BIPOLAR DC PARAMETER DETERMINATION WITH UTMOST

FINAL STAGE REPORT
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The Gummei Poon model is a model that describes the functioning of the bipolar transistor. The DC part describes the collector and base currents as a function of the applied voltages, $V_{BE}$ and $V_{CE}$. These functions contain parameters and these can be obtained by measuring the transistors under certain useful bias conditions and determining a slope, an intersection point etc. of the graphics that are obtained (see [1]). The noise part describes the noise in the base current and is assumed to be composed of shot noise and white noise (in the Gummei Poon model).

In this work the DC and noise parameters of bipolar transistors were determined and it was done for the company Alcatel in Brussels, Belgium. A new program, UTMOST, was used to measure the bipolar transistors and also to determine the parameters out of the graphics that were measured. The transistors were supplied by Alcatel, three vertical NPN types of different geometries and two lateral PNP types with a small difference in the base length. The program UTMOST has the possibility to measure, extract from the measured curves and simulate with the extracted results. Observation learned that optimisation was needed for some parameters, since there were differences between the measured and simulated results. This is because the extraction method of UTMOST is not depending on earlier extracted parameters and because parasitic PNP transistors with the substrate as one terminal, are not included in the model but in reality present. Optimisation of only a few parameters was needed to get better simulated results (i.e. close to the measured results). Finally five different set ups for the different transistors were developed, set ups that automatically measure the transistors, extract parameters and optimise were needed in order to have at last a complete DC model.

The noise parameters were measured manually and the parameters determined. Also, the base resistance for one NPN transistor is determined using the $1/f$ noise in the collector current.

Reference:
Conclusions

The conclusions that can be made from the DC extraction and optimising work with the UTMOST program is the following:

Advantages:

- It's very convenient to work with UTMOST; one sees the simulated results together with the measured results in one graph. Now it's easy to compare and easy to see where optimisation may be needed.
- Only a few parameters needed to be optimised, always RB, RBM, IRB and BF. For the PNP types also RC and IKF.
- The PNP can be modelled very well with UTMOST's optimising tool, but the lost of the physical meaning of IS and IKF is the price for that.
- For very small transistors UTMOST can facilitate the extraction of the low current parameters ISE and NE.

Drawbacks:

- RB parameter not physical for the smallest transistors. Probably also not for the others: the RB routine is not accurate to extract the base resistance.
- Manual extractions of IKR and BR are needed for the small NPN types, also they are needed to display ISUB to avoid saturation.
- It's difficult to include the parasitic into the UTMOST program (but it is possible).
- UTMOST does not take into account the influences of other parameters when a parameter is extracted (BF too small).

Because of the advantages UTMOST is easy and convenient to work with and despite the few parameters that have to be optimised it does not loose physical meaning (except the IKF and IS value for the PNP, but then the parasitic should be included). UTMOST is therefore advised to work with to obtain the DC parameter sets.

- The used Gummel-Poon model can not model very well the high current behaviour of the NPN types, where the collector resistance cannot be considered anymore as a constant. Differences can be seen for the output characteristics at low VCE.
I Setup of the equipment

For the program UTMOST to work properly and let it perform the measurements on the bipolar transistors, the equipment should be defined and setup, also the transistors should be defined.

I.1 The experimental setup

First a scheme of the experimental setup is given in figure 1. The UTMOST program is the 'brain' of the used equipment and gives orders to and receives data from the HP DC Analyser. This communication is done via a RS232 interface and a GPIB-232 controller. The HP DC Analyser will have it's four source and monitoring units connected to the "device under test" (DUT). This connection is done with high quality triaxial cables. See also [1] for the connection and use of the HP 4145. The transistor finally, part of a test circuit of a wafer, is placed in a probe station which can be closed from (day)light. The station is made of metal so it functions also as the cage of Faraday.

I.2 The measured bipolar transistors and their regions of interest

I.2.1 The Mietec transistors

There are five bipolar transistors of Mietec that are on the test insert (a die) on the wafer. These transistors will be measured and table 1 gives the Mietec names and
types. See [2] for more detailed information.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Connections</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNH1A</td>
<td>NPN</td>
<td>28 27 22 21</td>
<td>minimum emitter size transistor (m.e.s.t.)</td>
</tr>
<tr>
<td>HNHPI0A</td>
<td>NPN</td>
<td>25 26 22 21</td>
<td>10 times m.e.s.t. with a plugged collector</td>
</tr>
<tr>
<td>HNHPI350A</td>
<td>NPN</td>
<td>23 24 22 21</td>
<td>350 times m.e.s.t. with a completely plugged collector</td>
</tr>
<tr>
<td>HPH1A</td>
<td>PNP</td>
<td>17 18 19 21</td>
<td>m.e.s.t. for PNP types; high $B_{VCE0}$</td>
</tr>
<tr>
<td>HPL1A</td>
<td>PNP</td>
<td>20 21 19 21</td>
<td>m.e.s.t. for PNP TYPES, low $B_{VCE0}$</td>
</tr>
</tbody>
</table>

A plugged transistor (only N-types) is a transistor with the collector terminal connected to the buried layer (BLN) through an N-plug (a highly doped diffused region from the terminal to the buried layer). See figure 12 in § II.3.5.1. Mietec has one completely plugged transistor which means that the plug surrounds the base (see also figure 19 in § II.3.5.1).

The difference between HPH1A and HPL1A is the base width. The HPH1A has a base width that is 1 μm larger than the HPL1A, which results in a higher $B_{VCE0}$ (collector-emitter breakdown voltage with open base).

### 1.2.2 The consideration of the interesting regions

From design considerations the following minimum currents are specified for the Mietec transistors:
HNHP350A and HNHPI0A: $I_C \geq 1 \mu A$;
HNH1A, HPH1A and HPL1A: $I_C \geq 100$ nA.

For the NPN transistors the maximum $I_C$ is about $I_{KF}$, where the gain is rolling off and because of it's low value becomes unappreciable. The PNP types, which have a

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* $I_{KF}$ is the parameter that models the $β$ rolling off; see the explanation of $I_{KF}$ given in the section on the ALL_DC routine setup.
bigger $B$, can be used for currents higher than $I_{KF}$ where the gain is still quite big ($>100$) so that they can still be used. Here the maximum $I_C$ will be three times $I_{KF}$.

The transistors that are used have not all the same purposes. The completely plugged transistor will be used as a power switching transistor but also as a diode (base-collector diode). When used as a diode, the characteristics are positively influenced when the emitter is shorted with the base and since this is done it effect should be modeled. Therefore the reverse of this fully plugged transistor needs to be accurately known. When used as a power switching diode the high currents as well as the saturation region is important. This becomes clear when the transistor is considered as an open collector driver. An important specification is then that the collector-emitter voltage is lower than a specified value when the transistor is on and takes a specified current (this voltage is called the saturation voltage).

For the other transistors especially the forward model is of interest; in the reverse region there's a big influence of the parasitics. This is also true even for the completely plugged transistor (see the sections on influences of the parasitics). Therefore a macro model is tried to make (for the not completely plugged NPN devices) to include the parasitic with some of it's parameters and to see if the simulation results are better (i.e. closer to the measured curves).

I.3 Hardware and device setup of UTMOST

I.3.1 Starting UTMOST and connecting ELDO

When UTMOST uses an external simulator, such as ELDO, it should be started by VYPER (ask the system administrator how to do this).

When VYPER is started UTMOST and ELDO need to be connected to VYPER. Once a program is connected to VYPER, it keeps the setup and there's no need to re setup the connection at an other session.

To connect press "Files", "Net Setup". The "VYPER CONFIGURATION" screen appears and here select "UTMOST" and press "Connect". Then a menu follows with:

- Host name: <your computer name>
- Path to UTMOST location: $SILVACO/bin
- Version: Press the button. Choose 10.10.7.C (improved
User ID to run UTMOST: <use your registered name>
Then press “Apply” and finally “Quit”

For ELDO select “ELDO” and press “Connect”. Then for the menu:
   Host name: <your computer name>
   Path to UTMOST location: /disk55/utils/comcad/anacad/bin
   User ID to run UTMOST: <use your registered name>
Then press “Apply” and “Edit Setup”. Change
“set ELDOOUT=$CURDIR/$NAMIN.chi” to
“set ELDOOUT=$PATHOUT/$NAMIN:r.chi”.

Press “Save” to save the changed setup file and automatically quit this menu.
Press the button between “UTMOST” and “Skematix” (it will probably show
“SmartSpice”). Choose “ELDO”, “Local”.

UTMOST can now be started by pressing “UTMOST”, “*bip*”. The “UTMOST III
BIPOLAR” screen will appear.

I.3.2 Load a setup file

Start from the “UTMOST III BIPOLAR” menu. Press “Files”, “File Manager” to
come into the “Files” menu. When a Taylor made setup file is already present for the
intended measurement and measurement equipment this file can be loaded. Otherwhise, when UTMOST must be adapted to use the measuring equipment and
must be setup for the devices to measure, then the standard setup file
“BIP.10.10.7.C” must be loaded and will be changed. Loading is performed by
dragging the icon onto the setup mailbox.

Quit this menu.

I.3.3 The common control setup

This menu can be obtained by pressing the “System” button in the “UTMOST III
BIPOLAR” menu. The “COMMON CONTROL SCREEN” should look like the
following:
Nominal Temperature (°C): Use a temperature meter in the prober station to obtain the right temperature. Here, it was 25 degrees.

Keep the other values to their original default. Press "TITLE BLOCK" to see the "TITLE BLOCK SCREEN". Fill in the desired information ("LOT NUMBER", "WAFER NUMBER" and "DIE NUMBER" will occur in the header of every measurement!). The "DEVICE ID" and "GROUP ID" will be filled in by UTMOST.

Then press "Quit" to leave this "COMMON CONTROL SCREEN".

### 1.3.4 The hardware setup

From the menu "UTMOST III BIPOLAR" choose "Hardware", "Configuration". In the "DEVICE CONFIGURATION" screen set the items as follows:

- **PLOTTER**: Postscript
- **File**: POSTSCRIPT
- **B/W**: Automatic
- **Autoplot**: Disabled
- **Scale (0.1-1)**: 1
- **SCANNER**: none
- **DC ANALYSER**: 4145
- **GPIB**: 24 (check the dip-switches on the back side of the DC analyser).
- **SMU defin.**: Collector 1, Base 2, Emitter 3, Substrate 4
- **Stimul Mode**: System
- **AC ANALYSER**: none
For the buttons on the bottom side:

CPU side: RS232 TTY
Baud rate: 9600

To check the connection press "POLLING" (make sure the modem and DC analyser are turned on and that the physical connection between computer and analyser is established). UTMOST should come back with the message "<4145> on line". Then press "Quit" to end this hardware setup.

I.3.5 The transistor setup

Make sure to be in the "UTMOST III BIPOLAR" menu. Choose "Hardware", "Probing", "Devices" to come into the menu "DEVICE PADS". The structure names of the devices that are to be measured should be filled in the "Structure Name" column*. Fill in:

<table>
<thead>
<tr>
<th>Structure name</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNH1A</td>
<td>N</td>
</tr>
<tr>
<td>HNHP10A</td>
<td>N</td>
</tr>
<tr>
<td>HNHP350A</td>
<td>N</td>
</tr>
<tr>
<td>HPH1A</td>
<td>P</td>
</tr>
<tr>
<td>HPL1A</td>
<td>P</td>
</tr>
</tbody>
</table>

The rest of the columns do no matter here.

Finally set "Group" to "1".
Quit this menu and the transistor devices are set up.

*With the "Edit Names" function set to "Enabled" it's now possible to enter names in the "Structure Name" column.
The next chapter defines the setup of routines that are used by UTMOST to obtain the DC parameters. During this setup already measurements are performed and a theoretical background is needed to know a good setup. Therefore, this setup part is explained, together with the measurement techniques and optimisation, in the following chapter.

On this point UTMOST can work with the used measurement setup and knows the devices that have to be measured.
II The setup of the UTMOST routines

Extraction means that parameters are obtained by getting particular data from specific measurements. This data can be a slope, an intersection point or anything else and with help of this data some parameters can be calculated. In UTMOST, routines are used to perform measurements and extractions and later on also for optimising some parameters.

Just a few routines are needed to get all the DC parameters [3]. See the table.

<table>
<thead>
<tr>
<th>Routine name</th>
<th>Extracted parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td>RC_sat</td>
<td>RE, RC</td>
</tr>
<tr>
<td>ALL_DC</td>
<td>ISE, NE, IS, NF, BF, IKF, ISC, NC, NR, BR, IKR, VAR</td>
</tr>
</tbody>
</table>

These routines have to be set up correctly in order to have the right region of each measurement to extract the parameters. Several preliminary measurements will have to be done to come to a right setup and therefore a little section will explain how to measure and also to choose the right transistor.

Another little section will tell about the way values should be inserted for both types of transistors.

Then all the used routines are treated. Theoretical background of the extracted parameters, the way they are extracted and the way to set the routines up is explained. A more rigorous examination of the effect of the parasitics on the performed measurements can be found in the last two sections of this chapter about influences of the parasitic PNP's on the transistors (§ II.4).

II.1 PNP and NPN transistors, sign of the entered voltages

The names for the voltages that are found in the measurement setup are correct for the NPN type bipolar transistors. The item VBE_start will have to be 0.4 V for instance. For a PNP, this value still needs to be 0.4 V and do not fill in -0.4 V. Although the same names are used, UTMOST automatically polarises the voltages in the way that is normal for the used type.
Furthermore, to obtain the Gummel-Poon plots the polarisation is used that is proposed by [4]. This means that $V_{CB}$ for the forward Gummel plot is zero; a lot of parameters in the current equations (see appendix 1) fall away and simple equations remain. Now extraction and calculation can easily be done. But with this polarisation for the forward Gummel plot (FGP) the emitter voltage is swept from approximately -0.5 to -1 V. In UTMOST, when for the $V_{CE}$ voltage 0 V is entered, UTMOST will automatically do the measurement with negatively swept $V_E$ (voltages filled in the items $VBE_{\text{start}}$ and $VBE_{\text{stop}}$ must still be positive).

