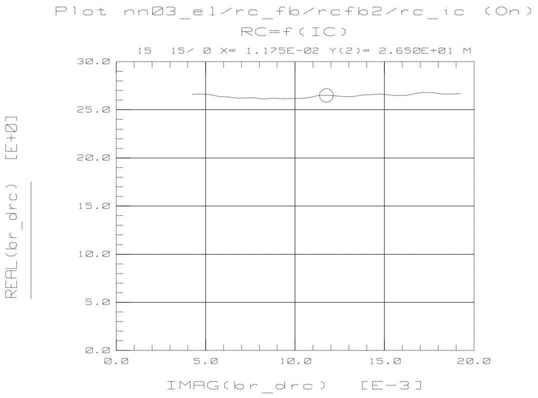


Fig. 16: R_C = f(I_C), B_{FB} = 2

3.2. Method by Ning

Fig. 17 shows the measured Gummel plot. The extracted parameters, necessary for the calculation of I_{Bo}, are I_S = 150 aA and B_F = 200. The extraction according to eqn (16) was made in the high current range from U_E = 800 ... 990 mV.

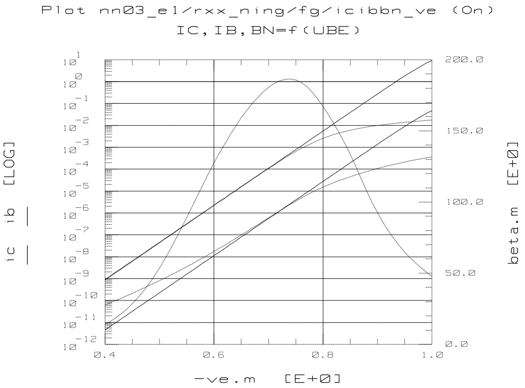


Fig. 17: Transfer curves I_C ,I_B ,B_N = f (U_{BE}), U_C = 0 V

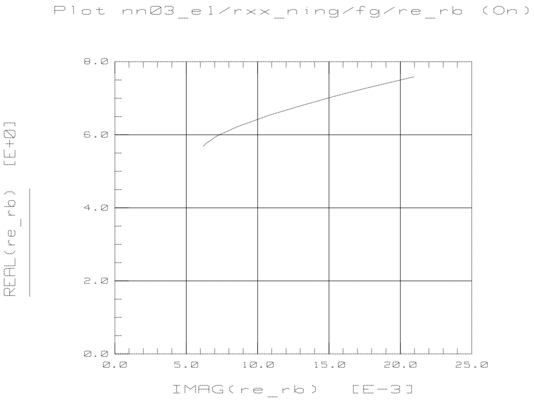


Fig. 18: Calculated result, according to eqn (16) vs. 1 / B_N

From Fig. 18 the slope gives R_{Bx} + R_E = 112 Ohm. From y - axis intercept we have (R_{BI} / B_N) + R_E = 5.3 Ohm. Using an intrinsic base sheet resistance of 6 kOhm / sq. and B_N = B_F we can calculate R_E :

$$R_E = 5.3 - \frac{6000}{200 * 12} = 2.8\,Ohm \tag{34}$$

This result deviates from the value R_E = 7.3 Ohm, calculated by the floating voltage method. It shows clearly the uncertainty of this method for evaluating the emitter resistance, caused by the uncertainty of calculating the term (R_{BI} / B_N). On the other hand the method is suitable for a fast estimation of the external base resistance. A comparison with the SPICE base resistance parameters RB = 176 Ohm and RBM = 51 Ohm /17/, calculated by the AC - circle diagram method, shows that this method gives a first roughly estimation for the SPICE - RB - parameter.

3.3. Method by Park

The measurements of the transfer characteristics for the downward method were made for collector voltages of U_C = - 0.3 V and U_C = - 0.35 V. The extraction range was chosed by I_{Sub} = 1E-9 ... 1 E-5 A. The calculated R_C - value depends slightly on the collector current, the maximum value is R_C = 33.8 Ohm. This represents the constant (saturation) value of the collector resistance (R_{BL} + R_{SK}) and is in good agreement with the value calculated by the forced beta method for B_{FB} = 20.

