

# Parameter Extraction for BJT Quasisaturation Models<sup>1</sup>

Jörg Berkner  
Frankfurt/Oder  
Germany

**Abstract** - A transistor acts in the state of quasisaturation (QS), if the external base - collector voltage is negative ( $V_{BCx} < 0$ ) and the inner base - collector voltage is positive ( $V_{BCi} > 0$ ), caused by the collector resistance voltage drop. QS is possible for each bipolar transistor, but it becomes important in practice especially for devices with lightly doped collector regions, operating at high current densities. This paper is concerned with BJT quasisaturation models. A short survey of QS models used in today's circuit simulators is presented. The parameters and their effects are discussed for the CadenceSPICE and the HSPICE model. Model parameter extraction methods are explained based on measurement results.

1 Quasisaturation Models .....	1
1.1 CadenceSPICE - Model .....	2
1.2 KULL - Model.....	2
1.3 PSPICE - Model.....	3
1.4 HSPICE - Model.....	4
2 Quasisaturation Model Parameters .....	6
2.1 CadenceSPICE - Model .....	6
2.2 HSPICE - Model.....	7
3 Quasisaturation Model Parameter Extraction .....	10
3.1 CadenceSPICE - Model .....	10
3.1.1 RCM, RCV, DOPE, CCO and CEX.....	10
3.1.2 Model Parameter Set .....	11
3.2 HSPICE - Model.....	11
3.2.1 VO , RC and GAMMA .....	11
3.2.2 BRS and BR.....	12
3.2.3 ISS and NS .....	13
3.2.4 QCO.....	14
3.2.5 Extraction Strategy .....	14
3.2.6 Model Parameter Set .....	14
4 Results .....	16
4.1 CadenceSPICE - Model .....	16
4.2 HSPICE - Model.....	16
5 References .....	19

## 1 Quasisaturation Models

The widespread SPICE - Gummel Poon model (SGP - model) is using a constant collector resistance. Usually an RC value is chosen, that results in a good fit of the saturation characteristic. For QS modeling, however, this constant RC model is not useful. The collector resistance of an integrated BJT usually consists of three parts: epitaxial layer, buried layer and sinker. Buried layer and sinker resistance are constant, whereas the epi layer resistance depends on both the collector current and the BC -voltage. Therefore, a QS model must create a decreasing collector resistance at decreasing collector voltage  $V_{BC}$ . This can be realized by a controlled collector resistance (e.g. the CadenceSPICE - model) or by a controlled current source (all models based on the Kull - model).

---

<sup>1</sup>This paper is intended for the HP User Meeting Oct. 1997 Berlin, Rev.: 6.6.97

## 1.1 CadenceSPICE - Model

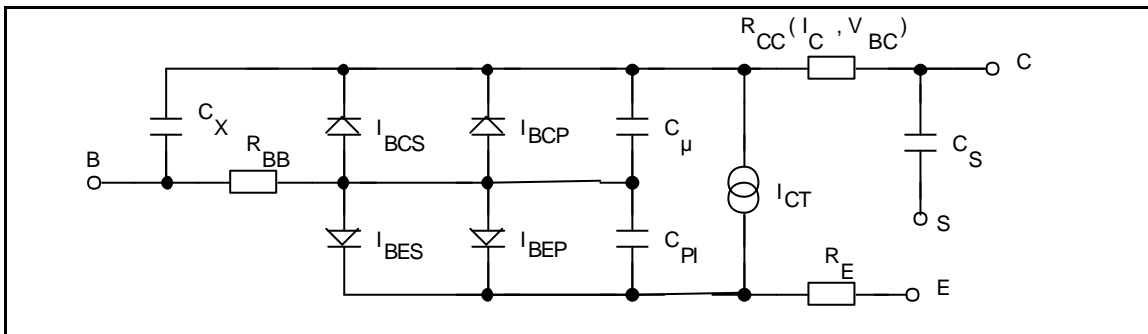
The CadenceSPICE quasisaturation model [2] is based on a variable collector resistance, dependent both on the collector current and the internal BC - voltage<sup>2</sup>:

$$R_{CC} = RCM + RCV * \frac{\left[ 1 + \left( \frac{I_C}{CC0} \right)^{CEX} \right]}{1 + \left( \frac{n_i}{DOPE} \right)^2 \exp\left( \frac{V_{BCi}}{NR * U_T} \right)} \quad (1)$$

This equation acts as follows<sup>3</sup>: For a reverse biased BC - junction the exponential term is small and the denominator of eqn (1) is nearly 1. Thus  $R_{CC}$  is constant for a given collector current. For a forward biased BC - junction, however, the denominator is  $> 1$  and the effective collector resistance is reduced. On the other hand, an increasing collector current increases the numerator and in this way the effective collector resistance is increased. The CadenceSPICE quasisaturation model does not include additional circuit elements for dynamic QS effects or substrate current simulation (Fig. 1).

**Table 1: CadenceSPICE - QS model parameters [2]**

Parameter	Description	Unit	Default
RCM	Minimum collector resistance	Ohm	0
RCV	Variable collector resistance	Ohm	0
CEX	Current crowding exponent	-	1
CC0	Current crowding normalization current	A	1
DOPE	Collector doping concentration	cm <sup>-3</sup>	0



**Fig. 1: CadenceSPICE - QS model equivalent circuit [2]**

## 1.2 KULL - Model

Kull et.al. [3] have examined the QS mechanism and developed an appropriate model in 1985. It is based on an equation for the current through the epi layer. This is completed by a term for the carrier velocity dependence on the field strength. Kull has proposed the following relationship for the epi layer current as a function of the internal and external BC - voltage ( $V_{cbo}$  and  $V_{cbw}$ ) and three additional model parameters  $R_{CO}$ ,  $V_O$  and  $\gamma$ :

<sup>2</sup>In this paper the original spelling is reproduced for original equations and figures. SPICE model parameters are written in capital letters

<sup>3</sup>The same equation (with  $NR = 1$ ) is used in the SPECTRE simulator too.

$$I_{epi} = \frac{\left[ K_1(V_{cbo}) - K_1(V_{cbw}) - \ln \frac{1 + K_1(V_{cbo})}{1 + K_1(V_{cbw})} \right] + \left[ \frac{V_{cbo} - V_{cbw}}{V_t} \right]}{\frac{R_{CO}}{V_t} * \left[ 1 + \frac{V_{cbo} - V_{cbw}}{V_o} \right]} \quad (2)$$

with

$$K_1(V) = \sqrt{1 + g * \exp\left(\frac{V}{V_t}\right)} \quad (3)$$

$$g = [2ni / N_I]^2 \quad (4)$$

The charge storage elements are modelled by:

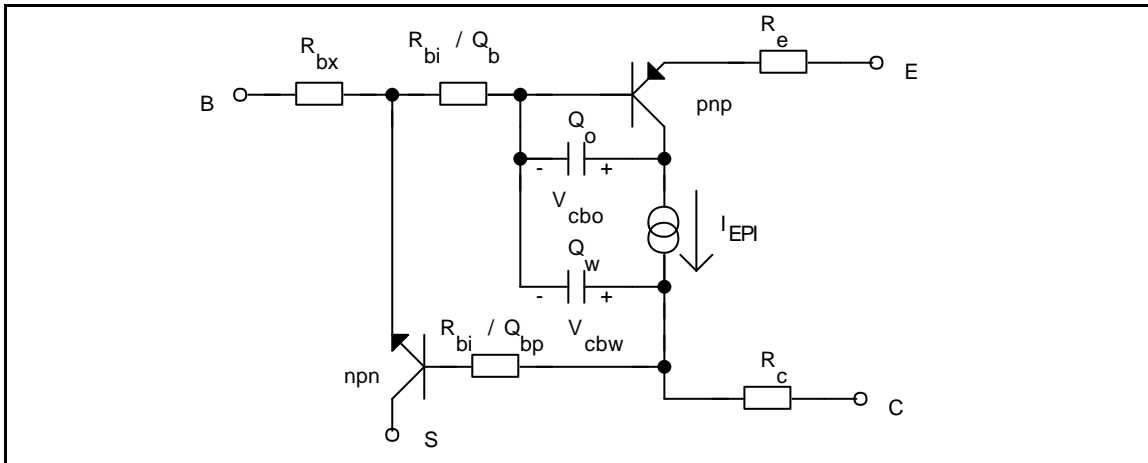
$$Q_o = Q_{CO} \left[ K_1(V_{cbo}) - 1 - \frac{g}{2} \right] \quad (5)$$

$$Q_w = Q_{CO} \left[ K_1(V_{cbw}) - 1 - \frac{g}{2} \right] \quad (6)$$

Fig. 2 shows the equivalent circuit of the Kull - model for an pnp - transistor. It includes as additional elements: the collector current source  $I_{EPI}$ , the parasitic transistor base - epi - substrate and the capacitances  $Q_o$  and  $Q_w$ , representing the additional charge stored in the epi layer.