II.2 Measurement techniques in UTMOST

In the subchapters where a good setup per routine will be defined, measurements are performed in order to come to good setup values. Before measurements are done by UTMOST there are a few things that have to be considered.

II.2.1 Number of measurements

Choose "Setups" from the "UTMOST III BIPOLAR" screen and the "Setup and Result Screen" appears. In this screen the routine should be chosen where the number of measurements have to be set for (the selected routine has a red diamond in its button).

Then press "Quit", "Routine Cntl" to come into the "ROUTINE CONTROL SCREEN". In the "Meas. Sections" box fill in the number of measurements. This number is given in each subchapter "Measurement setup" for the used routines.

II.2.2 Choosing the transistor

Choose "Setups" from the "UTMOST III BIPOLAR" screen and the "Setup and Result Screen" appears. In this screen the routine should be chosen where the number of measurements have to be set (the selected routine has a red diamond in its button). Then press "Quit", "Strategy" to come into the "MODEL STRATEGY" screen. Here the transistors indicated by a pink color will be measured. Choose the desired transistor. This should be done for all the used routines individually. When one transistor is measured and another is to be measured (an other type/geometry), then the setup should be overdone and the new transistor must be chosen for each routine.
II.2.3 Performing a measurement

When the setup of the used routines is ready for the specified transistor, the right transistor is chosen and the right number of measurements is filled in, then a (sequence of) measurement(s) may be performed. Choose "Extraction" from the "UTMOST III BIPOLAR" screen to come into the "Extraction Screen". Here a (sequence of) routine(s) can be chosen. The measurements will be performed by pressing "Measure".

Note: when a sequence is used, be aware that for the RC_sat routine an extra connection is needed to measure more accurately $V_{CE}$. This cable should be removed when other routines are measured.

For the Mietec transistors special setups are already made. The setup files automatically perform four routines (and their measurements) in a sequence: RH, RC_sat, ALL_DC and IC/VCE. See table 3 for the names of the setup files.

Table 3: The measurement setup files for the Mietec transistors.

<table>
<thead>
<tr>
<th>Transistor name</th>
<th>Setup file name</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNH1A</td>
<td>bipolar.HNH1A</td>
</tr>
<tr>
<td>HNHP10A</td>
<td>bipolar.HNHP10A</td>
</tr>
<tr>
<td>HNHP350A</td>
<td>bipolar.HNHP350A</td>
</tr>
<tr>
<td>HPH1A</td>
<td>bipolar.HPH1A</td>
</tr>
<tr>
<td>HPL1A</td>
<td>bipolar.HPL1A</td>
</tr>
</tbody>
</table>

II.2.4 Keeping the measurement information in a log file

A log file with the measurement data can easily be made. It's useful for optimisation afterwards and therefore it's strongly recommended to make these files. For each transistor an individual log file can be made. Take care for the correct measurement temperature when storing the data (at Mietec it was 25 °C).

Choose "Files", "Output Logfiles" from the "UTMOST III BIPOLAR" screen and the "OUTPUT LOG FILE SCREEN" appears. Here a log file name is specified and eventually a header. The functions of the buttons are:

OPEN NEW: A new log file can be opened. This screen can be quit and the measurements performed. After this, this screen can be recalled...
and the log file closed. Then the log file is saved in the current directory and can be seen when "Files", "File Manager" is pressed in the "UTMOST III BIPOLAR" menu.

**APPEND:**
This function should be used when an existing log file is to be extended with data of extra measurements. Preferably of other routines, since data of earlier performed measurements of the same routines will be overwritten by the new data of the same routine.

**OVERWRITE:**
Use this when an existing log file must be totally overwritten. All data will be lost.

**Log X data:**
When set to DISABLED the log file will consume the least amount of disc capacity by just storing the measurement values, not the headers and parameter names.

**Log names:**
When set to DISABLED the log file will consume the least amount of disc capacity.

### II.3 The routines

A routine consists of a measurement, followed by a fit to extract the desired parameter(s). This fit is hard coded in the program and uses specific parts of the curve of a measurement. Depending on the parameter that has to be extracted it performs an extrapolation, the slope or anything else.

Since these fits are not depending on values of earlier extracted parameters an optimisation is needed for some parameters*.

To limit the variation of the parameters during the optimisation, minimum and maximum values can be set for each parameter. An analysis will be given to determine some reasonable extreme values, not to loose physically reasonable values.

In the next sections the routines will be individually explained in detail, all use the following subchapters:

- **Extracted parameters:** Here the parameters that are extracted in this routine are given, with their notation in ELDO.

- **Meaning of the parameters:** A short explanation is given of the effect that the parameters model. Sometimes the physical background is given.

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*Almost never only one parameter can be extracted from a (part of a) curve; there's always the influence of other parameters that determine the extracted value, though this influence may be smaller.*
• Extraction method: This explains how the fit is done to get the parameter values. This normally consists of determining the slope of a line or an intersection point with one axe.

• Measurement setup: Here the measurement range for voltages and/or currents for any transistor is to be determined; the deduction is valid for both types and all geometries.

• Hardware measurement scheme: This reveals the hardware setup; at what terminals what voltages or currents are applied.

• Optimisation region, example of the simulated effect: Some of the determined parameters will not be very accurate since UTMOST does not correct for parasitic effects nor for the effect of other parameters. So they have to be optimised and a simulation is done (with the ALL_DC routine) where these particular parameters are changed so that it is clear where the optimisation regions are.

Note: In order to see the effects at low VCE (saturation region) for the IC(VCE) curve, an extra measurement is made for low VCE (routine IC/VCE). The setup for this routine is shortly explained.
II.3.1 Routine RB (3)

Extracted parameters:
RB: zero bias base resistance;
IRB: current where the base resistance falls to mid value;
RBM: minimum base resistance.

Meaning of the parameters:
These parameters model the dependency of the base resistance on the base current (see figure 2). RB is the maximum base resistance at very low currents; RBM is the minimum base resistance at very high currents and IRB is the value of IB where $r_{BB'}$ falls halfway between RB and RBM.

The equation that describes $r_{BB'}$ as a function of $I_B$ with help of these three parameters is given here:

$$r_{BB'} = RBM + 3(RB - RBM) \cdot \frac{\tan(Z) - Z}{Z \cdot \tan^2(Z)},$$

where:

$$Z = -1 + \left[1 + 1.44 \frac{I_B}{\pi^2 IRB}\right]^{0.5}$$

When all the three parameters are specified, $r_{BB'}$ depends only on $I_B$. 

Figure 2: Variation of effective base resistance with base current.
The base resistance effect is recognised by the deviation from the straight line on the plot of \( I_B \) (log scale) versus \( V_{BE} \) (the forward and reverse Gummel plot, compare appendix 3 with appendix 2).

For this deviation to be visible and large enough to be accurately measured, current levels must be large enough, or the base resistance itself has to be large enough. But at high currents the \( r_{BB'} \) value is substantially smaller than \( R_B \).

By running device simulators there are several values proposed for \( R_B \), \( I_{RB} \) and \( R_{BM} \) and these simulated curves are superimposed upon the measured one. Determination of \( R_{BM} \) is difficult, because for high currents the emitter resistance (\( R_E \)) has the same effect on the forward Gummel plot (compare appendix 4 to appendix 2) as \( r_{BB'} \) has.

One first should correct this forward Gummel plot for \( R_E \) and then try to extract the three \( r_{BB'} \) parameters from it. This is not possible in UTMOST (does not take \( R_E \) into account) and therefore these three parameters will have to be optimised.

**Measurement setup:**
To come into the setup screen press "Setups" from the "UTMOST III BIPOLAR" screen. Set "Analysis Filter" to "DC" and choose the desired routine. Then press "Set Measurem." to come into the "DC MEASUREMENT SCREEN" where the setup should be as defined here.

Integr. Time: Long integration time gives the same results as medium integration time, the extracted base resistance parameters are the same. So take medium integration time.

General remark on the integration time setting: Measurements at short, medium and long integration time should be performed and the results compared. The short integration time gives instable results for low currents but does not heat the device so much at high currents. Short should not be used when medium and/or long integration time do not overheat the device at high currents. This can be controlled by comparing the measurement results for high currents. Only if the results between short and medium differ much, then overheating may be the case during the medium integration time and short integration time should be used at for measurements at higher currents.
BIPOLAR DC PARAMETER DETERMINATION WITH UTMOST

Range ($V_{BE}$): Not too low, otherwise noise effects or inaccuracy effects of the measurement setup will disturb the measured results, the fit and therefore the extraction. Determine manually the starting value for $V_{BE}$ so that a little change in this value does not change the RB result (for the Mietec devices look at the voltage at which the minimum $I_C$ occur). Choose the end value not higher than the compliance limits of the device itself; for Mietec devices see [2]. Take especially care not to reach the compliance limit since the limiting result will disturb the extractions.

No. of points: Take the number of points so that the step is about 10 mV.

$\text{No.} = 1 + \frac{V_{BE_{max}} - V_{BE_{min}}}{0.01}$.

General remark on the number of points: Be aware that the number of points yields a step value that not needs to be rounded off. A rounded off step value implies a bigger or smaller range than desired. With this routine, the rangelength has a serious effect on the extracted results, so the range should be a big as we desire. Use therefore a even step value.

Wait: Set to 0 (ms). There’s no delay needed for the setup is not unstable and does not need time to stabilise.

Compliances: $I_{max}$ is normally limited by the size of the smalles contacts. Fill in the value found in specs [2].

Subs_bias: Set to the lowest potential that is used. The way the Gummel-Poon plot is measured here, follows [4]*. This implies that $V_{SUB}$ is equal to the lowest $V_E$ value (with $V_B = 0$ V, and $V_{BE}$ has 1 V as a maximum, $V_{SUB} = -1$ V).

VCE_constant: In [4] 0 V is used.

V_BC offset: Set to the value that is needed to keep the substrate current very low compared to the base current; avoid saturation (see: § II.4). For small transistors about 1 or 2 V (only for NPN types). An extra measurement should be done to see the amplitude of the $I_{SUB}$. This measurement should be done with the DC analyser alone; it’s not possible to measure $I_{SUB}$ with UTMOST.

---

*In [4] a Gummel-Poon plot is measured using the following biasing. FGP: $V_b=V_c=0$ V, $V_e=-0.5/-1$ V and $V_{SUB}=-1$ V. This biasing is done because with these voltages applied there are a lot of terms zero in the transistor’s current equations (see appendix 1). Sometimes though $V_c$ must be raised in order to keep the parasitic in a off position (for NPN types, see the chapter about parasitics in NPN types trasistors).
Here it should be set to 0, since the regular bipolar measurement structure is used. Set to 1 only when a Kelvin structure is used for RB measurement (four terminal measurement structure).

**FITVARS screen:**

**IB sim_start and IB sim_stop:** Take the range where the transistor will normally be used.

**Min deltaVBE:**

Take the range where the transistor will normally be used. This value is very important. A too low value gives computing errors, because the voltmeters will have difficulties to determine accurately the delta (the deviation between the straight line and the real IB line, see figure 4). A too big value gives an insufficiently number of deviation points. UTMOST will alert with a warning. So take a value that yield a rather smooth $R_{bb'}$ vs $I_B$ curve, no spikes, humps or other irregularities. Start with a low value (about 10 mV) and increase (for the Mietec devices 20 mV is good).

**Old=0, AMD=1:**

Set to 0; AMD is used only for multi-emitter devices where $V_{BE}$ can be swept until 1,5 V.

**1/BF fitstrt & 1/BF fitstop:**

Are only used for AMD.

**Model type:**

Set to 0 in order to get not only RBM and RB but also IRB.

**Number of measurements:** 2 (one for $I_C$ and one for $I_B$).

**Hardware measurement scheme:**

Figure 5* depicts the measurement scheme, this scheme is used for measuring the Gummel plots.

---

*The substrate is connected to the most negative voltage. This can be the collector or emitter depending on the type of transistor and the type of measurement (forward/reverse).*
Optimisation region, example of the simulated effect:
With help of two simulations, one without and one with RB, it can easily be seen that
the effect is on the high current regions of the Gummel plots (compare appendix 3 to
appendix 2). The regions where the differences can be seen should be used for (local)
optimisation.
For these parameters an optimization is really needed, for the used measurement
technique gives to little information to extract the parameters accurately (for
example: a change in the \(V_{BE}\) range will also result in different values for the
parameters).
II.3.2 Routine RC_sat (6)

Extracted parameters:
RC: collector resistance;
RE: emitter resistance.

Meaning of the parameters:
RC models the resistance between the transistor's active collector region and its collector terminal. RE models the resistance between the active emitter region and the emitter terminal.
Although the collector resistance may be depending on $V_C$ and $I_C$, there's only one parameter $R_C$ for the collector resistance and is therefore in the Gummel-Poon model considered to be a constant.

Extraction method:
RE:
When a transistor is in saturation, the next equation holds for $V_{CE}$ [5]:
$$V_{CE} = \frac{kT}{q} \ln \left( \frac{\beta_R + 1}{\beta_R} \right) + R_E I_B.$$  \hspace{1cm} (3)

The first term is the intrinsic voltage, the second term is the voltage drop across $R_E$.
For very low $I_B$, the $\beta_R$ value decreases (because of more recombination in the base) which increases the intrinsic voltage and therefore $V_{CE}$. This is called the flyback effect; the method to determine $R_E$ is therefore called the flyback method (fig. 6).
Sometimes the flyback effect is difficult to observe. Also are the high currents effects.
A general remark on this measurement method is that the resistance can be determined too high [2], but the resistance should be determined for those $I_B$ which represent frequently used values for the transistors. As value for the $I_B$ is chosen the value of the $I_C$ where $\beta_F$ starts to roll off (use the routine BFvsIC to determine this $I_C$).

\*The transistor is useful for $\beta$'s that are constant and high. Here, the extraction is done for those current values where $\beta_F$ is about it's maximum value for the highest current. At higher currents, the $\beta$ rolls off and modeling in this region is not interesting.
RC(\textsubscript{sat}): 
When a similar curve is measured as the one for RE, but now for a bigger constant collector current, the new curve will lie more to the right because of the voltage drop across RC (see figure 5, make a copy and move it to the right).