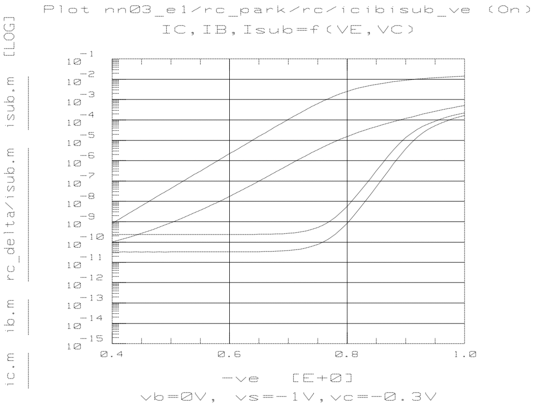


Bild 19: Transfer curves I_C ,I_B ,B_N = f (U_{BE}) U_C = - 0.3 / -0.35 V for downward mode

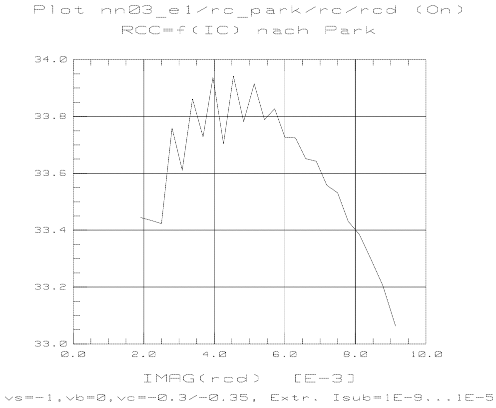
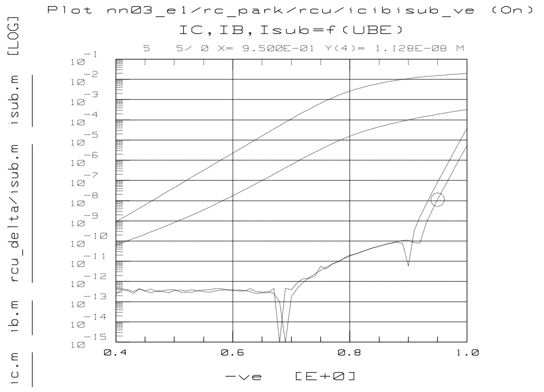


Fig. 20: R_C = f (I_C) for downward mode extraction range: I_{Sub} = 1E-9 ... 1 E-5 A

Additional measurements in the upward mode were made with a collector potential of U_C = + 1V and a substrate potential of U_{Sub} = 0.85 V and 0.9 V, respectively. Despite of these values (the substrate potential is lower than the collector potential) the epitaxy - substrate transition was in the forward mode, because off the inner collector resistance voltage drop. The extraction was made in the same substrate current range and we obtained R_C = 36.5 Ohm. That is about 10 % higher than the value extracted in the downward mode.



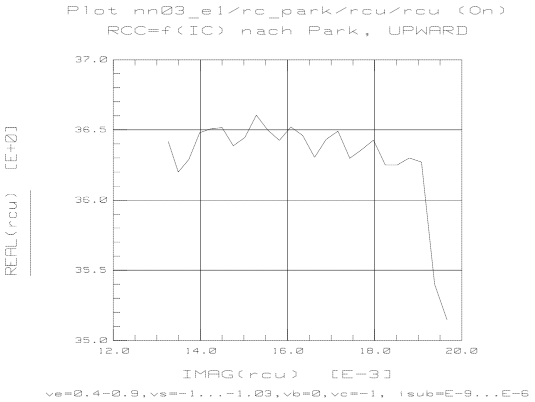
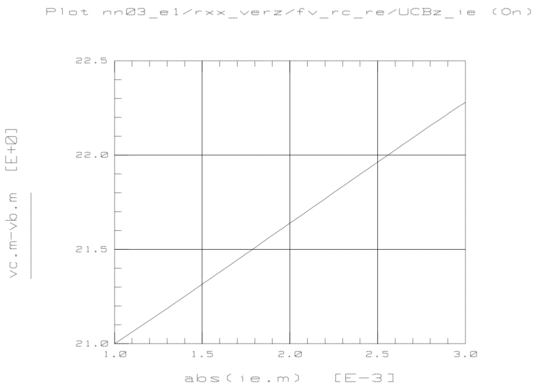


Fig. 21: Transfer curves I_C ,I_B ,B_N = f (U_{BE}), U_C = 1V, U_{Sub} = 0.85 / 0.9 V, for upward mode

Fig. 22: R_C = f (I_C) for upward mode, extraction range: I_{Sub} = 1E-9 ... 1 E-5 A

3.4. Method by Verzellesi

According to eqns (26) and (28) it was necessary to extract the parameters for the Early voltage and the emitter saturation current: VAF = 67 V and IS (I_E) = 163 aA. Using circuit 2 in Fig. (9) we measured the characteristics U_{CBz} = f (I_E) and U_{BEz} - U_{bez} = f (I_E). From the slope of these characteristics we have R_E = 8.5 Ohm and R_C = 647 Ohm. The value for the emitter resistance is nearly in agreement with the value, calculated by the floating voltage method. Note, that this high collector resistance represents the value for the forward active mode.