**Table 2: Kull - QS model parameters [3]**

Parameter	Description	Unit	Default
$R_{CO}$	Epitaxial resistance under equilibrium condition	Ohm	-
$V_o$	Carrier saturation velocity voltage	V	-
$\gamma$	Epitaxial dope coefficient	-	-
$Q_{CO}$	Epitaxial charge coefficient	C	-



**Fig. 2: Kull - QS model equivalent circuit [3]**

### 1.3 PSPICE - Model

The PSPICE model for QS [4] is based on Kull's equation as well:

$$I_{epi} = \frac{VO * \left[ V_i \left[ k(Vbc) - k(Vbn) - \ln \left[ \frac{1 + k(Vbc)}{1 + k(Vbn)} \right] \right] + Vbc - Vbn \right]}{RCO * [|Vbc - Vbn| + VO]} \quad (7)$$

with

$$K(v) = \sqrt{1 + GAMMA * \exp \frac{v}{vt}} \quad (8)$$

The storage charge is given by:

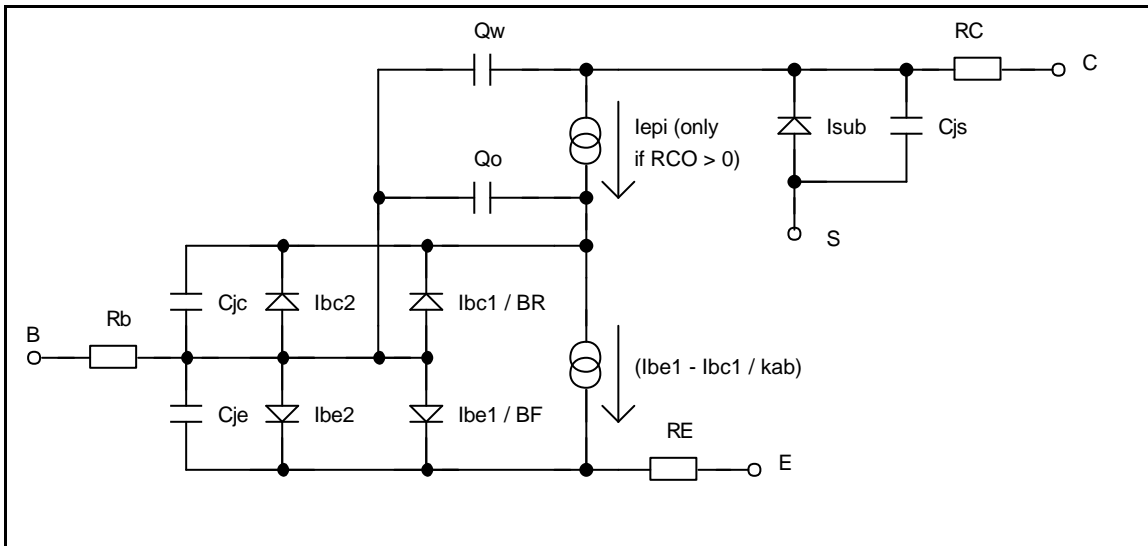
$$Q_o = QCO * [K(Vbc) - 1 - GAMMA / 2] \quad (9)$$

$$Q_w = QCO * [K(Vbn) - 1 - GAMMA / 2] \quad (10)$$

Table 3 shows the PSPICE - QS - model parameters. Additional to the usual constant collector resistance RC a QS - parameter RCO exists. This parameter acts as a switch too: for RCO > 0 the QS model is used.

**Table 3: PSPICE - QS model parameters [4]**

Parameter	Description	Unit	Default
GAMMA	Epitaxial region doping factor	-	1 E -11
QCO	Epitaxial region charge factor	C	0
RCO	Epitaxial region resistance	Ohm	0
VO	Carrier mobility knee voltage	V	10
ISS	Substrate saturation current	A	0
NS	Substrate emission coefficient	-	1



**Fig. 3: PSPICE - QS model equivalent circuit [4]**

### 1.4 HSPICE - Model

The HSPICE - QS model is also based on the Kull model. It is called the LEVEL2 - BJT model and defined as follows [5]:

$$I_{epi} = \frac{ki - kx - \ln\left[\frac{1+ki}{1+kx}\right] + \frac{vbc - vbcx}{NEPI * vt}}{\left[\frac{RC}{NEPI * vt}\right] * \left[1 + \frac{|vbc - vbcx|}{VO}\right]} \quad (11)$$

with

$$ki = \sqrt{1 + GAMMA * \exp\left(\frac{vbc}{NEPI * vt}\right)} \quad (12)$$

$$kx = \sqrt{1 + GAMMA * \exp\left(\frac{vbcx}{NEPI * vt}\right)} \quad (13)$$

$$GAMMA = \left[\frac{2n_i}{n_{epi}}\right]^2 \quad (14)$$

The emission coefficient NEPI is introduced here as an additional parameter (default = 1). The parasitic pnp substrate transistor is represented by the current source  $I_{bs}$  and the diode  $I_{sc}$ .

$$I_{bs} = BRS * (I_{bc} - I_{sc}) \quad (15)$$

where

$I_{bc}$  = npn reverse transfer current, caused by forward biased BC - junction

and

$$I_{sc} = ISS * \left[\exp\left(\frac{vsc}{NS * vt}\right) - 1\right] \quad (16)$$

From a physical point of view the current at the substrate terminal, in the npn reverse mode (forward biased BC junction), is the forward transport current of the parasitic pnp. This current  $I_{bs}$  is defined in the HSPICE model by eqn (15) using the parameter BRS and the currents  $I_{bc}$  and  $I_{sc}$ . Note, that  $I_{bc}$  is the npn reverse transfer current (not the BC - diode current), caused by forward biased BC - junction. The charge storage elements  $q_i$  and  $q_x$ , respectively the capacitances  $C_x$  and  $C_i$ , are determined by:

$$q_i = QCO * [ki - 1 - GAMMA / 2] \quad (17)$$

$$C_i = \left[\frac{GAMMA * QCO}{2 * NEPI * vt * ki}\right] * \exp\left(\frac{vbc}{NEPI * vt}\right) \quad (18)$$

and

$$q_x = QCO * [kx - 1 - GAMMA / 2] \quad (19)$$

$$C_x = \left[\frac{GAMMA * QCO}{2 * NEPI * vt * kx}\right] * \exp\left(\frac{vbcx}{NEPI * vt}\right) \quad (20)$$

The HSPICE - QS parameters are summarized in Table 4. Note the difference in meaning of RC for LEVEL1 and LEVEL2. Fig. 4 shows the equivalent circuit of the model.

**Table 4: HSPICE - QS model parameters [5]**

Parameter	Description	Unit	Default
LEVEL	LEVEL1 = SGP - model, LEVEL2 = QS - model	-	1
GAMMA	Epitaxial doping factor	-	0
NEPI	Emission coefficient	-	1

QCO	Epitaxial charge factor	C	0
RC	LEVEL1 = ohmic collector resistance, LEVEL2 = epitaxial layer resistance under equilibrium condition	Ohm	0
VO	Carrier velocity saturation voltage (zero indicates an infinite value)	V	0
BRS	Current gain of the parasitic substrate transistor	-	1
ISS	Reverse saturation current bulk to collector	A	0
NS	Substrate emission coefficient	-	1

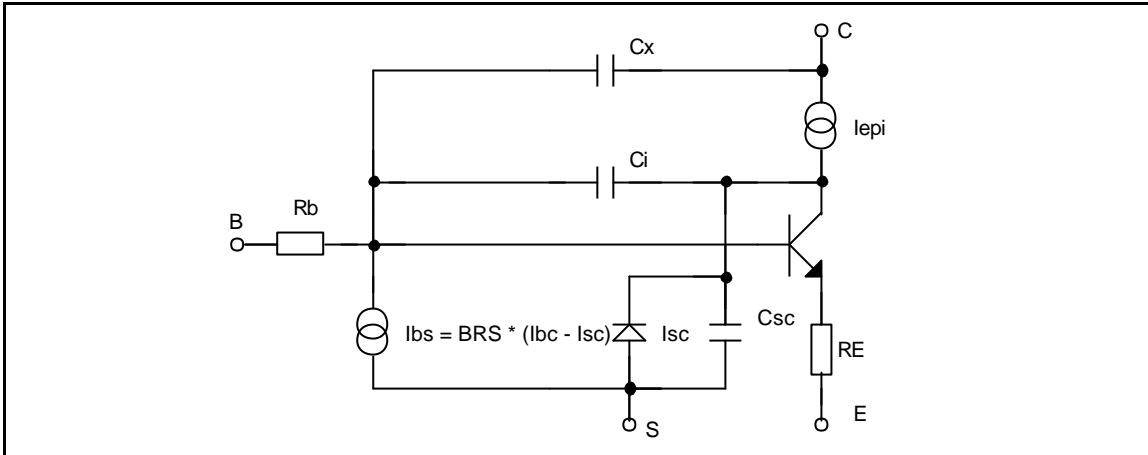


Fig. 4: HSPICE - QS model equivalent circuit [5]

## 2 Quasisaturation Model Parameters

In this section the effects of the QS parameters for two models, the CdsSPICE - and the HSPICE - model, on BJT characteristics are investigated.