With help of these two curves RC can be calculated using (4) \cite{6}.

\[
V_{ce} = \frac{kT}{q} \ln \left[ \frac{1 + \frac{1}{I_s} \left( \frac{1 - \alpha_R}{1 - \frac{I_c}{R}} \right)}{\alpha_R \left( 1 - \frac{I_c}{B F I_s} \right)} \right] + I_E \cdot RE + I_C \cdot RC. \tag{4}
\]

This RC value is the saturated value. It is the value that is extracted from the upper part of the curve in figure 6, for the high $I_B$ (there's also a possibility to extract $RC\_normal$ from the part of the curve close to the flyback region \cite{5}, but this is not done in UTMOST).

To easily compute RC out of (4) it's needed to keep the following parameters constant for the two used $I_C$: $\alpha_R$, T, BF, RC, RE and $I_C/I_B$. When now $\Delta V (=V_{CE}(I_{C2}) - V_{CE}(I_{C1}))$ is computed, the first, difficult term in (4) cancels out. The routines BR and BF (see the ALL\_DC routine) should be done first in order to know the maximum value for $I_{C2}$.

UTMOST uses the simplified equation (5):

\[
RC = \frac{\Delta V_{CE}}{I_{C2} - I_{C1}}. \tag{5}
\]

which is valid when $I_B >> I_C$ (since RC is determined in the region for high $I_B$ currents this is OK) so a change in BF doesn't matter anymore. When also $\alpha_R$ is not very close to 0 the first term in (4) will be negligible. Then if RE is assumed a lot smaller than RC, the only term that's left in (4) is the last one, which yields equation (5).

If $\alpha_R$ is very close to 0, then (5) is still accurate when it's value is constant for the two used $I_C$, since the term will still cancel when substracting the two voltages at the two different $I_C$. So measure BR (see the ALL\_DC routine) to be sure of it's constant range; secondly, don't take the $I_{C2}$ value too high but significantly lower than the maximum $I_B$.

Note: For the PNP devices the extracted RC can be too big because of the parasitic that conducts (see § II.4.2). When the measurement is done and $I_C$ is set, a bigger $I_E$ will flow ($I_C + I_B + I_{SUB}$) and will result in a voltage drop across RE that will increase $V_{CE}$ ($I_{SUB}$ will cause an extra voltage drop).
**Measurement setup:**
To come into this setup screen see the RB routine. Instead of choosing the RB routine now choose the RC_sat routine.

**Integr. time:** Medium gives results as good as high integration time.

**IB_step & points:** I_B starts from 0 A, the end value which is points · I_B step, should be about IKF for NPN types (perform the BFvsIC routine to know I_C where β starts to roll off, this is close to IKF). For PNP types, where β_F is quite high, the maximum I_B may be several times bigger than IKF, since β_F is still high.

Use that many points so that the end value will be reached; use a step so that the resulting curves are smooth (no little spikes); a ten millivolt step will do.

**IC1:** as explained before: as low as possible. If there's noise in the measurements, increase this value (about 0.1 μA).

**IC2:** as high as possible, the maximum current where α_R is still the same as at I_C2, but significantly lower than I_B_max.

**Compl_e (A) and _s (A):** See RB routine.

**Compl_b (V):** Use 2 (V) (should be enough).

**Compl_c (V):** Use 2 (V) (should be enough).

**Wait:** Set to 0 (μs).

**Subs_bias:** Set to the lowest potential that is used (here 0 V).

**Number of measurements:** 2.

**Hardware measurement scheme:**
Figure 7 shows the measurement scheme to measure RE and RC_(sat). I_C1 and I_C2 are little currents, I_B is stepped.

Remark for the HP4145: pay attention to a connection between vm1 and the collector, in order to accurately measure the collector voltage. DO NOT FORGET to remove this cable after the measurement, for it can disturb the DC bias especially at low currents (leakage).

**Optimisation region, example of the simulated effect:**
To know the effects of an RC and RE on the behaviour of a BJT device, two simulations are done and can be found in appendix 3 (influence of RE) and appendix 4 (influence of RC).

RE influences the forward Gummel plot and limits I_E in the reverse Gummel plot. That's why the β_R decreases at high I_E.
RC influences, apart from some computational irrealities (see the comment) the starting slope in the IC/VCE measurements (linear region) and the deviation of the straight lines of $\ln(I_E)$ and $\ln(I_B)$ on the reverse Gummel plot.

For optimisation, the high current region of the forward Gummel plot should be used to optimise RE. The high current region of the reverse Gummel plot can be used to optimise RC and/or eventually the starting slope of the IC/VCE curve. The latter is normally used to optimise RC but when parasitic effects are seen in the forward characteristic (see § II.4.1), the optimisation of RC should not be used but instead the parasitic should be simulated also with the original transistor (a macro model).
II.3.3 Routine ALL_DC (24)

This routine performs in total four different measurements. First the forward Gummel plot (FGP). From this measured information the plot $\beta_F(I_C)$ is calculated. The second measurement is the IC/VCE curve for a constant $I_B$ (forward characteristic measurement) and the forward characterisation is performed with these measurements. For the reverse characterisation the reverse Gummel plot (RGP) is measured and IE/VEC is measured, for a constant $I_B$. From the RGP $\beta_R(I_E)$ is calculated.

These are measurements that can also be done by separate routines. It's more convenient to use several of these routines in order to determine the setup values for good measurements, rather than executing this ALL_DC routine over and over to come to a good setup, for every time a test measurement is performed all the four measurements are made.

That's why the routines gummel (14) and IC/VCE (1) are set up first, then also for the reverse mode rgummel (15) and IE/VEC (29). Finally the setup is given for the ALL_DC routine which will simply be a copy of the current- and voltage values used in the separate routines.

II.3.3.1 Routine gummel (14)

*Extracted parameters:*

- **IS:** transport saturation current (A);
- **NF:** forward current emission coefficient (ideality factor; no unit);
- **ISE:** B-E leakage saturation current (A);
- **NE:** B-E leakage emission coefficient (no unit);
- **BF:** ideal maximum forward beta (no unit);
- **IKF:** corner for forward beta high current gain roll-off (forward knee current; no unit).

*Meaning of the parameters:*

$I_B$ and $I_C$ are already given in appendix 1. In the equation for $I_B$ the term with $ISE$ and $NE$ is called the non-ideal base-emitter current and this term models the extra recombination in the depletion layer of the base-emitter junction (also some other secondary order effects [7]). $I_B$ will be dominated by this term for very low $V_{BE}$ where $I_B$ is low.

IS is the saturation current of the transistor; the generation current which flows as only current when a junction is reverse biased [8].

NF is the inverse of the slope of both currents in the mid current region (i.e. $V_{BE}$ between 0.5 and 0.8 V [4]). In the same mid current region, BF models the maximum
value of $I_C/I_B$.

The high current region is modeled by the resistances $R_E$ and $R_B$ (eventually also $R_{BM}$ and $R_{IRB}$) and $IKF$, where $IKF$ models the effect of the high current injection into the base. The excess carriers that result from the high injection have an effect on the collector current that has been calculated by Webster [9] who showed that at high current levels $I_C$ asymptotes to:

$$I_C(\text{high level}) \propto e^{\frac{qV_{BE}}{2kT}}. \quad (6)$$

**Extraction method:**

In the low current region parameters $ISE$ and $NE$ are extracted; $ISE$ as the intersection of the extrapolated low base current curve with the y-axis (where $V_{BE} = 0$ V) and $NE$ as the slope of this base current dependency on $V_{BE}$. See figure 8.

Appendix 6 shows the effects of these low current parameters by a simulation. On the FGP it's difficult to see the departure of the low $I_B$ of the straight line. But in the calculated $\beta_F(I_C)$ plot it's seen more easily: the $\beta_F$ rolls off at lower $I_B$. The determination of the two parameters is not very easy when only some slight departure of the straight line is observed and here a computer is needed to try out some couples of values of $ISE$ and $NE$ and come via iteration to values with the least squared difference (between a simulation and measurement).

**Note:** for all the Mietec transistors these low current effects are not seen and therefore the parameters not determined. First, this is due to the very low value that $ISE$ has (the used measuring equipment can only measure currents accurately which are bigger than 1 pA). Secondly, the interesting current ranges for the smallest transistors are determined by the design people of Mietec and start only at 100 pA, where the low current effects are not seen.

In the mid current region (i.e. $V_{BE}$ between 0.5 and 0.8 V [4]), saturation current model parameter $IS$ and the ideality factor $NF$ are extracted. The saturation current is found at the intercept of the linear regression fit of the low $I_C$ values and the y-axis. The ideality factor parameter models the deviation of the saturation current regression fit from $kT/q$. For use in a SPICE model, this parameter should be kept to 1. If this parameter has a value that is not close to 1, then the temperature modeling of
the Gummel-Poon model for a wide temperature range will be difficult to accomplish. So the value of NF should be set to 1 before the entire Gummel-Poon model simulation/optimization is performed. Increasing IS linearly increases the entire current versus voltage curve. An increase of NF results in a decreasing slope of the current versus voltage curve.

In fact, the extraction of NF is not correctly done in UTMOST. The effect of VAR on the collector current should be included this extraction since for the mid current region of the FGP the collector current is expressed as (see also appendix 1):

$$I_c = \frac{IS}{Q_b} \cdot \exp \left( \frac{V_{BE}}{NF \cdot V_t} \right).$$  \hspace{1cm} (7)$$

When the extraction is done several magnitudes below the high current injection point, IKF may be ignored and the base charge factor is reduced to:

$$Q_b = \frac{1}{1 - \frac{V_{BC}}{VAF} - \frac{V_{BE}}{VAR}}.$$  \hspace{1cm} (8)$$

Normally VAR is much smaller than VAF so only the effect of VAR should be taken into account when extracting NF. UTMOST does not correct for the value of VAR and therefore NF may differ from 1. Also, if the temperature is not accurately specified, there's an error in the value of the extracted NF (Vt in (7) is different). For the measurement laboratory in Mietec Oudenaarde, the ambient temperature is 25 °C.

In the mid current region BF also is extracted. BF is the maximum value of IC/IB, and can be easily found in the calculated BF (Ic) curve. Also, this value can be too low compared with the real value; there's the effect of the parasitics (always PNP types) that lead to a bigger IB and therefore a smaller BF (here for PNP transistors). See for a detailed explanation § II.4. As a result the corrected BF is bigger than the calculated maximum of IC/IB.

In the high current region this gummel routine only extracts IKF. The hitline of the mid current part of the collector current curve crosses the hitline of the high current part of the collector current and the current value of this crossing point is IKF. But these hitlines are determined for the collector current as a function of internal base emitter voltage (VBE'E')! So when the FGP is measured, a reduction of VBE to VBE'E' should be made. By UTMOST this parasitic voltage drop correction is done as follows:
1. The ideal base current $I_B$ plot is extrapolated as a straight line with a slope of $q/kT$ to the high current region.

2. The horizontal distance from the extrapolated ideal base current $I_B$ line to the measured base current $I_B$ curve is $\Delta = RB \cdot I_B + RE \cdot I_E$. This amount is to be subtracted from the corresponding $I_C$ data point, i.e., the $I_C$ data point is shifted to the left for $\Delta$.

3. Step 2 is repeated for all points until the full $\ln(I_C)$ versus $V_{BE}$ plot is obtained (see figure 9).

Sometimes a correction for $\Delta = RB \cdot I_B + RE \cdot I_E$ can give an overcorrected $I_C$ that lies to the left of the ideal $I_C$ curve over some range. This is typically caused by the recombination of the effects of the crowding phenomenon and lateral injection from the emitter sidewall. To handle this situation, the corrected $I_C$ curve is forced to always lie either on or to the right of the ideal line.

**Measurement setup:**

- **Integration time:** Again use medium integration time.
- **$V_{BE}$ range:** Extend this range as much as possible; take also care for the minimum current that can be measured with the measuring equipment. For the Mietec devices, only currents above 100 pA are of interest. Try to find the $V_{BE}$ value that leads to currents over 100 pA. The maximum $V_{BE}$ value is the same as used in the RB routine.

- **No. of points:** See RB routine.
- **Wait:** Set to 0 (μs).
- **Compliances:** See RB routine.
- **$V_{CE}$ start and $V_{CE}$ step:** Both 0 (V), are in [4] not used.
- **$V_{CB}$ start:** Take the same value as used in the RB routine.
- **$V_{CB}$ stop:** Set to 0 (V).
- **Number of measurements:** 2.
Hardware measurement scheme:
See figure 5.

Optimisation region, example of the simulated effects:
For the parameters ISE and NE a simulation example is done in appendix 6. When the $\beta_{F\text{vslC}}$ curve decreases for lower collector currents the parameters should be extracted and definitely optimised, since there's only little information on the departure of the straight line. The extracted values may therefore be wrong. Optimisation should be performed in the low current region of the FGP and the low current region of the $\beta_{F\text{vslC}}$ curve.
The parameter IS has an effect on the two current curves of the FGP. It lifts or puts the curves linearly with its value. Optimisation should be done on $I_C$ in the FGP.
Parameter NF should be set to 1. Optimisation is not used.
Parameter BF should be optimised, but the value can be approximated with help of the analysis in § II.4.2. It should be optimised with help of the $BF_{vsIC}$ curve in the mid current region.
Parameter IKF finally can be optimised also using the $BF_{vsIC}$ curve, where the $\beta$ starts to roll off and has its mid value at the forward knee current IKF. It's effect is also seen on $I_C$ in the FGP, where the effect of the resistances is the same. Therefore it can be hard to optimise IKF in the high collector current region of the FGP. See appendix 7.