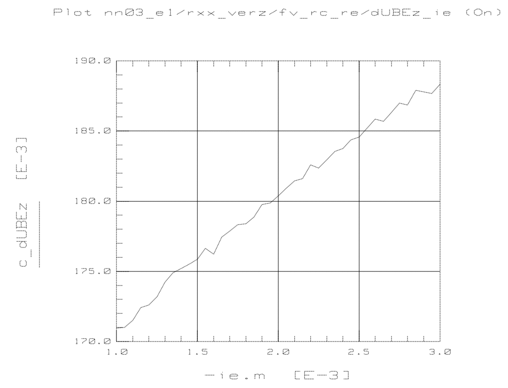


Fig. 23: U_{CBz} = f (I_E) , U_C = 23 V, I_E = 1.. 3 mA, Step = 50 µA

Fig. 24: U_{BEz} - U_{bez} = f (I_E), U_C = 23 V, I_E = 1.. 3 mA, Step = 50 µA

3.5. The DIsub - method

The measurement of the transfer characteristic was made at a collector voltage of U_C = - 0.3 V (see Fig.25). Than R_C was calculated according to eqn (33) using the linear range of the substrate current characteristic (extraction bounds U_E = 760 ... 900 mV). The result is a characteristic with a clear maximum, Fig. 26 shows R_C - values between 32.3 and 34.3 Ohm. Because the main assumption for this method, made by eqn (31), is only given in the truly linear range of the substrate current characteristic, we can conclude that the maximum value of R_C = f (I_C) is the true R_C value. This value depends only slightly on the used substrate potential. In summary we can say, these results are in good agreement with the results of the downward method and the forced beta method for B_{FB} = 20.

U_{Sub}	- 0.2 V	- 0.3 V	- 0.4 V
Extraction bounds U_E / mV	800 ... 950	760 ... 900	700 ... 900
R_C / Ohm	33.8	34.3	34.0

Table 2: Extracted R_C - values according to the ΔI_{Sub} - method

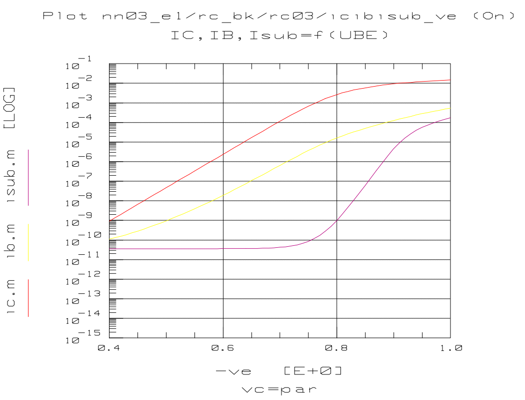


Fig. 25: Transfer curves I_C ,I_B ,B_N = f (U_{BE}), U_C = - 0.3 V, U_{Sub} = -1 V, for the ΔI_{Sub} - method

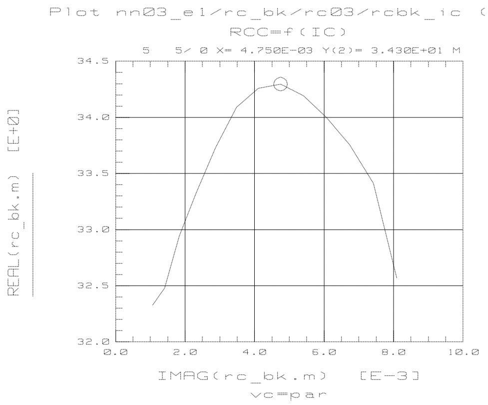


Fig. 26: R_C = f (I_C) according to eqn (33), extraction bounds U_E = 760 ... 900 mV

4. Conclusions

A survey of the most important DC - methods for determining the series resistances of integrated npn - bipolar transistors has been presented. Measurements were made for the methods by Kulke and Miller (floating voltage method), Logan (forced beta method), Ning (ΔI_B - method), Park (Upward and downward method) , Verzellesi (base current reversal method) and the ΔI_{Isub} - method. All these methods are easy and fast to use. In summary we can say:

- The emitter resistance can be evaluated by the floating voltage method and the base current reversal method.
- The constant part of the collector resistance (saturation value) can be found easily by the ΔI_{Sub} - method, the downward method or the forced beta method. The results of these methods are in good agreement.
- The collector resistance for the active forward mode can be derived by the base current reversal method.
- A value for the base resistance can be estimated by the ΔI_B - method.

Method	R_E / Ohm	R_C / Ohm	R_B / Ohm
Floating voltage	7.3	-	-
Forced beta		33.8 (B_{FB} = 20)	-
ΔI_B	2.5	-	about 100
Downward method		33.8	-
Upward method		36.5	-
Base current reversal	8.5	647 (RC_{act})	-
ΔI_{Isub}		34.3	-

Table 3: Comparison of calculated values for R_B ,R_C and R_E

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