### 2.1 CadenceSPICE - Model

If the parameter DOPE is specified, the output characteristics are bended, because the effective collector resistance is decreased for decreasing voltage  $V_{CE}$  (Fig. 5).

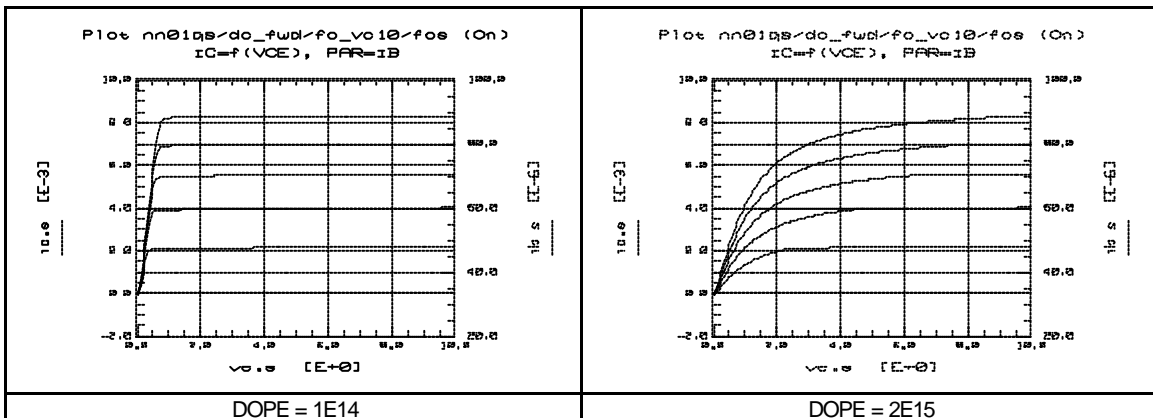


Fig. 5: Effect of DOPE on the output characteristic

The reference current CCO and the exponent CEX create a shift in the output characteristic at high currents (Fig. 6), e.g. for a decreasing value of CCO the effective collector resistance is increased and thus the collector current is reduced.

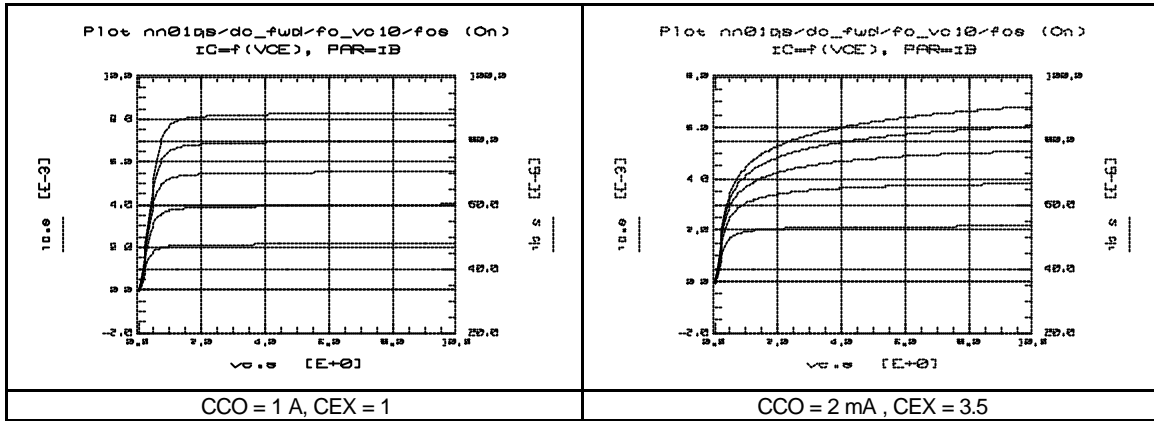


Fig. 6: Effect of CCO and CEX on the output characteristic

RCV, the variable collector resistance, determines the rise of the output characteristic in the saturation mode, if the other parameters are default (Fig 7). Typical values are about 1K.

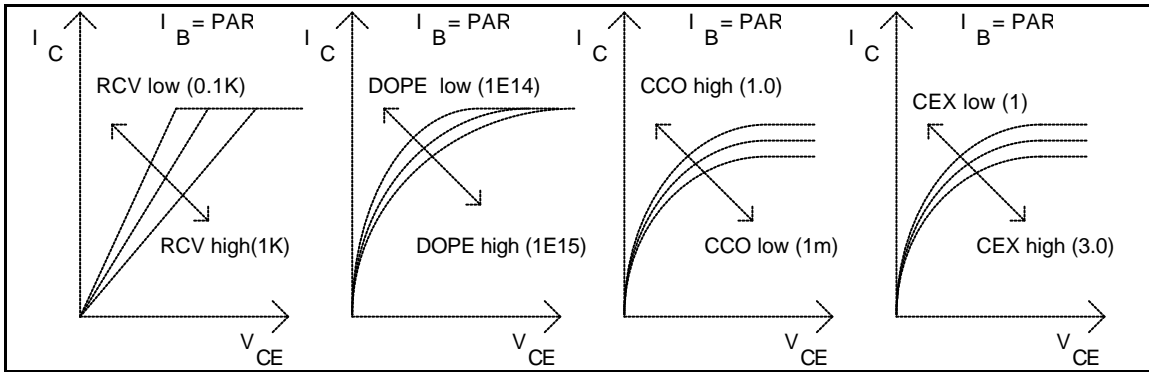


Fig 7: Effect of RCV, DOPE, CCO and CEX on the output characteristic

## 2.2 HSPICE - Model

Examining the effect of the HSPICE - QS parameters GAMMA, VO and RC<sup>4</sup> it is useful to consider eqn (11) more in detail. Rearranging this relationship for NEPI = 1, it reduces to:

$$I_{epi} = \frac{V_{COR} + V_{EPI}}{RC * \left[ 1 + \frac{V_{EPI}}{VO} \right]} \quad (21)$$

where

$$V_{COR} = V_T \left[ ki - kx - \ln \left[ \frac{1 + ki}{1 + kx} \right] \right] \quad (22)$$

and

$$V_{EPI} = V_{BCi} - V_{BCx} \quad (23)$$

$V_{COR}$  here is a correction voltage, depending both on epi layer doping GAMMA and the epi layer voltage drop  $V_{EPI}$ . This correction voltage is added to  $V_{EPI}$ . In the active normal case ( $V_{BCx} < 0$ ,  $V_{BCi} < 0$ )  $V_{COR}$  is zero, but in the QS  $V_{COR}$  increases. For a given RC value this results in an increasing value for the current source  $I_{epi}$ . In this way the effective collector resistance is reduced. The carrier velocity saturation effect is modelled using the parameter VO. If the epi layer voltage drop reaches VO, the effective collector resistance increases and  $I_{epi}$  is decreased. The effect of GAMMA, VO and RC on the output characteristic was examined with simulations using

<sup>4</sup>Note: In the HSPICE - QS model the epi resistance parameter is unfortunately called RC instead of RCO, e.g. the LEVEL1 parameter RC is **not** identical to the LEVEL2 parameter RC.