II.3.3.2 Routine BFvsIC (9)
This routine is only used to obtain a curve of $\beta_F(I_C)$ where some information is needed to perform an $I_C(V_{CE})$ measurement. The most interesting part of the measured transistor is that region where $\beta_F$ is reasonably high. For NPN types this is valid until the forward knee current IKF is reached where $\beta_F$ already fell halfway its maximum value. So the value where $BF$ starts to roll off is an interesting value for the NPN types where an $I_C(V_{CE})$ measurement can be done. The extracted results are valid for this region where the transistor effectively is used.
For the PNP the $\beta_F$ is much higher than the value for the NPN types. These transistors can effectively be used for currents in the region where $\beta_F$ is already decreasing but still above a reasonable value. So, for the PNP transistor a "rule of thumb" is used and the $I_C(V_{CE})$ measurement will be performed for currents up to three times IKF.

There are no extra extracted parameters in this routine and it's setup is the same as the setup for the FGP. The value of $I_C$ that is found is used for the $I_C(V_{CE})$ measurement.
II.3.3.3 Routine VAF (7)

Extracted parameter:
VAF: Forward Early Voltage (units V);

Meaning of the parameter:
The Early voltage models the effect on the transistor characteristics of basewidth modulation due to variations in the collector base space charge layer. An increasing reverse bias increases the space charge layer of that junction [8]. The Early voltage is always a positive number.

Extraction method:
A simple method of obtaining VAF (though one prone to significant measurement error) is the extrapolation of the $I_C$ versus $V_{CE}$ characteristics when the transistor is in the common emitter configuration. As shown in figure 10*, the Early voltage is approximately the value of the voltage on the -$V_{CE}$ axis where the extrapolated output characteristics meet. This extrapolation can be performed graphically from either a plot of the characteristics or directly with UTMOST. UTMOST does take the smallest slope of these characteristics (the highest VAF value).

With these measurements a constant $I_B$ is used, the $I_B$ that flows at the chosen collector current from the $\beta_F(I_C)$ curve. See the BFvsIC routine.

Measurement setup:
Integ, Time: See RB routine.
$VC_{start}$: Set to 0 (V).
$VC_{stop}$: Set to 20 (V); this is normally the voltage range where the transistor in the integrated circuit is used (here HBIMOS is considered). When transistors of an other process are used this range can be different and therefore an other value of $VC_{stop}$ should be used.
$IB$ or $VBE$: Here the base current value calculated from the collector current found in the $\beta_F(I_C)$ curve is entered.

*In reality the intersection is not equal for all the extrapolated curves but differs. Though, when the extracted result for a collector current is obtained following this method, the simulation in the interesting currents region of the transistor will match the measured curves (here the slope of the characteristics will be the same).
VE: There's no constant emitter voltage used; 0 (V).
Points: Use a 100 mV step, since here the voltage range is big and there's a need to have reasonable differences between the collector current values between measurement points. A difference that is too small will result in a slope of zero and an erroneous VAF value.
Compliances: For the base terminal use 2 (V); for the other terminals see the RB routine.
Subs_bias: The lowest used voltage: 0 (V) for NPN, and -20 V for PNP-types.
IB=0 or VB=1: Use 0 for a current driven base.
Wait: Set to 0 (μs).
Number of measurements: 1.

Hardware measurement scheme:
See figure 11. The base is current driven and V_CE is swept from VC_start to VC_stop.

Optimisation region, example of the simulated effect:
When VAF is extracted in the way presented here, the simulated curves will have the same slope as the measured curves have. In this case there's no optimisation needed. An example of the simulated effect is given in appendix 8; there are quite a few influences. First, the slope of the output characteristics. It is difficult to see but the currents are increasing for higher collector emitter voltages. Then, β_F is somewhat bigger than the originally 100. This comes from the base charge factor which now is less than one (with V_CE=2 V and V_BE starting from 0.5 V, the resulting V_BC is -1.5 V that decreases the value of Q_B). I_C is increased which yields a bigger β_F. See the equations in appendix 1.
For higher V_BE the voltage V_CB decreases and the base charge approaches unity. Therefore, β_F decreases. Anyway, this decrease of both β's due to VAF can be neglected compared to the roll off due to high current effects (modeled bij IKF and IKR).
This effect is more severe for the reverse Early voltage (VAR) which value will be much smaller. In this case there's a similar but bigger effect on the β's.
II.3.3.4 Routine rgummel (15)

Extracted parameters:
NR: reverse current emission coefficient (reverse ideality factor; no unit);
ISC: B-C leakage saturation current (A);
NC: B-C leakage emission coefficient (no unit);
BR: ideal maximum reverse beta (no unit);
IKR: corner for reverse beta high current gain roll-off (reverse knee current; no unit).

Meaning of the parameters:
See also the explanation of the equivalent forward parameters, explained in the routine gummeI.
ISC and NC describe the non ideal base collector current and this term models the extra combination in the depletion layer of the base collector junction. $I_B$ will be dominated by this effect for very low $V_{BC}$ where $I_B$ is low.
NR is the reverse of the slope of both currents in the mid current region of RGP; model parameter BR is the maximum value of $IE/IB$.
In the region of high currents parameter IKR models the beta roll off due to the same effect as with the parameter IKF.

Extraction method:
The extraction methods are exactly the same as the methods used for the determination of the equivalent forward parameters. Only IS is not extracted here, since this same parameter is used for the forward and reverse characterisation.
This means that the same errors are made with the extraction of the different parameters.
First NC and ISC. These are again calculated by the computer but since the deviation effect again is very small, the calculation is very inaccurate. With the interesting current regions above 100 pA (for the smallest Mietec devices) there are no low current effects observed (best seen on the $BR(IE)$ curve).
The extraction of NR is done in the same way as NF, but again UTMOST does not take into account the parameter VAR. Also, the temperature has a big effect on the value of NR.
The value of BR is very hard to determine. For the NPN types that are not completely plugged there's a big influence of the parasitic NPN that makes the value of BR many times lower than without this effect. Even for the completely plugged transistor the BR value is likely to be bigger than extracted. For the PNP types, there's the effect of two parasitic PNP's that make the extracted $BF$ and $BR$ smaller respectively a lot smaller than the corrected ones.
Measurement setup:
Integ. Time: Use medium integration time.
VBe range: Extend the range as much as possible. The minimum IC for each
transistor is now the minimum IE.
No. of points: See RB routine.
Wait: Set to 0 (μs).
Compliances: See RB routine.
Subs_bias: Set to the lowest used value (this is the -I\text{B}_{\text{stop}}\text{ value}).
VEC\text{start}, VEC\text{step}, VEB\text{start} and VEB\text{step}: Set to 0 (V).
Number of measurements: 2.

Hardware measurement scheme:
See figure 5.

Optimisation region, example of the simulated effects:
The parameters that have to be optimised are the equivalent parameters in the
forward region: NC, ISC and BR. NC and ISC can be turned off (ISC=0, NC=1) when
the $\beta_R(I_E)$ curve is flat for low $I_E$. When IKR is optimised this can better be done on
the $\beta_R(I_E)$ curve, where the effect of the IKR is better to observe.
NR not needs to be optimised. The effects on the characteristics given by the
ALL_DC routine are the duality of the effects seen of the forward parameters.

II.3.3.5 Routine BR (10)
This routine is only used to obtain a curve of $\beta_R(I_E)$ where some information is
needed to perform an $I_E(V_{EC})$ measurement. The most interesting part of the measured
transistor is the region where it’s $\beta_R$ is reasonably high. Since $\beta_R$ cannot be measured
directly due to the effect of the parasitic PNP(‘s), it’s value should be corrected for
these parasitic effects. This cannot be done by UTMOST and manually performed
measurements should be done. With these measurements (explained in the sections
about the parasitic effects on both types of transistors), the real $\beta$’s can be
approximated and the currents where the $\beta$’s are starting to roll off can be
determined. Now the currents can be found at which the $I_E(V_{EC})$ characteristics
should be measured.
But only the fully plugged transistor is used in the reverse mode (as a diode), all the
others are not used in the reverse mode; there’s no special need to model these
transistors with very high accuracy for the reverse mode. Anyway, the $I_E(V_{EC})$
characteristics should be measured for those currents who are of interest and
manually performed measurements are needed.
The same currents as specified for the forward region are used (with a difference
between the NPN and PNP transistors).
As in the BFvsIC routine, there are no extra extracted parameters in this routine (BR) and it’s setup is the same as the setup for the FGP.

II.3.3.6 Routine VAR (8)

Extracted parameter:
VAR: Reverse Early Voltage (units V);

Meaning of the parameter:
The Early voltage models the effect on the transistor characteristics of basewidth modulation due to variations in the emitter base space charge layer. An increasing reverse bias increases the space charge layer of that junction. The Early voltage is always a positive number.

Extraction method:
See the extraction method presented in the VAF extraction. This time it is done on the $I_E(V_{EC})$ curve. The difference is that this value will be much smaller than the VAF value*; it’s effect is more severe on the characteristics.
With these measurements a constant $I_B$ is used, $I_B$ that flows at the chosen $I_C$ from the $\beta_R(I_E)$ curve. See the BR routine.

Measurement setup:
Integ, Time: See RB routine.
$VE_{start}$: Set to 0 (V).
$VE_{stop}$: The maximum voltage applied to the emitter though can just be a fraction of the maximum $V_C$ for the forward characteristic. This is due to the higher doping concentration of the emitter compared to the base. The depletion region extends further into the base and since the base is narrow, punch trough or avalanche breakdown [8] will occur already at low voltages (normally around 4-5 V). This is seen on the graph when the curve is increasing rapidly.
$IB$: Here the base current value calculated from the collector current found in the corrected $\beta_R(I_E)$ curve is filled in.
$VC$: There’s no constant $V_C$ used; 0 (V).

*With the emitter base junction in reverse bias, the extension of the space charge region will be more in the base. This is due to the more heavily doped emitter: a small increase of the emitter area in the depletion region calls for a large penetration of this region into the base. Only then charge neutrality is maintained. As a result the base width is more sensitive to $V_{bc}$ variation than it is to $V_{be}$ variation.
Points: Use a 100 mV step, since here the voltage range is big and there's a need to have reasonable differences between the $I_C$ values of different measurement points. A difference that is too small will result in a slope of zero and an erroneous VAR value.

Compliances: For the base terminal use 2 (V); for the other terminals see the RB routine.

Subs_bias: The lowest used voltage: 0 (V).

Wait: Set to 0 ($\mu$s).

Number of measurements: 1.

**Hardware measurement scheme:**
See figure 11. The base is current driven and $V_{EC}$ is swept from $VE_{start}$ to $VE_{stop}$.

**Optimisation region, example of the simulated effect:**
When VAR is extracted in the same way as VAF, the simulated curves will have the same slope as the measured curves have. In this case there's no optimisation needed. An example of the simulated effect is given in appendix 9; there are the same (but dual) influences as there are with VAF. First, the slope of the reverse characteristics. It is easy to see that the currents are increasing for higher emitter collector voltages. The effects on the $\beta$ curves are bigger but still, compared to the roll off due to the high injection effects (modeled bij IKF and IKR), these declinations are negligible.

Since now all the routines are explained, the setup of the ALL_DC routine can be filled in, with use of the regions determined with all the individual routines.

**Measurement setup:**

*Integ. Time:* Since all the sub routines use medium, here also medium satisfies.

*To model:* Set to ALL DC.

$V_{BE_{start\_GP}}$ and $V_{BE_{stop\_GP}}$: Use the start and stop values found in the FGP setup.

*Points:* Use about a 10 mV step for the FGP.

*Wait:* Set to 0 ($\mu$s).

*Compl_all(A):* See RB routine

*Compl_b(V):* Set to 2 (V).

*Subs_bias:* See RB routine. This bias will also be used for the reverse measurements and the $I_C(V_{CE})$ and $I_E(V_{EC})$ measurements, where it's not needed. Anyway, the differences are negligible.

*$V_{BE_{start}}$:* See rgummel routine (the name should be VBC_start).
BIPOLAR DC PARAMETER DETERMINATION WITH UTMOST

VCE_const_GP: See the RB routine. This bias is also used for the RGP. Again, differences in the currents in the RGP are negligible.

VCE_start: Set to 0 (V).

VCE_stop (F): Set to the value used in the VAF routine.

IB_start (F): Set to 0.8 times the value used in the VAF routine.

IB_step (F): Set to 0.1 times the value used in the VAF routine (with three measurements the final value will be the current used in the routine VAF).

IB_start (R): Set to 0.8 times the value used in the VAR routine.

IB_step (R): Set to 0.1 times the value used in the VAR routine.

VBE_start: Doesn't matter.

VBE_step: Doesn't matter.

IB=0 or VB=1: Set to 0.

VCE_stop (R): Set to the stop value used in the VAR routine.

Number of measurements: 3 (this number is only used for the I_C(V_CE) and I_E(V_CE) measurements. During the optimisation it's convenient to have several curves to increase the ease of comparing the simulated results with the optimised results.

Optimisation region, example of simulated results:

This routine will be used to optimise all the parameters extracted in the different routines that form the ALL_DC routine. Also the resistances can be optimised in this routine; local optimisation is used for this. This local optimisation on the Mietec transistors will be explained in the following chapter.
II.3.4 Routine IC/VCE (1)

This routine is used to measure IC as a function of low VCE (the transistor is mostly in saturation region). When the extraction of the parameters is done this measurement can be used to compare the simulated results with the measured results. This region is of interest when the transistors are used as drivers: they can be switched on and off and work in the saturation region. The fully plugged transistor HNHP350A is used for this purpose.

For the PNP types this routine is also used to improve the simulated results. The extracted RC for these types in the RC_sat routine gives values that are too high (see the RC routine) so the RC value is extracted by determining the starting slope of the $I_C(V_{CE})$ curves.

*Measurement setup:*

This setup can be copied from the ALL_DC routine, except for the $V_C$ values, which should be kept low (from 0 to approximately 2 V).
II.4 Influences of the parasitics in the original transistors

This section explains the effect of the parasitic PNP transistors that are present in both NPN and PNP transistors where there's a substrate terminal. In some bias states of the original transistor these parasitics conduct and therefore the terminal currents may be influenced. These influences do sometimes have a destructive effect on the parameter extraction of the original transistor but sometimes it's possible to correct for the parasitic currents. This cannot be done with UTMOST but can be done when manually performed measurements are made with the HP 4145 DC Analyser stand alone.

