

## Project Assignment 2 (*Solution*) Extracting SPICE Model Parameters for the Bipolar Junction Transistor

EE 5342 - Semiconductor Device Modeling and Characterization  
Spring 2005 - due April 14, 2005

**General Instructions:** All projects should be submitted on 8.5" x 11" paper with a cover sheet attached, or electronically as a single document file which will print as such. If submitted as a paper project report, it should be stapled only in the upper left-hand corner and no other cover or binder or folder should be used. The cover sheet should include

- (1) your name,
- (2) the project title,
- (3) the course name and number, and
- (4) your e-mail address.

The report should include clearly marked sections on

- (a) purpose of the project and the theoretical background,
- (b) a narrative explaining how you did the project,
- (c) answers to all questions asked in the project assignment, and a
- (d) list of references used in the order cited in the report (the reference number should appear in the report each time the reference is used).

All figures and tables should be clearly marked with a figure or table number and caption. The caption and labels on the figures should make the information in the figure comprehensible without reading further in the text of the report. Definitions of the setups and data ranges used should be given explicitly in the text of your report. Auxiliary information (such as SPICE data outputs, etc.) should be included in appropriate Appendices at the end of the report. Be sure to describe exactly how all results were obtained, giving enough information for anyone who understands EE 5342 to repeat your work. All work submitted must be original. If derived from another source, a full bibliographical citation must be given. (See all of Notes 5 and 6 in the syllabus.)

- a. To download a sample project solution - [http://www.uta.edu/ronc/5342/projects/Project\\_1Solution.pdf](http://www.uta.edu/ronc/5342/projects/Project_1Solution.pdf)
- b. See the course syllabus for Pspice resources.

### Project Definition

1. Download the file <http://www.uta.edu/ronc/5342/projects/Project2sp05>, to obtain the data and IC-CAP (iccap) model file to use for BJT characterization. You will need to put this file in the directory of your gamma.uta.edu account where you plan to do your characterization work. It is recommended to create a special sub-directory (such as 5342project2) in your account for this project. Once the file is in the proper directory, change the name so that it is Project2sp02.mdl. In order to start iccap, you need to execute the command "source /usr/local/iccap/00setup.iccap", and then type iccap at the prompt. If you start iccap in the same directory the \*.mdl file was stored in, you .
2. Use the data given (forward Gummel, reverse Gummel, forward early and reverse early) and the definitions of the static Gummel-Poon SPICE model for the BJT to extract values for IS, NF, BF, IKF, ISE, NE, NR, BR, IKR, ISC, NC, VAF, VAR, RB = RBM = Rbmax, RC and RE. **Give the results in the form of a table showing both the SPICE parameter and the best value you have extracted.**

**First, we extract values for VAR and VAF, applying the equations**

$$\text{VAR}_{\text{extr}} = \left[ \frac{\partial v_{BE}}{\partial (\ln(i_E))} \right]_{V_{BC}=\text{Const}, V_{BE}=0}, \text{ and } \text{VAF}_{\text{extr}} = \left[ \frac{\partial v_{BC}}{\partial (\ln(i_C))} \right]_{V_{BE}=\text{Const}, V_{BC}=0} \quad \text{to the rgummel and}$$

fgummel setups respectively. Choosing the data for the smallest value of  $v_{BC}$  in the first case, and  $v_{BE}$  in the second, we get  $VAR_{extr} = 20.4$  V and  $VAF_{extr} = 67.1$  V in the second. Note that in all cases, the calculations are done on measured data, using  $ib.m$ ,  $ic.m$ , etc., in  $iccap$ .

Next, we apply the  $N_{eff}$  and  $I_{Seff}$  models to  $i_C \cdot q_B$  and  $i_B$  in the fgummel data and  $i_E \cdot q_B$  and  $i_B$  in the rgummel data.  $q_B = (1 - v_{BE}/VAR - v_{BC}/VAF)^{-1}$ .

To calculate  $N_{Feff}$ , one needs to know  $V_t$ . This can be determined by simulating a diode with  $N = 1$ , and  $R_S = 0$ . In this case,  $dv/d(\ln(i)) = kT/q = V_t$  (= 25.86419 mV for the default spice2 simulator in  $iccap$ ). The minimum value for  $N_{eff}$  for the fgummel  $i_C$  data is  $1.120 = N_{Fextr}$  (for  $v_{BE} = 0.55$  V). The maximum value for  $N_{Eeff}$  for the fgummel  $i_B$  is  $1.746 = N_{Eextr}$  at  $v_{BE} = 0.4$  V.

Evaluating  $I_{Seff}$  ( $= \exp[\ln(i) - v/(N_{eff} \cdot V_t)]$ ) at the same condition as  $N_E$  and  $N_F$  were extracted gives  $2.347E-15$  A =  $I_{Sextr}$  and  $1.04E-14$  =  $I_{SEextr}$ .

Looking at the  $i_C/i_B$  or  $di_C/di_B$ , we find a maximum value of  $64.8 = B_{Fextr}$ . Considering that the model equations suggest that  $i_C/i_B \sim BF/2$  at  $IKF$ , we have  $IKF_{extr} = 11.4$  mA

Taking the derivative of  $di_B/di_B = 1$ , one finds that  $di_B/dv_{BE} - NF \cdot V_t/i_B \equiv r_{pi,adj} = R_E \cdot di_C/di_B + (R_B + R_E)$ . Such a plot of  $r_{pi,adj}$  vs.  $h_{fe} \equiv di_C/di_B$  gives a slope of 1.61 (=  $R_{Eextr}$ ) and an intercept of 5.86 ( $\Rightarrow R_{Bextr} = 4.25$ ). Since we are told the  $IR_B = 0$ , and  $R_{BM} = R_B$ , that extracts all values except  $R_C$ .