HSPICE 93a. Each parameter was varied using the following default values for the other parameters: LEVEL = 2, RC = 500, VO = 0, QCO = 0, GAMMA = 0, NEPI = 1, ISS = 1a, IS = 400a, BF = 75, VAF = 75. The effect of QCO was investigated using the full parameter set of transistor nn01 for a transit frequency simulation. (see Fig. 8 to Fig. 12). We can summarize the effect of the HSPICE - QS parameters as following:

- GAMMA causes a flattening in the QS range of the output characteristic. High GAMMA values correspond to low increase of the characteristic. Meaningful GAMMA values are in the range of 1 ... 100 n.
- VO causes a rounding off in the QS range of the output characteristic. The lower the VO value, the higher the effect. Meaningful VO values are in the range of 1 ... 10 V.
- RC acts as the normal ohmic resistance for  $VO = \infty$  and GAMMA = 0 (Fig. 10). If VO and GAMMA are specified, RC acts in the QS range as shown in Fig. 13. Changing the slope of the output characteristic in the saturation range for the HSPICE model is only possible using an additional constant collector series resistance (RCex). Note, that the value of the LEVEL2 - parameter RC is distinctly higher than the RC value of the SGP - model. Meaningful RC values are in the range of 1 ... 10 K
- QCO causes a sharp decrease of the  $f_T$  - characteristic, if the device reaches QS (Fig. 12).