Almost all of the corrections here assume that the base of the original transistor delivers $I_{SUB}$. An assumption which holds when $\beta_F$ of this parasitic is big (which normally is in the range of 100-300 for not completely plugged transistors). This revealed for some measurements an $I_{SUB}$ as big as $I_B$ for the $I_C(V_{CE})$ measurements at low $V_{CE}$.

The corrections proposed for some parameters can be used for maximum and minimum guarding limits with the local optimisation.

First the effects of the parasitic PNP on the NPN transistors is treated, then the parasitic PNP's on the PNP transistors.

II.4.1 Influences of the parasitic PNP on NPN transistors

When the NPN transistors are measured in order to get the parameters that describe the model used for simulation purposes, especially two types of measurements are done: the Gummel-Poon measurement (forward and reverse) and the forward and reverse characteristic measurement ($I_C(V_{CE})$ and $I_E(V_{EC})$).

The way the Gummel plots are measured in this report is the way proposed bij [4]. This means for forward Gummel plots that the collector and emitter are not polarised (0 V), the emitter is swept from -0.5 V to -1 V (approximately; this is not for all transistors exact), the substrate at the most negative voltage, in this case -1 V. The range of $V_E$ depends on the measured magnitudes of the currents; with the actual measurement setup the lowest limit is 1 pA and the upper limit is set by the maximum allowed current through the device itself [2].
With this polarisation the parasitic PNP is not functioning. Figure 12 gives a cross sectional view of the not (completely) plugged NPN transistors fabricated in Mietec (HNH1A and HNHPI0A). Here the parasitic lies on the side where there's no plug, since the parasitic base is here less heavily doped and therefore better. The explanation of the parasitic effect and the corrections for a completely plugged transistor (HNHP350A) are explained later on in this chapter.

For the forward Gummel polarisation there's for low currents no $I_{\text{SUB}}$ measurable. The collector and base voltages are zero and the parasitic transistor is turned off. Only a leakage current will flow. When the currents become higher, a rapidly increasing $I_{\text{SUB}}$ can be measured and it is the base current that increases due to this. See figure 13 for an example.

This effect can be explained when $RC$ is seen as a distributed resistance in the collector region. Therefore, the base of the parasitic lies somewhere in the total collector resistance (see figure 14). For high $I_C$ the voltage at the base $b'$ will become lower than zero and then this parasitic will start to conduct. This can be solved by applying a positive voltage to the collector. In this case higher currents are needed to pull the voltage at the parasitic
base below zero and to let the parasitic conduct. For the reverse Gummel plot the polarisation is different. In this case zero volt is applied to the base and the emitter and -0.5 V/-1 V is applied to the collector. Again, the substrate is polarised at the lowest voltage, -1 V. Now (see also figure 12) the base delivers the current for the reverse transistor action (the current from the emitter to the collector) but also it delivers the main current for the parasitic transistor! The base delivers $I_e$ for the parasitic PNP which will be, if $\beta_F$ of the parasitic is high enough, almost totally $I_{SUB}$ (see figure 15).

Normally, the parasitic, which is of type PNP, has a $\beta_F$ that is very high and so it's $I_B$ will be negligible. This means that $I_B$ used for the reverse transistor action is:

$$I_{BCOR} = I_B - |I_{SUB}| \quad \text{(if $\beta_{FPNP} \gg 1$).} \quad (9)$$

Now $I_{BCOR}$ is corrected and from this Gummel plot the $\beta_{RCOR}$ of the normal NPN can be calculated ($\beta_{RCOR} = I_E/I_{BCOR}$). BR is then the maximum value of $\beta_{RCOR}$.

For the application of (9) it is recommended to measure the PNP separate from the actual NPN to assure that ($\beta_{FPNP} \gg 1$). See for an example figure 16, where the parasitic PNP is measured just by not using the emitter terminal of the NPN. The amplification factor is for low and medium current levels higher than ten.

For the forward characteristic measurement $I_C$ is measured as function of $V_{CE}$, at a constant $I_B$. This is not true for the range where $V_{CE}$ is low. Here, the NPN is in saturation mode in which the collector voltage is lower than the base voltage and therefore the parasitic PNP is conducting. This

---

*This parasitic will start to conduct earlier than a normal transistor. The built-in potential is lower due to the lower doping concentrations of the collector and base and therefore the saturation current is bigger ($V_0 = kT/q \cdot \ln (N_aN_d/n_i^2)$ [8]).
ends where $V_{CE}$ increases and becomes bigger than $V_B$. For normal measurements VAF is extracted for higher $V_{CE}$ so there's no influence of the PNP transistor. VAF can be extracted and no correction is needed.

In the part of the curve where $I_C$ increases the collector resistance $RC$ can be extracted. It's just the part where $V_{CE}$ is low and $I_{SUB}$ is delivered by $I_B$. So, $I_C$ should be corrected for the lost to the substrate; the resulting $I_C$ comes from $I_{BCOR}(9)$. The corrected $I_C$ ($I_{CCOR}$) which would come from $I_B$ is then $I_B/I_{BCOR}$ times bigger than $I_C$ that is measured (see (10)).

$$I_{CCOR} = I_C \cdot \frac{I_B}{I_B + I_{SUB}},$$ (10)

where $I_{SUB} < 0$ for the current flows out of the device. From $I_{CCOR}$ the slope can be determined and the value of $RC$ can be extracted as the inverse of the slope value (figure 17).

For the reverse characteristic the parasitic PNP again is polarised in forward mode ($V_E$ from 0 to 20 V, and a defined $I_B$), $V_B$ to maintain $I_B$ is bigger than $V_C$ and therefore the PNP conducts. Though, a part of $I_B$ is used for the reverse transistor action and this part can be calculated again with (9), where now the constraint for $\beta_{FPNP}$ doesn't matter.

As long as $V_{BC}$ stays the same there's no change in the part of $I_B$ that flows to the substrate so the part that is used for the reverse transistor action also stays the same. VAF should be extracted where $I_{BCOR}$ is constant and punchthrough is still not actual.

The effect of the parasitic PNP is less severe for the completely plugged transistors, because the collector serves as the base of the parasitic PNP transistor and since the collector is heavily doped (the plug), there's a lot of recombination in the collector and therefore the $\beta_F$ of the parasitic is very low. See figure 19 for a completely
plugged transistor. The plug surrounds the base.
For the forward Gummel plot there's only an ISUB when the currents are high and RC is high (see earlier explanation). In this case the completely plugged transistor is a power transistor (HNHP350A) and due to his completely plug RC will be rather low. Therefore VC need not to be increased. Eventually, ISUB can be controlled by an extra measurement.

For the reverse Gummel plot again ISUB is low, but since the polarisation of the parasitic is in such a way that it is in forward mode, a correction is desirable. With help of figure 20 the correction can be calculated.

When BF of the parasitic is very low, which can be controlled by an extra measurement of the parasitic alone and the emitter of the NPN not connected, then

\[ I_{BCOR} = I_B - |I_{SUB} - |I_{BPNP}| \]  \hspace{1cm} (11a)

and with

\[ I_{BPNP} = \frac{I_{SUB}}{\beta_{FPNP}} \]  \hspace{1cm} (11b)

we have:

\[ I_{BCOR} = I_B - \left(1 + \frac{1}{\beta_{FPNP}}\right)|I_{SUB}|. \]  \hspace{1cm} (12)
When $\beta_F$ of the parasitic is very low, $I_{BCOR}$ will be quite smaller than the measured (external) $I_B$ which means that $\beta_R$ of the NPN is bigger than calculated from $I_E/I_B$.

Finally see figure 21 for a result of a measurement of $\beta_{FPNP}$.

Since the HNHP350A transistor has only a parasitic with a very small $\beta_F$, these equations to correct will not be applied but instead the effect of the parasitic will be neglected.

**II.4.2 Influences of the parasitic PNP’s on PNP transistors**

There are two bipolar PNP transistors available for test measurements in Mietec. The HPH1A and the HPL1A. The only difference is the $B_{VCES}$ of the types. The L type has a lower value for $B_{VCES}$ than the H type.

There are only four measurements done on each transistor to extract the DC parameter set and the effect of the parasitic PNP’s on the measured currents is analysed for these four measurements. The measurements are the Gummel-Poon measurements and the forward and reverse characteristic measurement.
Since the PNP by Mietec is a lateral type, there are two parasitic PNP's. See figure 22. One of the PNP's is located at B-C-S (number 2 in the figure) and the other (number 1 in the figure) at B-E-S.

As one could already see from the figure is that the three PNP's will have different β's. Transistor number 1 will be the worst one, since it has the largest base. Next comes parasitic 2, with a more narrow base and the best should be the PNP where it is all about, the original transistor (not numbered in the figure).

When measuring the forward Gummel plot the following biasing is applied:

\[ V_E = 0.4/1.0 \, \text{V}; \, V_{\text{SUB}} = 0 \, \text{V}; \, V_C = V_B = 0 \, \text{V}. \]

The emitter voltage has a range where the currents that are measured lies between 100 pA and 1 mA.

With this polarisation there's only parasitic 1 who conducts (see also figure 23). There's also a base current in the totally measured base current that comes from this parasitic. The corrected I_B is:

\[ I_{\text{BCOR}} = I_B - \frac{I_{\text{SUB}}}{\beta_{F1}}, \quad (13) \]

where the correction is small when \( \beta_{F1} \) is big. Measurements on β's of the parasitic are done with the other terminal disconnected: for parasitic 1 the collector is disconnected, for parasitic 2 the emitter is disconnected.

Now \( I_{\text{BCOR}} \) is somewhat smaller than the measured \( I_B \) and therefore \( \beta_F \) of the PNP is bigger.

When the reverse Gummel plot is measured the same voltages are applied only the emitter and collector terminals are changed. Now parasitic 2 is conducting and with it's smaller base this parasitic is better and has a higher β. This parasitic conducts very well and \( I_{\text{SUB}} \) will be quite high. The effect on the base current is this current divided by it's forward β (see (13). Use \( \beta_{F2} \) instead of \( \beta_{F1} \)).

The correction term in (13) will be relatively bigger and therefore it's influence on \( \beta_R \).

The real \( \beta_R \) of the PNP will be bigger than the calculated one from the emitter and base current measurements.
When measuring $I_C(V_{CE})$ the polarisation is as follows:
$V_C = 0/-5V; V_E = 0 V; I = I_0; V_{SUB} = -2 V$.

The polarisation needs to be explained. The substrate normally carries the most negative voltage of the circuit, to keep the p-n junction between the base and substrate in a off-position. But here the base is fed with a base current and herefor a voltage is needed in the normal bias range for a diode (around 0.8 V). The substrate-base junction is already in a off position when the substrate carries a voltage of -2 V. When -20 V is applied to the substrate the depletion width of the base decreases and the $B$ of the parasitics will increase (early effect), so that the parasitics will even have more effect and there's more to correct. This makes correction harder.

The voltages applied doing the $I_C/V_{CE}$ measurement make parasitic 1 function (see figure 24) and parasitic 2 function only when $V_{CB}$ is sufficiently positive. When $V_{CB}$ is very negative parasitic 2 can conduct the reverse way. Therefore $I_{SUB}$ comes from the two parasitics and the part from each transistor is not known. A correction for the currents in this region cannot be made and RC cannot be extracted. For higher voltages the effect of the parasitics will becomes less compared with the real PNP. $V_{AR}$ can be extracted as the intersection point with the $V_{CE}$ axis.

$I_E(V_{EC})$ is also measured for the PNP transistor and the same biasing is valid only the collector and emitter terminals are changed. Now parasitic 2 functions constantly and with it's higher $B$ this will result in a bigger $I_{SUB}$. $V_{AR}$ can be extracted though, since the polarisation of parasitic 2 will stay the same and there's an $I_{SUB}$ that has a constant value (see figure 25). That's why parasitic 2 only takes a constant part of the total base current as his base current. The PNP has the rest of the base current which is constant. Now $V_{AR}$ can be extracted in the normal way.
III The extraction and optimisation with UTMOST

This chapter will explain how the extractions are performed on previously made log files. These log files were created for each transistor and contain the information of the routines described in the previous chapter.

In the first section globally the way how the extractions and optimisations are done is explained, so that a bit insight is gained about the way UTMOST works and how it should be set up for optimising purposes. Then a short section explains what should be changed on the setup file that first is used to measure the data. This changed setup should be, together with the added local optimisation for some parameters, saved under another name.

Then, as a sort of example, the way of how the extraction and optimisation is done is explained more in detail for each transistor.

With all this the reader should be able to use UTMOST and setup a new setup file to extract and optimise for a new (HBIMOS) bipolar transistor.

III.1 UTMOST’s way of extracting and optimising

When the measurements are performed and all data is written in a log file, then extraction and optimisation can be done on the measurement data. The extraction is done with built-in fitting algorithms and explained in the routines setup subchapters.

The setup file that is made after the routines were set up, is now used to recall the measurement data and perform a regular fit. For this, the setup file should slightly be changed.

Then the routines RB, RC_sat and ALL_DC are recalled in this order. The three parameters extracted in the RB routine have to be optimised and when the data of the other routines is displayed, a fit should be done (the IC/VCE routine is done without fit, to see how the output characteristics at low V_{CE} are simulated).

Now the parameters are extracted (except for the base resistance parameters which are optimised) and a simulation is done with all the parameters in the ALL_DC routine. This gives a screen with the measured curves and the simulated curves together in the same graphs. Differences can easily be seen and with help of the "optimisation region, example of the simulated effects" sections of the previous chapter the right parameters can be optimised to improve the simulations.
Local optimisation* is used to optimise some of the total set of parameters; a certain region of a certain curve is used to optimise specific parameters. When a plot is available of the ALL_DC routine with the measured and simulated data then this plot is used to determine the regions where some parameters have to be (locally) optimised. For this, UTMOST works with special strategies.

Each strategy contains a maximum set of steps and in each step some parameters to optimise can be chosen. For the strategy a routine (which means a special measurement) must be chosen so that UTMOST knows on what curve to optimise. Here the ALL_DC routine cannot be chosen, only routines that perform one specific measurement (of the ALL_DC routine only the routines gummei (14) and BFvsIC (9)**).