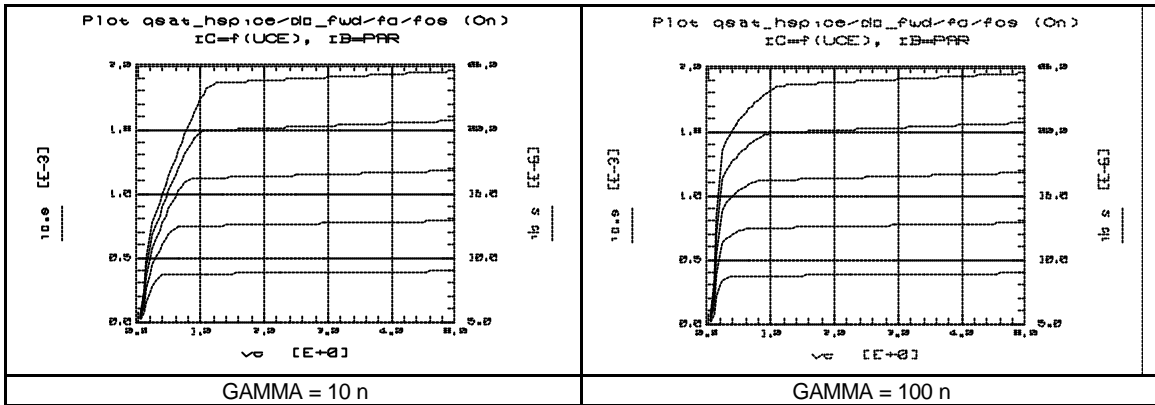


Fig. 8: Effect of GAMMA on the output characteristic

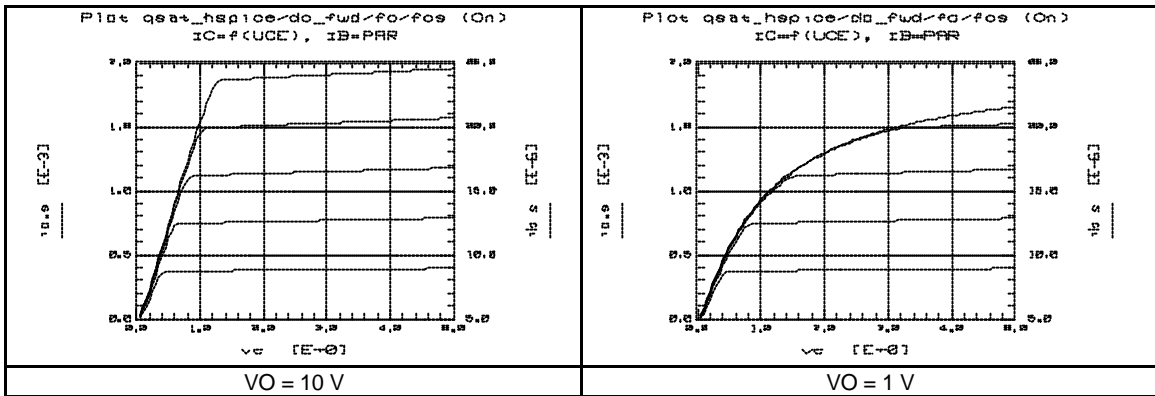


Fig. 9: Effect of VO on the output characteristic

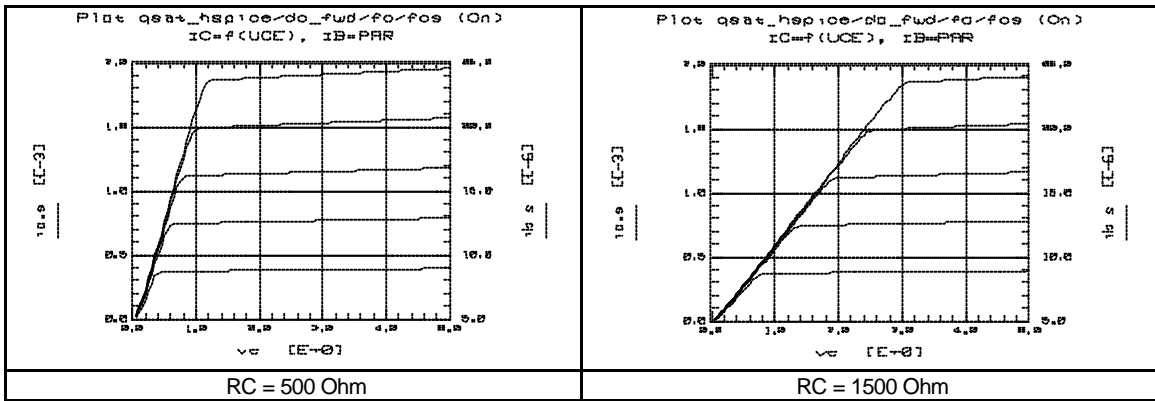


Fig. 10: Effect of RC on the output characteristic

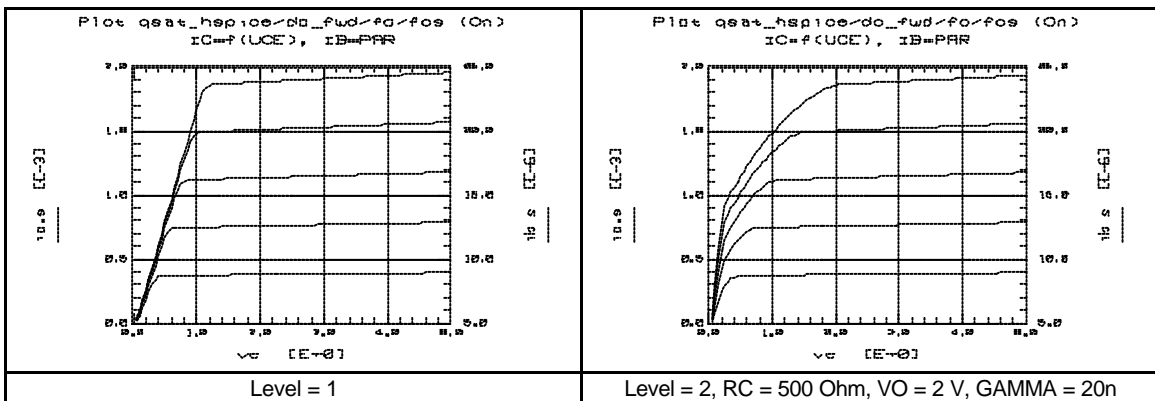


Fig. 11: Effect of GAMMA, VO and RC on the output characteristic

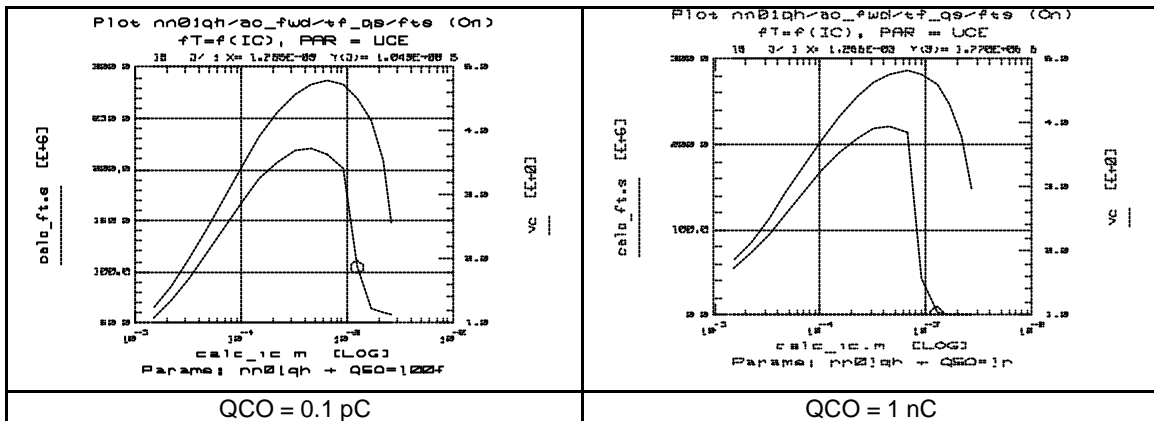


Fig. 12: Effect of QCO on the  $f_T$  - characteristic

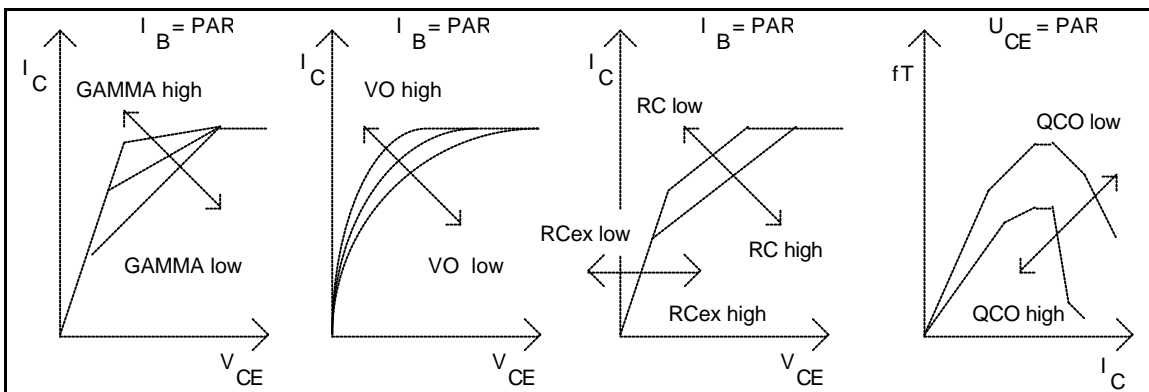


Fig. 13: Effect of the model parameters GAMMA, VO, RC, RCex and QCO

### 3 Quasisaturation Model Parameter Extraction

This section outlines procedures to determine the parameters for the CadenceSPICE - and the HSPICE - QS model. The DUT used for parameter extractions is an integrated npn transistor nn01, characterised by the following typical values:  $V_{CE} = 50$  V,  $I_{Cmax} = 5$  mA,  $A_E = 16 \times 16 \mu\text{m}^2$ .

#### 3.1 CadenceSPICE - Model

##### 3.1.1 RCM, RCV, DOPE, CCO and CEX

A number of methods is available for the determination of RCM, according to the usual collector resistance determination, e.g. the forced beta method or the  $\Delta I_{sub}$  - method [6]. RCV is given by the reciprocal increase of the line between the origin and the point, where the onset of QS takes place for high currents (Fig. 14). In the next step we can determine DOPE by an optimization on a medium current output characteristic. The parameters CCO and CEX may be determined then by an optimization in the high current range of the output characteristic (Fig. 15). Useful start values are found as  $CCO = 10 \times I_C (B_{Nmax})$  and  $CEX = 2$ . Using this way, we found the following QS - parameters for nn01:  $RCM = 55$ ,  $RCV = 1000$ ,  $DOPE = 4E14$ ,  $CCO = 2$  m and  $CEX = 3.5$ .

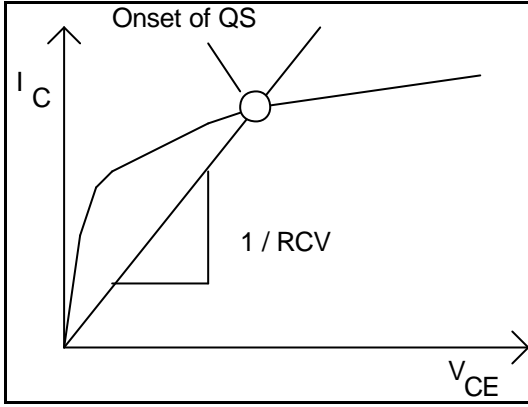


Fig. 14: Determination of RCV

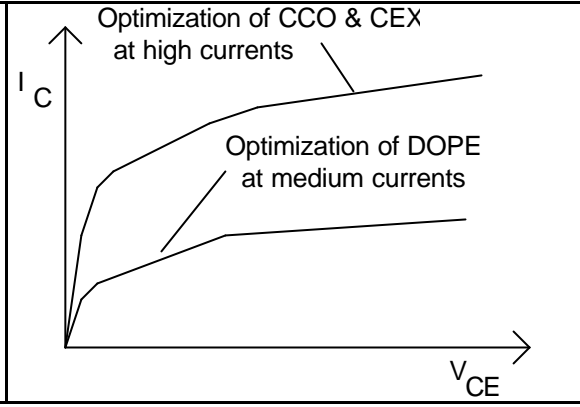


Fig. 15: Determination of DOPE, CCO, CEX

### 3.1.2 Model Parameter Set

The following table shows the full parameter set for nn01, used for the CadenceSPICE simulations in the section Results

Table 5: CadenceSPICE model parameter set

Parameter	Value	Parameter	Value	Parameter	Value
DOPE	4E+14	RCV	1000	RCM	55
CCO	0.002	CEX	3.5	IS	1.41E-16
BF	125	ISE	1.8E-16	IKF	0.02
NE	1.45	NF	0.986	BR	0.28
ISC	2E-16	IKR	0.1	NC	1.1
NR	0.995	VAF	244	VAR	18
RE	2.43	RB	160	RBM	40
IRB	2E-05	TF	4.6E-10	XTF	10
VTF	8	ITF	0.02	TR	2E-07
PTF	0	XCJC	1	FC	0.85
CJE	5.44E-13	VJE	0.664	MJE	0.308
CJC	4.44E-13	VJC	0.415	MJC	0.262
CJS	1.183E-12	VJS	0.415	MJS	0.318
XTB	1.043	XTI	3.244	EG	1.11

## 3.2 HSPICE - Model

### 3.2.1 VO, RC and GAMMA

For the extraction of VO we have to choose two points P1 and P2 in the output characteristic, at which the transistor nearly enters the QS range (Fig. 16) [3]. At these point we can assume  $V_{BCi} \approx 0$  ( $k_i \approx 1$ ) and  $V_{BCx} \ll 0$  ( $k_i \approx 1$ ). Therefore we have for the correction voltage  $V_{COR} = 0$  and eqn (21) reduces to:

$$I_{epi} = \frac{V_{BCx}}{RC * \left[ 1 + \frac{V_{BCx}}{VO} \right]} \quad (24)$$

Rearranging this equation and using the values of point P1 and P2, we have for VO:



We can simply measure now both the currents  $I_{bc}$  and  $I_{bs}$ .  $I_{bc}$ , the reverse transfer current of the npn transistor, is the current at the emitter terminal ( $I_{bc} = I_E$ ).  $I_{bs}$ , the forward transfer current of the parasitic pnp transistor, is the substrate terminal current ( $I_{bs} = I_{Sub}$ ). Thus we get the parameter BRS as the ratio of two transfer currents. In practice, this ratio is current dependent and we can use the maximum value as the model parameter:

$$BRS = \left[ \frac{I_{Sub}}{I_E} \right]_{MAX} \quad (27)$$

The reverse current gain of an npn - transistor for the SGP - model is usually defined as the ratio of the reverse transfer current ( $I_E$ ) and the appropriate base current ( $I_B$ ):

$$B_I = I_E / I_B \quad (28)$$

Using the LEVEL2 - model we have to work with a modified definition of the npn inverse current gain, because the base terminal current  $I_B$  is now divided in two parts: the substrate current  $I_{Sub}$  and the true npn base current  $I_{Bnpn}$ :

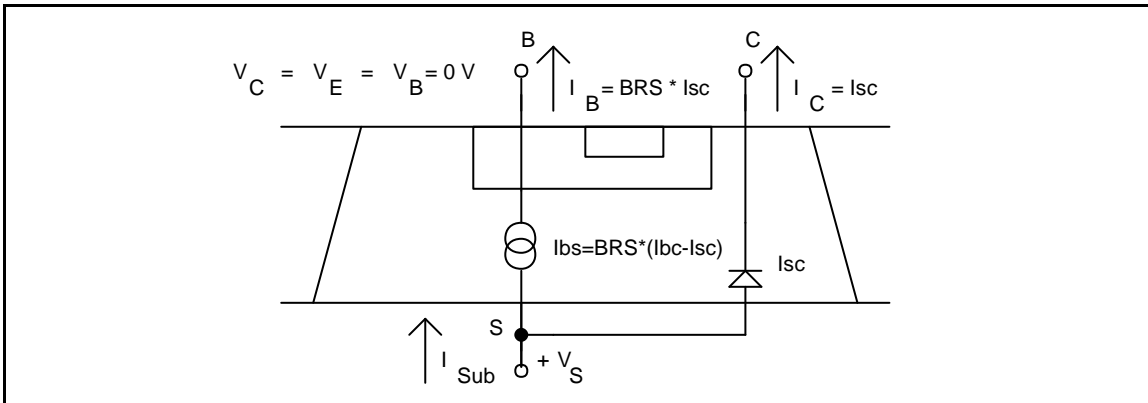
$$B_I = \frac{I_E}{I_B - |I_{Sub}|} \quad (29)$$

The ratio  $B_I$  is current dependent too. We can use the maximum  $B_I$  - value for the model parameter BR again.

$$BR = B_{I_{max}} \quad (30)$$

### 3.2.3 ISS and NS

Based on the definition in eqn (16) we have to measure the forward biased substrate - epi diode for the determination of the parameters ISS and NS. As shown in Fig. 19, we can measure this current at the collector terminal ( $I_{sc} = I_C$ ).



**Fig. 19: Determination of ISS and NS, forward biased substrate - epi junction**

We can apply the following two - point equations on the diode characteristic  $I_C = f(V_{SC})$  with  $V_{BE} = V_{BC} = 0$  for the calculation of ISS and NS:

$$ISS = \frac{I_{C1} \left[ \frac{V_{SC2}}{V_{SC2} - V_{SC1}} \right]}{I_{C2} \left[ \frac{V_{SC1}}{V_{SC2} - V_{SC1}} \right]} \quad (31)$$

and

$$NS = \frac{V_{SC2} - V_{SC1}}{V_T \ln \frac{I_{C2}}{I_{C1}}} \quad (32)$$

There seems to be a second possibility to determine the parameter BRS. For  $V_{BC} = 0$  the substrate current source  $I_{bs}$  reduces to the form

$$I_{bs} = BRS * (-I_{sc}) \quad (33)$$

and BRS is given, using the terminal currents  $I_B$  and  $I_C$  :

$$BRS = I_B / I_C \quad (34)$$

However, this value (typical  $< 1$ ) strongly deviates from the BRS - value based on eqn (27). This contradiction is caused by the model definition itself: the substrate current source  $I_{bs}$  is defined referring two currents using only one gain parameter BRS. Consequently the model under this bias conditions is not able to simulate exactly the base and the substrate terminal currents.

### 3.2.4 QCO

The best way for determining QCO is a fit on a  $f_T$  - characteristic under QS conditions. Note, that the DC - QS parameters affect the  $f_T$  - characteristic too. Thus an additional fit of the parameters CJE, CJC, TF and ITF was necessary for transistor nn01, before QCO was fitted.

### 3.2.5 Extraction Strategy

The parameters BR and BRS affect the division of the base terminal current and consequently the simulated output characteristic. Therefore it is useful to determine first BR and BRS and then RC, VO and GAMMA (Table 6). In addition, it was found advantageous to use an external collector resistance RCex. Using the described extraction methods, we determined for the transistor nn01 the following QS - parameters: RCEX = 55, RC = 365, VO = 2.07, GAMMA = 120 n, BRS = 10, ISS = 3.256 f, NS = 1.008, QCO = 100 f, BR = 30.

Step	Parameter	Characteristic	Condition	Mode
1	ISS, NS	$I_C = f(V_{SC})$	$V_{BE} = V_{BC} = 0$	Substrate diode = Forward biased
2	BR, BRS	$I_{sub}, I_B, I_E = f(V_{BC})$	$V_{BE} = V_{SC} = 0$	NPN = Reverse mode
3	VO, RC	$I_C = f(V_{CB})$	$I_B = PAR$	NPN = QS
4	GAMMA	$I_C = f(V_{CE})$	$I_B = PAR$	NPN = QS
5	QCO	$f_T = f(I_C)$	$V_{CE} = PAR$	NPN = QS

**Table 6: Extraction strategy**

### 3.2.6 Model Parameter Set

The full parameter set, used for the simulations in the section Results is shown in Table 7.

**Table 7: HSPICE - LEVEL2 model parameters for nn01**

Parameter	Value	Parameter	Value	Parameter	Value
RCEX	55.00	BR	30.00	CBE	325.0f
LEVEL	2.000	NR	996.5m	CBC	197.0f
RC	365.0	VAR	18.00	CCS	952.0f
VO	2.070	IKR	100.0m	CJE	744.0f
GAMMA	120.0n	ISC	200.0a	CJC	644.0f
BRS	10.00	NC	1.100	CJS	1.183p
ISS	3.256f	RB	160.0	VJE	664.0m
NS	1.008	IRB	20.00u	VJC	415.0m
QCO	100 f	RBM	40.00	VJS	415.0m
IS	141.2a	RE	2.430	MJE	308.0m

BF	125.0	TF	320.0p	MJC	262.0m
NF	989.6m	XTF	10.00	MJS	318.0m
VAF	244.0	VTF	8.000	XCJC	1.000
IKF	20.00m	ITF	1K	FC	850.0m
ISE	180.0a	PTF	0.000	XTB	1.043
NE	1.450	TR	200.0n	XTI	3.244

## 4 Results

### 4.1 CadenceSPICE - Model

Using the CadenceSPICE - model, we simulated the output characteristic both in a low and a high current range of the DUT. As can be seen, the simulation results are sufficiently in agreement with the measurements.

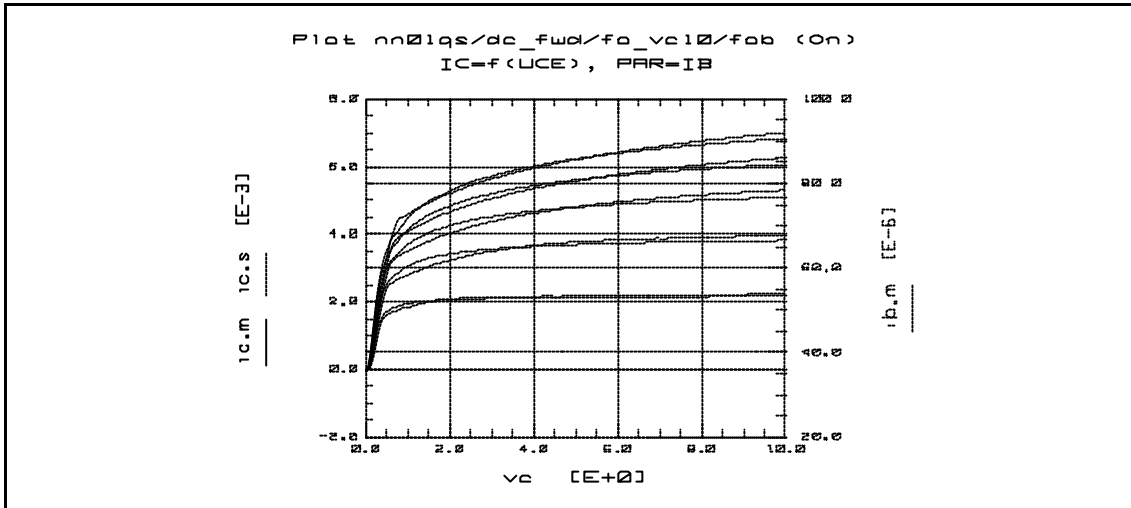


Fig 20: Output characteristic  $I_C = f(V_{CE})$ ,  $I_B = 20 \dots 100 \mu\text{A}$ ,  $V_{CE} = 0 \dots 10 \text{ V}$