Rest now to fill in the optimisation part of the curve where the parameters of each step have to be optimised. It's also possible to optimise for several curves at once when several measurements are done in one routine (for example the gummei routine, optimising on both IC and IB).

The way UTMOST is optimising is as follows. One can choose the way how to optimise and the evaluation way used here to minimise the error is to minimise \[ \frac{(\text{sim} - \text{meas})}{\text{abs(\text{meas})}} \]. This means a certain way to optimise the parameters. When the simulated curve lies too low compared to the measured curve for one part of the curve and it lies too high for the other part of the curve, take care of the optimising region. When as optimising region the whole curve is taken, do not expect the optimiser to work; here it concludes that the differences cancel since on one part there is a surplus and the other part a deficit. So use only that part of the curve where the error is mostly in one way (positive or negative) and take care to use the right region of the curve.

This way of optimising is used in each step of one strategy. The order of several strategies can be chosen for some routines in UTMOST (ALL_DC, IC/VCE and IE/VEC). For each routine a sequence of strategies can be chosen which will be

* Push "System" and set "Local Optimisation" to "ENABLED". Now local optimisation is performed whenever the fit button is pressed in the "Graphics" screen. The sequence of strategies set in "Routine Ctrl", "Local Opt. Seq." will be performed.

** Since the IC/VCE routine is especially used to measure additional forward characteristic information, the data for this file will not be got from the ALL_DC routine but will be the data of the separately performed IC/VCE measurement.
performed for this routine; then for each measurement there's a strategy which contains several steps; each step refers to a certain region of the measurement where some specified parameters will be optimised. Optimising is done by minimising 
\[
\frac{\text{abs}(\text{meas})}{\text{abs}(\text{meas})}
\]

This short introduction has told globally how UTMOST can be used to obtain a set of parameters that can well simulate the transistor's behaviour. In the next chapters the extraction and optimisation will be explained more in detail for each transistor.

The problem with optimising is that sometimes the physical meaning of a parameter can be lost. This is because the parameter is used to improve the simulation results with the measured results. To keep the value of the parameter close to the extracted value, guarding limits can be used and the parameter value can not go beyond these values. Because UTMOST does not take into account the effects of other parameters when extracting a parameter, and secondly UTMOST does not recognise the effect of parasitics in the transistor, there's an error in the determination of some parameters. In the theory sections of the previous chapter there's explained what some parameter values will be like and this can help with setting the guarding limits. Anyway, since there are not a lot of parameters that have to be optimised the guarding limits are not needed.

The number of parameters that have to be optimised is also explained in each transistor section.

### III.2 Preparing the setup files for extraction

The setup files created in the previous chapter, with all the routines setup to measure the transistors, are now slightly changed so that they are ready to use for extraction and later on for optimisation. At the end this changed setup file should be saved with a different name; so finally there's one setup file for measuring and the other for extracting and optimising.

**Preparing the parameters:**

From the start there are two parameters that are fixed: NF=1 and NR=1. These parameters should be set to NOFIT in the “Parameters”, “Attributes” screen. For the two not completely plugged NPN devices (HNH1A and HNHP10A) the reverse is severely influenced by the parasitic PNP and for these transistors BR and IKR are extracted manually. The obtained values should be filled in the “Parameters” screen.
(in the optimised column) and their attributes set to NOFIT.

For all transistors the low current parameters for the reverse, ISC and NC, are not used since they have an influence on the output characteristics at low $V_{CE}$ (see appendix 1, the equation for $I_C$) and not needed for the small transistors (no real interest in the reverse). Only for the biggest NPN the reverse in of interest but here there are no small current effects observed. So ISC=0 and NC=1 and both have the NOFIT attribute.

For the eighteen DC parameters holds that they all are used for spice simulation. So the SPICE flag should be set in the “Attributes” screen for the following parameters:

$\text{ISE, NE, IS, BF, NF, IKF, VAF, ISC, NC, BR, NR, IKR, VAR, RB, RBM, IRB, RE and RC.}$

Setting the routines:

The routines that are used should get their parameters for simulation purposes from the optimised column of the parameters screen. This is set for each routine by selecting this routine in the “Setup and Results Screen” and next press “Strategy”.

Set the button “Model” behind the marked transistor to “Opt.” Do this for each routine (RB, RC_sat, ALL_DC and IC/VCE).

For the RB routine the parameters RB, RBM and IRB should be tagged in the parameters screen (under “Opt.”). This means that, when the routine is used and a (global) optimisation is performed, these parameters will be optimised so that they will fit with the measured result. Leave the guarding limits far away from the extracted results that come from the measurement.
III.3 Extracting and optimising the parameters of the HNH1A

This section explains more in detail how UTMOST is set up to extract and optimise the parameters for the HNH1A. First the changes to the measurement setup file, explained in the previous section, have to be made. When this is done, the following sequence of routines is used and also actions per routine are noted.

<table>
<thead>
<tr>
<th>routine</th>
<th>actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>Optimise the parameters RB, RBM and IRB.</td>
</tr>
<tr>
<td>RC_sat</td>
<td>Perform a fit (automatically done).</td>
</tr>
<tr>
<td>ALL_DC</td>
<td>Perform a fit, then a simulation. Make a hard copy of this.</td>
</tr>
<tr>
<td>IC/VCE</td>
<td>Perform a simulation. Make a hard copy of this.</td>
</tr>
</tbody>
</table>

When this sequence is done, the parameters that are in the optimised column of the parameters screen are used for the simulation.

The latter routine is performed to know a bit more about the simulation at the low $V_{CE}$ region of the output characteristics. This hard copy is not used to improve the simulation results by optimising. Instead, a marco model in which the parasitic is added to the model should give simulation results that resemble.

The differences between simulation and measurement and the related parameters:
In appendix 10 a hard copy of the simulation result is found that will be used to define the parameters to optimise and also the regions of the special measurements where they have to be optimised. The following conclusions can be made.

- $I_C$ of the FGP is well modelled so there's no need to optimise $I_S$. Also, the slope is correct so with $NF=1$ there's no problem.
- $I_B$ is not well modelled and this is due to the bad extraction of $ISE$ and $NE$, due to the small amount of deviation information. The $BF(I_C)$ curve is used to decide whether to use $ISE$ and $NE$ or not; when an significant increase of $BF$ is noticed for increasing low $I_C$ then low current effects are present and in order to model this the parameters should be used. Here only a slight increase is mentioned, but for other HNH1A's on other lots, bigger decreases are seen. Therefore is decided to keep the $ISE$ and $NE$ values and optimise them.
At high currents in the FGP the simulated curves are smaller in values than the real measured curves. For \( I_B \) parameters \( R_B, R_BM, I_RB \) and \( R_E \) determine the deviation from the straight line (the extrapolated line from the mid-current region of \( I_B \)). For \( I_C \) also \( IKF \) determines it's deviation. Here the parameters \( R_B, I_RB \) and \( R_BM \) are chosen to be optimised, since their determination has not been very accurately (see the explanation in the previous chapter on the RB routine).

The value \( IKF \) is about 700 \( \mu A \) (found in the parameters screen) which is too low when the \( \beta_F(I_C) \) curve is inspected. \( \beta_F \) is decreasing but is at 1 mA still not at it’s half maximum value. Therefore a manually performed extrapolation is needed to estimate the \( IKF \) value (the current where \( \beta \) is fallen halfway it’s maximum value).

Since the low current parameters \( ISE \) and \( NE \) are used, these will have a decreasing effect for \( \beta_F \) at low \( I_C \). Therefore the maximum \( \beta_F \) found in the \( \beta_F(I_C) \) curve can be smaller than the real maximum \( \beta_F \). So when the \( ISE \) and \( NE \) parameters are used, \( \beta_F \) will probably be needed to increase to improve the simulated results (i.e. more close to the measured results).

On the reverse there's a lot of difference, due mostly to the effect of the parasitic PNP transistor. Since this effect is not included in the Gummel-Poon model the reverse will be impossible to model. Because this transistor is not completely plugged, the parasitic has a severe effect in the reverse bias. That's why with this transistor the reverse is not optimised.

In appendix 11 the hard copy of the \( I_C(V_{CE}) \) curve at low \( V_{CE} \) is found. There's a big difference. The effect that the slope of \( I_C \) starts from zero is because the parasitic PNP is conducting. This effect can be modeled by an additional parasitic in the model.

*Inclusion of the parasitic pnp in the transistor model:*

This parasitic pnp has an effect on the output characteristics at low \( V_{CE} \) and has a more severe effect on the reverse characteristics. Since the main interest is to model correctly the output characteristics (for this small NPN transistor), only the simulated results for the forward measurements are compared when this parasitic is added.
The parasitic is (manually) measured with the emitter terminal of the original transistor left floating. Only three parameters were measured: IS, BF and IKF. These three form the model of this parasitic transistor.

For simulation this transistor is added to the original transistor, outside even all resistances. Simulation results revealed that the simulations for the output characteristics correspond with the measured curves at this region. See figure 26 for the model where the original and parasitic transistor are put together: a macro model.

Creation of optimisation strategies and determination of the regions to optimise the related parameters:
With the comments of the previous section just a few strategies are needed: only for the FGP and BF(Ic) measurement. The following table gives the used strategies for the HNH1A transistor. Also, the parameters and the used optimisation regions per routine (here: measurement) are given.

<table>
<thead>
<tr>
<th>Strategy #5</th>
<th>BF STRATEGY</th>
<th>Routine #9 BFvsIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>BF STRATEGY</td>
<td>Routine #9 BFvsIC</td>
</tr>
<tr>
<td>ISE, NE</td>
<td>1E-9</td>
<td>1</td>
</tr>
<tr>
<td>BF</td>
<td>1E-5</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 7: The optimisation strategy on FGP for the HNH1A.

<table>
<thead>
<tr>
<th>Strategy #1</th>
<th>GUMMEL: IC=1, IB=2</th>
<th>Routine #14 gummel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>VBE_start</td>
<td>VBC_stop</td>
</tr>
<tr>
<td>ISE, NE</td>
<td>0.5</td>
<td>0.65</td>
</tr>
<tr>
<td>RB, RBM, IRB</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>RB, RBM, IRB</td>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

With help of the optimisation examples in the previous chapter the regions where to optimise the specific parameters are known. These regions are now used to optimise some parameters:

ISE and NE are optimised in the low current part of IB in the FGP; also they are optimised on the low IC part of the BF(IC) curve. In the latter the effect of NE and ISE is better seen.

BF is optimised in the medium current range of BF(IC). Here the optimisation changes (increases) the BF value until a good resemblance exists between the simulated and measured curves. IKF is manually determined and does not need to be optimised. It cannot be optimised, since UTMOST has not enough data around the BF/2 point (here, there's no data available where BF=60).

RB, RBM and IRB are used to optimise the high current regions of both currents in the FGP.

Results of the optimisation on the simulated curves:

When the ALL_DC routine is displayed on the screen the local optimisation can be performed. To make a local optimisation possible the “Local Opt.” option should be set to ENABLE. Then via “Routine Cntl”, “Local Opt. Seq.” set the strategy numbers in the desired sequence. Here: 1, 5, 1, 5.

Finally, the setup file is saved under the name “bipolar.HNH1A.lo”. See table 8 how it works (IKF, BR and IKR are manually determined parameters).
The parasitic transistor has to be measured (manually) to obtain the three important parameters: IS, BF and IKF. With a simulation program (again ELDO) an input deck can be made with the macro model. The simulation should be done for the output characteristics at low $V_{CE}$.

See finally appendices 12 for the simulation results after running this setup file on the measured data of an HNH1A log file, and see appendix 13 for the output characteristics simulation after including the parasitic into the model.

For the forward region there's a little difference when $\beta_F(I_C)$ is considered (for higher currents). The decay is so fast that it cannot be modeled by the used Gummel-Poon model. This model assumes a constant collector resistance $RC$ and this is not true for higher $I_C$[10].
III.4 Extracting and optimising the parameters of the HNHP10A

This section has the same setup as the previous section. Here the detailed explanation is found on the extraction of the parameters and the optimising of certain of them.

First a simulation example of the fitted parameters is needed, in order to decide which parameters to optimise. The same sequence of measurements is used as for the HNH1A (see table 5) and again two hard copies are made: one for the ALL_DC routine and one for the IC/VCE routine (with measured and simulated curves).

The differences between simulation and measurement and the related parameters: See appendix 14 and 15 for the measured and simulations results with the extracted parameters only (and some of them fixed).
For the forward measurements there's a lot of resemblance but still an optimisation can be done to improve the high currents region and the $\beta_F(I_C)$ curve. BF should increase to have more resemblance for low currents.
Also, the RB, RBM and IRB parameters should be optimised since their determination is depending on too many measurement variables (see explanation on the RB routine). The simulated curves in the FGP lie under the measured curves.

As with the HNH1A, the $I_C(V_{CE})$ plot will be used only to see if improvement is achieved when the parasitic is added to the model.

Inclusion of the parasitic PNP in the transistor model: Since there's a lot of difference between the simulated and measured results on the output characteristics at low VCE, the parasitic should also be modelled. This is done the same way as it is done for the HNH1A. Only three parameters are needed to know: IS, BF and IKF.

Creation of optimisation strategies: Also for this transistor only two optimisation strategies are needed, the same strategies as used for the HNH1A. See the tables for the strategies and the optimisation regions.
Table 9: The optimisation strategy on $\beta_F(I_C)$ for the HNHPI0A.

<table>
<thead>
<tr>
<th>Strategy #5</th>
<th>BF STRATEGY</th>
<th>Routine #9</th>
<th>BFvsIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>IC_start</td>
<td>IC_stop</td>
<td>Sweep # start</td>
</tr>
<tr>
<td>BF</td>
<td>1E-8</td>
<td>1E-3</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 10: The optimisation strategy on FGP for the HNHPI0A.