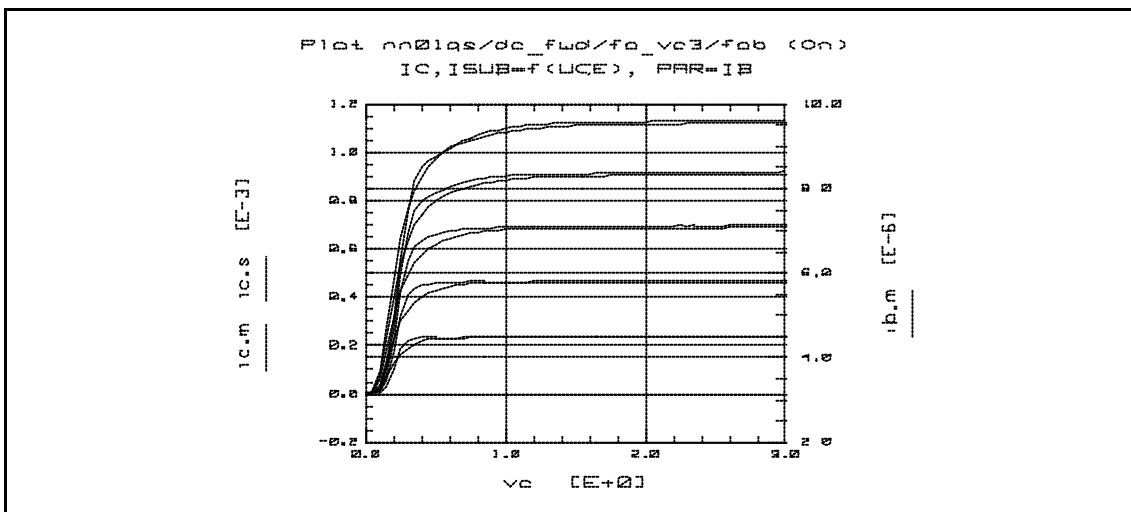


Fig 21: Output characteristic  $I_C = f(V_{CE})$ ,  $I_B = 2 \dots 10 \mu\text{A}$ ,  $V_{CE} = 0 \dots 3 \text{ V}$

### 4.2 HSPICE - Model

As the output characteristic (Fig. 22 and Fig. 23) shows, the typical QS flattening is well reproduced by the model. However, the substrate current, additionally shown in both the characteristics, is overestimated by the simulation in the QS range. This illustrates the main disadvantage of the model, caused by the simplified definition of the substrate current source  $I_{bs}$ . The forward transfer characteristic demonstrates the inaccurate substrate current simulation of the HSPICE - QS - model too: while the measured current increases at  $V_{BE} \approx 800 \text{ mV}$ , the simulated current increases already at  $740 \text{ mV}$  (Fig. 24). The reverse mode simulation illustrates, that,  $I_b$  and  $I_{sub}$  are nearly identical (Fig. 25). This means, the npn base current ( $I_b - I_{sub}$ ) is relative small an BR reaches a high value (about 30 for nn01). For the reverse mode of the parasitic pnp transistor (substrate - epi junction forward biased), the model simulates



only the current at the collector terminal exactly Fig. 26). Because of the substrate current source definition (only one gain BRS for both directions) the simulated currents at the substrate and the base terminal are much to high. Usually this disadvantage is not important, because this mode in most cases is not allowed for an integrated transistor.

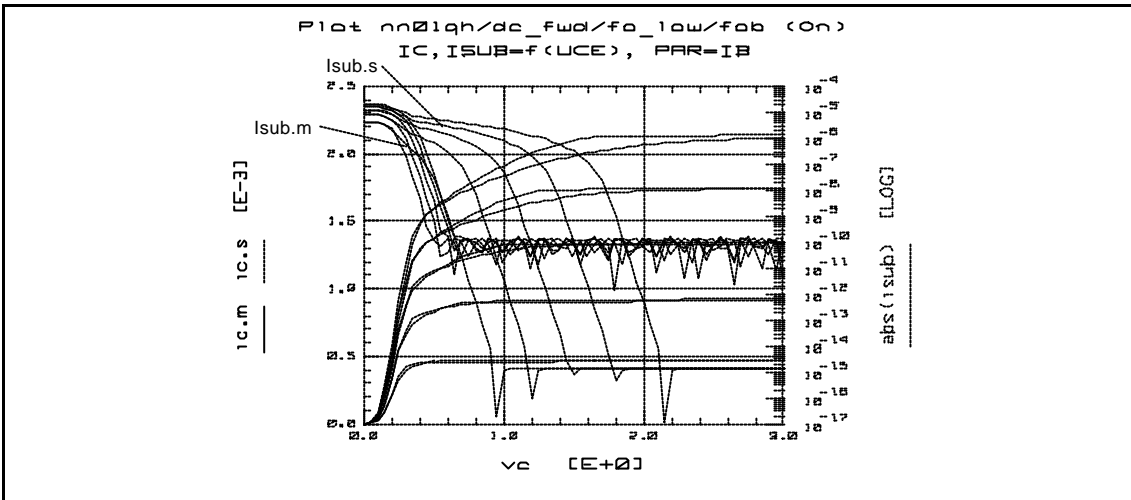


Fig. 22: Output characteristic  $I_C$ ,  $I_{Sub} = f(V_{CE})$ ,  $V_{CE} = 0 \dots 3 \text{ V}$ ,  $I_B = 4 \dots 20 \mu\text{A}$ , Step =  $4 \mu\text{A}$

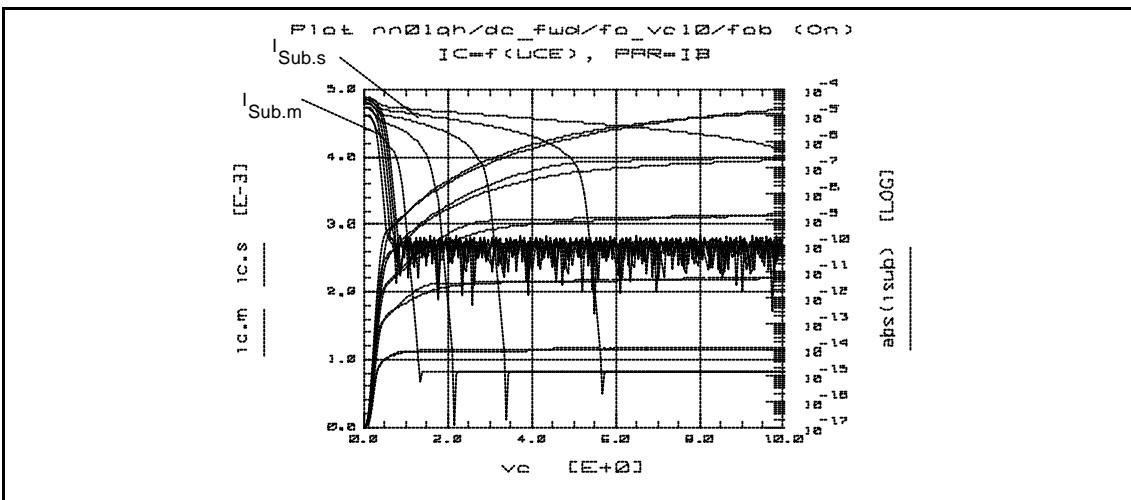


Fig. 23: Output characteristic  $I_C$ ,  $I_{Sub} = f(V_{CE})$ ,  $V_{CE} = 0 \dots 10 \text{ V}$ ,  $I_B = 10 \dots 50 \mu\text{A}$ , Step =  $10 \mu\text{A}$

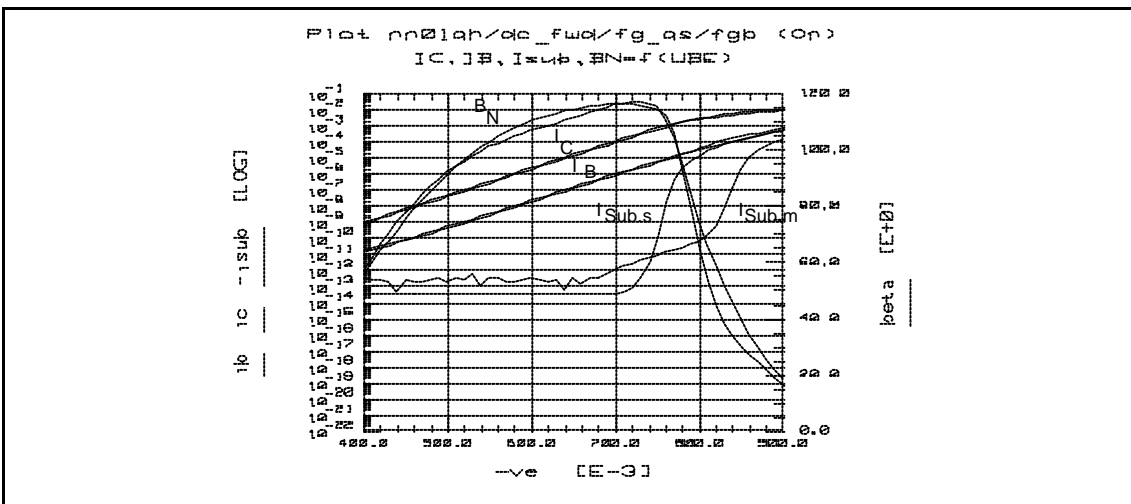


Fig. 24. Forward Gummel plot  $B_N$ ,  $I_C$ ,  $I_B$ ,  $I_{Sub} = f(V_{BE})$ ,  $V_{SC} = -1 \text{ V}$ ,  $V_{BC} = 0 \text{ V}$