<table>
<thead>
<tr>
<th>Strategy #1</th>
<th>GUMMEL: IC=1, IB=2</th>
<th>Routine #14</th>
<th>gummel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>VBE_start</td>
<td>VBC_stop</td>
<td>Sweep # start</td>
</tr>
<tr>
<td>RB, RBM, IRB</td>
<td>0.7</td>
<td>1.0</td>
<td>2</td>
</tr>
</tbody>
</table>

The BF parameter is now optimised in a larger current range, since the measurement results show that the maximum $\beta_F$ lies at the smallest $I_C$.

Results of the optimisation on the simulated curves:
For the ALL_DC routine use the same local optimisation sequence as used for the HNH1A.
Table 11 shows how the setup file for the HNHPI0A ("bipolar.HNHPI0A.lo") works.

Table 11: Sequence, extraction- and optimisation methodology of the HNHPI0A setup file.

<table>
<thead>
<tr>
<th>Routine sequence</th>
<th>Action</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. --</td>
<td>Fixed parameters</td>
<td>NF, NR, BR, IKR, ISE, NE, ISC, NC</td>
</tr>
<tr>
<td>1. RB</td>
<td>Global Opt.</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td>2. RC_sat</td>
<td>Fit</td>
<td>RC, RE</td>
</tr>
<tr>
<td>3. ALL_DC</td>
<td>Fit</td>
<td>IS, VAF, VAR, IKF</td>
</tr>
<tr>
<td></td>
<td>Fit + Local Opt.</td>
<td>BF</td>
</tr>
<tr>
<td></td>
<td>Local Opt.</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>All</td>
</tr>
<tr>
<td>4. IC/VCE</td>
<td>Simulation</td>
<td>All</td>
</tr>
</tbody>
</table>
See finally appendix 16 for the simulation results after running this setup file on the measured data of an HNHP10A log file.

When the parasitic transistor is measured (manually) and the three important parameters - IS, BF and IKF - are obtained, the simulations for the forward $I_C(V_{CE})$ can be done. See appendix 17 for the results of one transistor.

For the forward region there's a little difference when $\beta_F(I_C)$ is considered (for higher currents). The decay is so fast that it cannot be modeled by the used Gummel-Poon model. This model assumes a constant collector resistance $R_C$ and this is not true for higher $I_C[10]$. 
III.5 Extracting and optimising the parameters of the HNHP350A

After the changes made to the setup file as proposed in the second section of this chapter, this section explains the extraction and optimisation setup for the fully plugged HNHP350A.

First, the sequence of routines as shown in table 5 has to be performed. Then, with help of the ALL_DC plot, the following can be concluded (appendix 18 and 19):

- For the forward measurements there's a lot of resemblance but still an optimisation can be done to improve the high currents region and the $\beta_F(I_C)$ curve. BF should increase to have more resemblance for low currents.
- Also, the RB, RBM and IRB parameters should be optimised since their determination is depending on too many measurement variables (see explanation on the RB routine). The simulated curves in the FGP lie under the measured curves.

When appendix 19 is considered there's no clear influence of the parasitic. This is because this transistor is completely plugged, which kills the parasitic. There's no need to include a parasitic into the model.

Also the slope is changing slowly. This is because the collector resistance is not a constant but changes at high currents [10].

Creation of optimisation strategies:
Also for this transistor only two optimisation strategies are needed, the same strategies as used for the HNH1A. See the tables for the strategies and the optimisation regions.

<table>
<thead>
<tr>
<th>Table 12: The optimisation strategy on $\beta_F(I_C)$ for the HNHP350A.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy #5</strong></td>
</tr>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>$\beta F$</td>
</tr>
<tr>
<td>$IKF$</td>
</tr>
</tbody>
</table>
Table 13: The optimisation strategy on FGP for the HNHP350A.

<table>
<thead>
<tr>
<th>Strategy #1</th>
<th>GUMMEL: IC=1, IB=2</th>
<th>Routine #14 gummel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>VBE_start</td>
<td>VBC_stop</td>
</tr>
<tr>
<td>RB, RBM, IRB</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>RB, RBM, IRB</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The parameter IKF needed to be optimised at the high current part of the $\beta_F(I_C)$ curve. From the fit it was clear that here the simulation yielded values for IKF that were too small. By optimising this parameter in this region where the error is to one side, the IKF value is expected to increase and will go beyond the maximal measurable current (with the HP analyser 100mA). There's apparently enough information near the BF2 point to determine the IKF value.

The RB, RBM and IRB parameters are optimised on both $I_B$ and $I_C$. When optimising only on $I_B$ (or only on $I_C$), the other current wouldn't resemble so much with the measured one.

Results of the optimisation on the simulated curves:
For the ALL_DC routine use the same local optimisation sequence as used for the HNH1A.
The table shows how the setup file for the HNHP350A ("bipolar.HNHP350A.lo") works.
Table 14: Sequence, extraction- and optimisation methodology of the HNHP10A setup file.

<table>
<thead>
<tr>
<th>Routine sequence</th>
<th>Action</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. --</td>
<td>Fixed parameters</td>
<td>NF, NR, ISE, NE, ISC, NC</td>
</tr>
<tr>
<td>1. RB</td>
<td>Global Opt.</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td>2. RC_sat</td>
<td>Fit</td>
<td>RC, RE</td>
</tr>
<tr>
<td>3. ALL_DC</td>
<td>Fit</td>
<td>IS, VAF, VAR, IKF, IKR, BR</td>
</tr>
<tr>
<td></td>
<td>Fit + Local Opt.</td>
<td>BF</td>
</tr>
<tr>
<td></td>
<td>Local Opt.</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>All</td>
</tr>
<tr>
<td>4. IC/VCE</td>
<td>Simulation</td>
<td>All</td>
</tr>
</tbody>
</table>

See finally appendix 20 for the simulation results after running this setup file on the measured data of an HNHP350A log file.

The parasitic is not modelled for this transistor, since the full plug makes the parasitic very weak. See for the results of the forward characteristics appendix 21.

For the forward region there's a little difference when $\beta_F(I_C)$ is considered (for higher currents). The decay is so fast that it cannot be modeled by the used Gummel-Poon model. This model assumes a constant collector resistance $RC$ and this is not true for higher $I_C[10]$. This non constant collector resistance is also the reason why at the output characteristics the $I_C$ current has a region where the slope has a moderate value.
III.6 Extracting and optimising the parameters of the HPH1A and HPL1A

The PNP types are treated together, since the geometry is almost the same (the HPL has a base that is 1 μm narrower than the HPH). The setup file for the types is equal, only the devicename is different (in the strategy screen).

The changes on the setup files have to be made so that with optimising and extracting UTMOST works with the parameters found in the optimised column.

The same sequence of routines and fitting as shown in table 5 has to be done for these transistors, to obtain a first view of the results. See for the HPH type appendices 22 and 23.

There is a lot of difference:

- The IS value is too big. When NF would be extracted, it's value would be about 1.08 (probably due to the fact that parallel to the original transistor, the parasitic also conducts). The IS that's extracted with this value for NF will be higher than it would be when NF=1. The simulation is done with NF=1. Therefore will the simulated curves lie higher than the measured curves. IS needs to be optimised (lowered in value).

- When IS is lowered, the curves will proportionally move down, and for the high currents there will be a deviation. So RB, RBM and IRB need to be optimised.

- At high currents (FGP) the limiting effect is caused by an overestimated RC, this parameter should better be fitted on the starting slope at low V_CE of the output characteristics.

- At low I_C the β_F is increasing. That's why ISE and NE are used. These parameters need also to be optimised.

- IKF is set to optimise because the departure from the straight line of I_C (FGP) is starting for already low V_BE. Also, the IKF value determination by UTMOST uses the I_B curve to extract IKF. This extraction can be disturbed by the fact that the I_B curve is not straight for low to medium V_BE (due to the parasitic that also conducts*, which increases the original I_B needed for the original transistor).

- BF needs to be optimised when ISE and NE are used and optimised.

---

*The area of the parasitic is bigger than the area of the original transistor (base of the original is emitter for the parasitic). Current densities are lower for the parasitic so at a higher total current the current density will be so high that high injection is valid.
Appendix 23 shows that the measured curves starts at positive $I_C$. This is because one parasitic PNP conducts in this voltage region (see § II.4.2). This parasitic is not included in the Gummel Poon model and this effect can therefore not be modelled. Appendix 23 also shows an RC that’s too big: the slope is too less steep (see for the explanation the RC_sat routine in the previous chapter).

Creation of optimisation strategies:

Two optimisation strategies are used for these transistors. See the tables.

Table 15: The optimisation strategy on $\beta_F(I_C)$ for the HPH1A and HPL1A.

<table>
<thead>
<tr>
<th>Strategy #5</th>
<th>BF STRATEGY</th>
<th>Routine #9 BFvsIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>IC_start</td>
<td>IC_stop</td>
</tr>
<tr>
<td>ISE, NE</td>
<td>5E-8</td>
<td>1E-6</td>
</tr>
<tr>
<td>BF</td>
<td>5E-7</td>
<td>1E-5</td>
</tr>
</tbody>
</table>

Table 16: The optimisation strategy on FGP for the HPH1A and HPL1A.

<table>
<thead>
<tr>
<th>Strategy #1</th>
<th>GUMMEL: IC=1, IB=2</th>
<th>Routine #14 gummel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>VBE_start</td>
<td>VBC_stop</td>
</tr>
<tr>
<td>ISE,NE</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>IS</td>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>RB, RBM, IRB</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>RB, RBM, IRB, IKF</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The RB, RBM and IRB parameters are optimised on both $I_B$ and $I_C$. When optimising only on $I_B$ (or only on $I_C$), the other current wouldn't resemble so much with the measured one. Together with these parameters $IKF$ is optimised on $I_C$.

Parameter IS is optimised on the forward Gummel plot and for $I_C$.

Parameter RC is just fitted on the starting slope of the $I_C(V_{CE})$ characteristics at low $V_{CE}$. When local optimisation is enabled, fitting can be done by not declaring any strategies in the “Local Optimisation Sequence”.
Results of the optimisation on the simulated curves:
For the ALL_DC routine use a different local optimisation sequence as used for the HNH1A. The IC/VCE routine is done before the ALL_DC routine, to fit the RC value. Also, VAF is extracted but will be overwritten by the VAF value extracted in the ALL_DC routine that comes after it.
The table shows how the setup files for the HPH1A and the HPL1A ("bipolar.HPH1A.lo" and "bipolar.HPL1A.lo") work.

Table 17: Sequence, extraction- and optimisation methodology of the HPH1A and HPL1A setup files.

<table>
<thead>
<tr>
<th>Routine sequence</th>
<th>Action</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. --</td>
<td>Fixed parameters</td>
<td>NF, NR, ISC, NC</td>
</tr>
<tr>
<td>1. RB</td>
<td>Global Opt.</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td>2. RC_sat</td>
<td>Fit</td>
<td>RC, RE</td>
</tr>
<tr>
<td>3. IC/VCE</td>
<td>Fit</td>
<td>RC</td>
</tr>
<tr>
<td>4. ALL_DC</td>
<td>Fit</td>
<td>VAF, VAR, IKR, BR</td>
</tr>
<tr>
<td></td>
<td>Fit + Local Opt.</td>
<td>IS, BF, IKF, ISE, NE</td>
</tr>
<tr>
<td></td>
<td>Local Opt.</td>
<td>RB, RBM, IRB</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>All</td>
</tr>
</tbody>
</table>

See finally appendix 24 for the simulation results after running this setup file on the measured data of an HPH1A log file.
See for the results of the forward characteristics appendix 25. This simulation is done with the parameter set after the ALL_DC optimisation was done.
IV Final parameter sets

With the obtained extraction and optimisation sequence, parameter sets that fit for the measured transistor are obtained and are here used to have the final parameter set for each type of transistor that is measured.

In Alcatel Mietec the policy is to use the worst case model, so the real circuit will function better than simulated. With help of the simulated and measured results the worst case for the parameters can be determined.

Figure 27: Examples of the 'safe' simulations.

For the FGP, the simulated results should lie under the measured curves: when the transistor is driven by an $I_B$, the resulted $V_{BE}$ will be lower.

For the $\beta_F(I_C)$ curve, the simulated results should also lie under the measured curve, so the minimum gain is assured.

At the output characteristics where the transistor is used as a driver, an $I_B$ is put to the base terminal and in reality $I_C$ that can flow is bigger than simulated (so the $V_{CE}$ voltage will be smaller than calculated).

See the table that shows what these constraints mean for the parameters.

<table>
<thead>
<tr>
<th>Parameter Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$NF, NR, ISC, NC$</td>
<td>fixed</td>
</tr>
<tr>
<td>$IS, BF, NE, IKF, VAF, BR, IKR, VAR$</td>
<td>minimum value</td>
</tr>
<tr>
<td>$ISE, RB, RBM, IRB, RE, RC$</td>
<td>maximum value</td>
</tr>
</tbody>
</table>

Out of the measured transistors, individual sets are available and of these sets the parameters are chosen according to table 18. The resulted set is then the worst case set.
See appendix 26 for the final parameter sets and appendix 27 for the simulated results per transistor. Also the parameters of the parasitics that have been included into the model are given, the FGP and the $\beta_F(I_C)$ curve are not changing when this parasitic is included. Only the output characteristics at low $V_{CE}$ are changing, improving the simulated results.

With the manual extraction of $BR$ and $IKR$ for the smallest NPN types the reverse model will also be better when the parasitic is included.

Surprising is the $RB$ value for the smallest transistors (HNH1A, HPH1A and HPL1A), which is very high. The optimisation has as a bad effect that it really tries to minimise the error, despite the physical meaning that these parameters have. Normally, guarding limits can be used but as long as there are no approximate values available for the base resistance, guarding limits can not be used here. If improvement of the base resistance extraction ($RB$ routine) is possible (for instance when $RE$ is also considered), then this routine can be more accurate.
BIPOLAR DC PARAMETER DETERMINATION WITH UTMOST

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"Solid State Electronic Devices"
[9] Webster, W.M.
"On the Variation of Junction-Transistor Current-Amplification Factor with Emitter Current"

"Compact Transistor Modelling for Circuit Design"
Springer-Verlag/Wien, New York, p. 113.
NOTE

These equations assume the following conditions:

- All voltages in these model equations are referenced to the internal nodes (inside the parasitic resistances) unless otherwise stated.
- A current with a positive polarity flows into the device.
- The model parameters are referenced to TNOM.
- TEMP is the simulation temperature and defaults to TNOM when not specified.

Thermal voltage:

\[ V_t = \frac{k \cdot \text{TEMP}}{q} \]  

(1)

Normalised base charge:

\[ Q_B = \frac{1}{1 - \frac{V_{BC}}{V_{AF}} - \frac{V_{BE}}{V_{AR}}} \left( 1 + \sqrt{1 + \frac{4 \cdot IS}{IKF} \exp \left( \frac{V_{BE}}{NF \cdot V_t} \right) - 1} + \frac{4 \cdot IS}{IKR} \exp \left( \frac{V_{BC}}{NR \cdot V_t} \right) - 1 \right) \]  

(2)

Collector current:

\[ I_c = \frac{IS}{Q_B} \left[ \exp \left( \frac{V_{BE}}{NF \cdot V_t} \right) - \exp \left( \frac{V_{BC}}{NR \cdot V_t} \right) \right] - \frac{IS}{BR} \left[ \exp \left( \frac{V_{BC}}{NR \cdot V_t} \right) - 1 \right] - ISC \left[ \exp \left( \frac{V_{BC}}{NC \cdot V_t} \right) - 1 \right] \]  

(3)
Base current:

\[ I_0 = \frac{I_S}{B_f} \cdot \left[ \exp \left( \frac{\Delta V_{BE}}{N_f \cdot V_t} \right) \right] + I_SE \cdot \left[ \exp \left( \frac{\Delta V_{BE}}{N_E \cdot V_t} \right) \right] - 1 + \frac{I_S}{B_R} \cdot \left[ \exp \left( \frac{\Delta V_{BC}}{N_R \cdot V_t} \right) \right] - 1 + \frac{I_{SC}}{B_R} \cdot \left[ \exp \left( \frac{\Delta V_{BC}}{N_C \cdot V_t} \right) \right] - 1 \] 

(4)

Base resistance:

\[ r_{0B} = R_B + 3(R_B - R_{BM}) \cdot \frac{\tan(Z) - Z}{Z \cdot \tan^2(Z)} \] 

(5a)

where:

\[ Z = \frac{1 + 1.44 \cdot \left( \frac{I_B}{I_{RB}} \right)^{0.5} \cdot \left( \frac{24}{\pi^2} \right) \cdot \left( \frac{1}{I_{RB}} \right)^{0.5}}{1 + \left( 1 + 1.44 \cdot \left( \frac{I_B}{I_{RB}} \right)^{0.5} \cdot \left( \frac{24}{\pi^2} \right) \right)^{0.5}} \] 

(5b)
Effects on FCP can be smoothed by the use of the RBM and IRB parameters.

Used parameters: see Appendix 2, but also RB=170 A.

Appendix 3: All DC Routine Simulation of HNH10A with RB
APPENDIX 4: ALL_DC ROUTINE SIMULATION OF HNHP10A WITH RE

Used parameters: see appendix 2, but also RE=3Ω.

1. Limiting effect because of RE and VEC. The higher VEC the higher the maximum current.
2. Result of 1 on BR. Normally the effect of 1 is not observed because of the influence of RB.
APPENDIX 5: ALL_DC ROUTINE SIMULATION OF HNHP10A WITH RC

Used parameters: see appendix 2, but also RC=140Ω.

1. \( \frac{V_{CE}}{R_C} = I_{MAX} \)

2. \( I_B = \frac{I_S}{\beta_F} \left( \frac{e^{\frac{qV_{CE}}{kT}}}{1} \right) + \frac{I_S}{\beta_R} \left( \frac{e^{\frac{qV_{CE}}{kT}}}{1} \right), \) \( V_C=0 \ V, \) so \( V_{BC}=V_B'E' \) and \( 1/\beta_R \approx 1/\beta_F \)

therefore \( I_B = \frac{I_S}{\beta_R} \left( e^{\frac{qV_{CE}}{kT}} - 1 \right). \)

3. Departure from the straight line, decreasing internal voltages due to the voltage drop across \( R_C. \)

4. Starting slope is smaller because of \( R_C. \)
APPENDIX 6: ALL DC ROUTINE SIMULATION OF HNH101A WITH ISE

Used parameters: see appendix 2, but also ISE=10, I/A and NE=2.
APPENDIX 9.

ALL DC ROUTINE SIMULATION OF HNHP10A WITH VAR

Used parameters: see appendix 2, but also VAR=20V.
IC vs VCE

IB step = 0.70E-7
IB start = 0.56E-6
MODEL: Gummel Poon

SILVACO International
APPENDIX 13:  I_(V_{CE}) ELDO SIMULATION OF HNH1A WITH EXTRACTED AND OPTIMISED PARAMETERS
IC vs VCE

IB step = 1.50E-6
IB start = 1.20E-5
MODEL: Gummel Poon

13:9:26
JUN/21/95

SILVACO International
APPENDIX 17: IC(VCE) ELDO SIMULATION OF HNHP10A WITH EXTRACTED AND OPTIMISED PARAMETERS
IC vs VCE

IB step = 2.00E-5
IB start = 1.60E-4
MODEL: Gummel Poon

SILVACO International
Run by: Steen
Device: HNHP350A
Temp. : 25

Lot: E427130
Waf: 07
Die: top

IC vs VCE

IB step = 2.00E-5
IB start = 1.60E-4
MODEL: Gummel Poon

15:48:50
JUN/21/95

SILVACO International
IC vs VCE

IB step = -2.00E-7
IB start = -1.60E-6
MODEL: Gummel Poon

Run by: Steen
Device: HPH1A
Temp. : 25
Lot: P436039
Waf: 03
Die: top

12:44:16 JUN/22/95

SILVACO International
FORWARD GUMMEL

-IC vs. IB (A)

VCE = 0.000
Rms error = 14.06
Ave error = 98.77
Max error = 98.77
MODEL: Gummel Poon

FORWARD BETA

RF (top 3)

VCE = 0.000
Rms error = 17.16
Ave error = 27.50
Max error = 99.51
MODEL: Gummel Poon

IC vs. VCE

IB step = -2.00E-7
IB start = -1.60E-6
Rms error = 1.96
Ave error = 1.69
Max error = 1.79
MODEL: Gummel Poon

REVERSE GUMMEL

-IE vs. IB (A)

VCE = 0.000
Rms error = 50.42
Ave error = 98.44
Max error = 98.44
MODEL: Gummel Poon

REVERSE BETA

IE vs. VEC

VCE = 0.000
Rms error = 14.06
Ave error = 98.77
Max error = 98.77
MODEL: Gummel Poon

IB step = -1.00E-7
IB start = -0.80E-6
Rms error = 98.53
Ave error = 98.53
Max error = 98.53
MODEL: Gummel Poon

5.00 15.00 25.00
-0.10 -0.20 -0.30 -0.40 -0.50
-0.60 -0.70 -0.80 -0.90 -1.00
-1.00 0.00 1.00 2.00 3.00 4.00
5.00 6.00 7.00 8.00 9.00 10.00

FORWARD GUMMEL

-IC vs. IB (A)

VCE = 0.000
Rms error = 14.06
Ave error = 98.77
Max error = 98.77
MODEL: Gummel Poon

FORWARD BETA

RF (top 3)

VCE = 0.000
Rms error = 17.16
Ave error = 27.50
Max error = 99.51
MODEL: Gummel Poon

IC vs. VCE

IB step = -2.00E-7
IB start = -1.60E-6
Rms error = 1.96
Ave error = 1.69
Max error = 1.79
MODEL: Gummel Poon

REVERSE GUMMEL

-IE vs. IB (A)

VCE = 0.000
Rms error = 50.42
Ave error = 98.44
Max error = 98.44
MODEL: Gummel Poon

REVERSE BETA

IE vs. VEC

VCE = 0.000
Rms error = 14.06
Ave error = 98.77
Max error = 98.77
MODEL: Gummel Poon

IB step = -1.00E-7
IB start = -0.80E-6
Rms error = 98.53
Ave error = 98.53
Max error = 98.53
MODEL: Gummel Poon

5.00 15.00 25.00
-0.10 -0.20 -0.30 -0.40 -0.50
-0.60 -0.70 -0.80 -0.90 -1.00
-1.00 0.00 1.00 2.00 3.00 4.00
5.00 6.00 7.00 8.00 9.00 10.00

FORWARD GUMMEL

-IC vs. IB (A)

VCE = 0.000
Rms error = 14.06
Ave error = 98.77
Max error = 98.77
MODEL: Gummel Poon

FORWARD BETA

RF (top 3)

VCE = 0.000
Rms error = 17.16
Ave error = 27.50
Max error = 99.51
MODEL: Gummel Poon

IC vs. VCE

IB step = -2.00E-7
IB start = -1.60E-6
Rms error = 1.96
Ave error = 1.69
Max error = 1.79
MODEL: Gummel Poon

REVERSE GUMMEL

-IE vs. IB (A)

VCE = 0.000
Rms error = 50.42
Ave error = 98.44
Max error = 98.44
MODEL: Gummel Poon

REVERSE BETA

IE vs. VEC

VCE = 0.000
Rms error = 14.06
Ave error = 98.77
Max error = 98.77
MODEL: Gummel Poon

IB step = -1.00E-7
IB start = -0.80E-6
Rms error = 98.53
Ave error = 98.53
Max error = 98.53
MODEL: Gummel Poon
IC vs VCE

IB step = -2.00E-7
IB start = -1.60E-6
MODEL: Gummel Poon

Run by: Steen
Device: HPH1A
Temp.: 25
Lot: E427130
Waf: 07
Die: top

17:17:54
JUN/21/95
<table>
<thead>
<tr>
<th>Parameter</th>
<th>HNH1A</th>
<th>HNH10A</th>
<th>HNHP35A</th>
<th>HPH1A</th>
<th>HPL1A</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS (10^-17A)</td>
<td>2.1</td>
<td>27</td>
<td>930</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>BF (-)</td>
<td>130</td>
<td>145</td>
<td>190</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>NF (-)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BR (-)</td>
<td>8</td>
<td>100</td>
<td>130</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>NR (-)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ISE (10^-19A)</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>NE (-)</td>
<td>1.1</td>
<td>1</td>
<td>1</td>
<td>1.22</td>
<td>1.2</td>
</tr>
<tr>
<td>ISC (A)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NC (-)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>VAF (V)</td>
<td>520</td>
<td>220</td>
<td>90</td>
<td>170</td>
<td>150</td>
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<tr>
<td>VAR (V)</td>
<td>18</td>
<td>10</td>
<td>8</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>IKF (mA)</td>
<td>1.5</td>
<td>5.6</td>
<td>100</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>IKR (µA)</td>
<td>0.16</td>
<td>~0.24</td>
<td>10</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>RB (kΩ)</td>
<td>50</td>
<td>3.3</td>
<td>0.13</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>RBM (Ω)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IRB (µA)</td>
<td>2</td>
<td>10</td>
<td>200</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>RE (Ω)</td>
<td>50</td>
<td>3.3</td>
<td>0.15</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>RC (Ω)</td>
<td>1200</td>
<td>64</td>
<td>1.8</td>
<td>340</td>
<td>360</td>
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</table>

<table>
<thead>
<tr>
<th>Parasitic PNP, parameter</th>
<th>HNH1A</th>
<th>HNH10A</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS (10^-17A)</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>BF (-)</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>IKF (µA)</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

Parameter sets are based on 11 transistor parameter sets over 5 different lots. For the UTMOST program, the parameter sets are saved in the spice library file: "bipolar.steen.l".
Run by: Step
Device: RUA
Lot: E427130
Temp.: 23
Die: Top

FORWARD GUMMEL
IC & IB (A)
10^12
VBC
Rms error = 3.000
Ave error = 79.06
Max error = 90.12
MODEL: Gummel Poon
Extrinsic VBE (V)
0.40
0.60
0.80
1.00

FORWARD BETA
10
0.40
IC (A)
10^10
VBC
Rms error = 3.000
Ave error = 15.44
Max error = 22.68
MODEL: Gummel Poon
VCE (V)
0.40
10

IC vs. VCE
100.00
IB step = 0.67E-7
IB start = 0.52E-6
Rms error = 7.000
Ave error = 16.44
Max error = 22.68
MODEL: Gummel Poon
VCE (V)
-5.00
5.00
15.00
25.00

REVERSE GUMMEL
IC & IB (A)
10^12
VBE
Rms error = 3.000
Ave error = 12.68
Max error = 22.68
MODEL: Gummel Poon
Extrinsic VBE (V)
0.40
0.60
0.80
1.00

REVERSE BETA
10
0.40
IC (A)
10^10
VBE
Rms error = 3.000
Ave error = 15.44
Max error = 22.68
MODEL: Gummel Poon
VBE (V)
-2.00
Extrinsic VBC (V)
0.40
0.60
0.80
1.00

IE vs. VEC
0.60
IB step = 1.61E-5
IB start = 2.6E-4
Rms error = 8.000
Ave error = 15.44
Max error = 22.68
MODEL: Gummel Poon
VCE (V)
-1.00
1.00
3.00
5.00

APPENDIX 27: THE ALL-DC SIMULATIONS WITH THE FINAL PARAMETER SETS FOR EACH TRANSISTOR
Device: HNH1A
Temp: 25
Device: HNHP10A
Temp: 25

I(VCC)_1:2  I(VCC)_2:2  I(VCC)_3:2
IC vs VCE

IB step = 2.00E-5
IB start = 1.60E-4
MODEL: Gummel Poon

Run by: Steen
Device: HNHP350A
Temp. : 25

Lot: P431029B
Waf: 11
Die: top

14:40:12 JUN/23/95
IC vs VCE

IB step = -2.00E-7
IB start = -1.60E-6
MODEL: Gummel Poon

14:43:46
JUN/23/95
IC vs VCE

IB step = -2.00E-7
IB start = -1.60E-6
MODEL: Gummel Poon

14:46:33 -VCE (V)
JUN/23/95