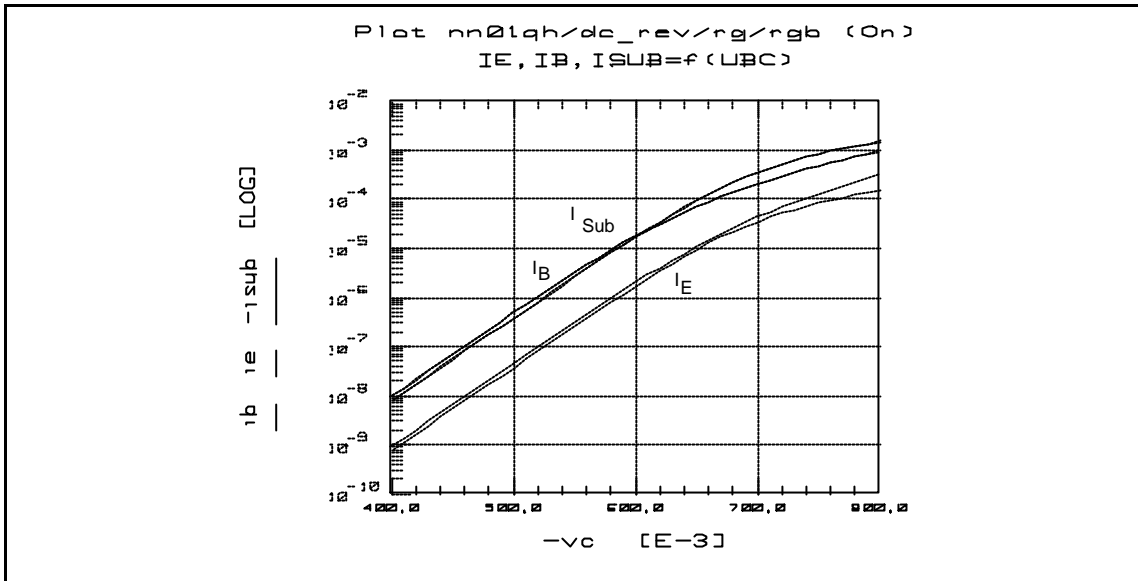


Fig. 25: Reverse Gummel plot  $I_E, I_B, I_{Sub} = f(V_{BC})$ ,  $V_{SC} = -1V$ ,  $V_{BE} = 0V$

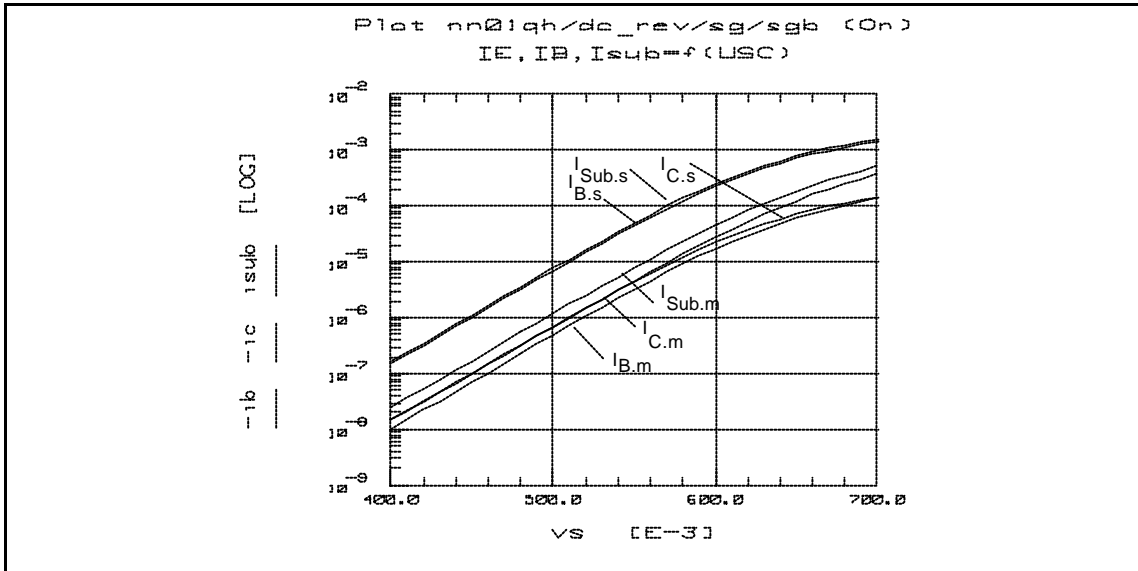


Fig. 26: PNP reverse mode Gummel plot  $I_C, I_B, I_{Sub} = f(V_{SC})$ ,  $V_{BE} = V_{BC} = 0V$

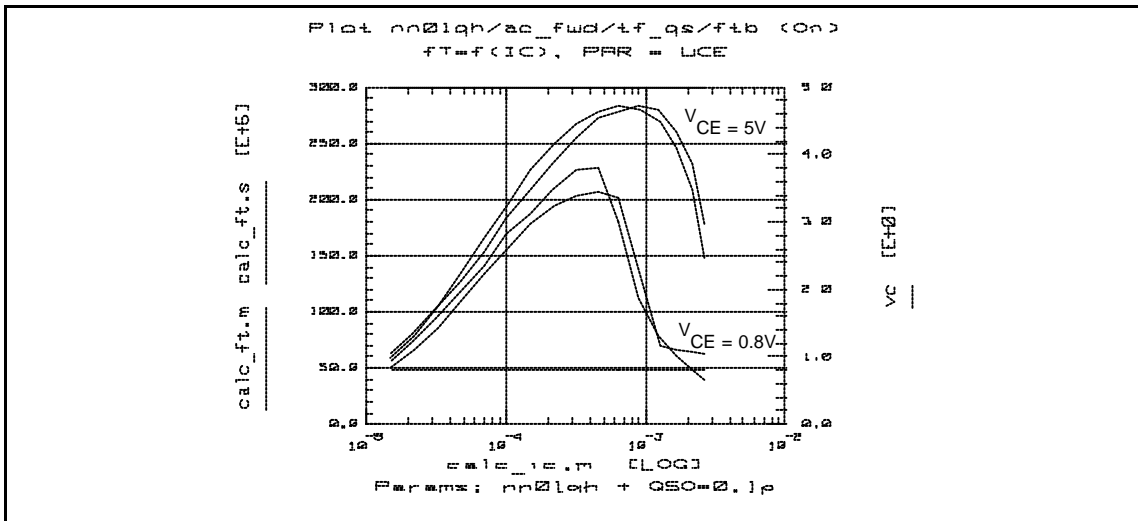


Fig. 27: Transit frequency characteristic  $f_T = f(I_C)$ ,  $V_{CE} = 0.8V, 5V$

## 5 References

- [1] Ryder, E.J. : Mobility of Holes and Electrons in High Electric Fields  
Phys.Rev.90:766 (1953)
- [2] Cadence: "Cadence Spice Reference Manual". Version 2.4 1991
- [3] Kull, G.M., et. al.: A Unified Circuit Model for Bipolar Transistors Including Quasi Saturation Effects. IEEE Transactions on Electron Devices, Vol. ED - 32, No. 6, JUNE 1985, pp.1103-1113
- [4] MicroSim Corporation: PSPICE Circuit Analysis Reference Manual. , Version 5.4, July 1993
- [5] Meta-Software, Inc.: HSPICE User's Manual. 1990
- [6] Berkner, J.: "A Survey of DC - Methods for Determining the Series Resistances of Bipolar Transistors including the new  $\Delta$  ISub - Method". In: 1st Combined European Hewlett Packard HP4062 & IC-CAP User Meeting Proceedings, 9. -12.10.94, Hourburg Wihr