Other schemes can be used. Full credit will be given if the theory is properly explained and the extracted value is closer to the true value.

Extraction of rgummel data proceeds much the same, with the exception that in order to extract a value for  $I_{SC}$  and  $N_C$ , one must use  $ib,rgummel - ie.m/BR$  (see the comments under 5 below, and note that  $VAF \gg v_{BC,rgummel}$ ).

We assume  $I_S$  is correct. Applying  $N_{eff}$  to  $ie.m,rgummel$ , we find  $N_{Rextr} = 1.000$  for  $v_{BC} \sim 0.5$  V.

In this case, it looks like  $I_{SCeff,rg}$  is minimum at 0.55  $v_{BC}$  with a value of  $2.205E-15$  =  $I_{SCextr}$ . For the same conditions,  $N_{Cextr} = 1.104$ . In this case, it is obvious that the  $BR$  term is small, (extracts using  $ie.m/ib.m$  to be 1.47). With these values, the simulation shows a maximum error of ~20% in  $ib.s$  relative to  $ib.m$  and ~6% in  $ic.s$  relative to  $ic.m$ .

The  $IKR$  value was estimated since it was clear  $BR$  is not correct and the data does not reach a level at which  $\beta_{etar} = ie.m/ib.m = \beta_{etar,max}/2$

Doing the same  $di_B/di_B = 1$  calculation for the rgummel data, one derives a relationship that  $di_B/dv_{BC} - NR \cdot V_t/i_B \equiv r_{mu,adj} = R_C \cdot di_E/di_B + (R_B + R_E)$ . Such a plot of  $r_{mu,adj}$  vs.  $h_{re} \equiv di_E/di_B$  gives a slope = 11.7 (=  $R_{Cextr}$ ), and an intercept = 14.8 ( $\Rightarrow R_{Bextr} = 3.1$ ).

- Document your parameter extraction methods and the values you have extracted. **Your narrative should cover the procedure you used to extract each parameter value in the same order that you numerically extracted that particular parameter. Do NOT use any of the iccap extraction programs, but develop your own extraction procedure.**

See above for parameter extraction procedures. The extracted parameters are in Table 1.

**Table 1. Extracted GP parameters. The values extracted using the procedure described in part 2.**

IS	234.7a
NF	1.120
BF	64.80
IKF	11.4m
ISE	10.40f
NE	1.746
NR	1.000
BR	1.470
IKR	20m
ISC	2.205f
NC	1.104
VAF	68.70
VAR	20.40
RB	4.250
RE	1.610
RC	11.70

- Run SPICE Gummel-Poon simulations using the extracted parameter values and compare to the data provided herein. Compare your simulation to the original data. Note: In doing the SPICE simulation, be sure that the global parameters GMIN and NUMDGT are set to values that give a proper simulation of the data desired.

**For the minimum value of di/dv observed, (di/dv)/GMIN should be >> 1000 for 3 significant error accuracy, >> 10,000 for 4 figure accuracy, etc. NUMDGT should be enough to get the number of significant figures needed. The default is usually OK.**

- Calculate the net rms relative error for your SPICE simulations in IC-CAP relative to the original data for each data set. For each data set, use the definition that

$$\text{NRE} = \text{net rms relative error} = 100\% * \left\{ \text{SUM}_{(\text{ALL DATA})} [(i_{\text{SPICE}} - i_{\text{DATA}}) / i_{\text{DATA}}]^2 / (\#\text{ofPts}) \right\}^{1/2}.$$

**This can be observed at the beginning of the optimizations. For the extractions in the fummel data, the maximum extracted parameter simulations of iB had a value of 20%, and for simulations of iC the maximum simulated error was 0.7%. The accuracy of iB simulations could have been improved significantly by doing the extraction algorithms on iB.m - ILE, where  $\text{ILE} = \text{ISE} * \exp(v_{\text{BE}} / (\text{NE} * V_{\text{t}}))$ .**

- Use the optimize functions in iccap to improve the estimate of the model parameters by running optimizations over restricted regions of the data. Do this to improve your estimate of IS, NF, BF, IKF, ISE, NE, NR, BR, IKR, ISC, NC, VAF, VAR, RB = Rbmax, RC and RE.

**The optimized values you obtain should be close to the values used to generate the data. These values are given in Table 2. The comparison to the extracted values are given also.**

**Table 2. Values used to generate the data used in this project. DATA represents values used to generate the data. EXTR represents the values extracted in this solution. EXTR ERR represents the relative error between the two.**

	DATA	EXTR	EXTR ERR
IS	234.5a	234.7a	0%
NF	1.120	1.120	0%
BF	76.54	64.80	15%
IKF	9.876m	11.4m	15%
ISE	12.34f	10.40f	16%
NE	1.789	1.746	2%
NR	1.000	1.000	0%
BR	12.34	1.470	88%
IKR	12.34m	20m	62%
ISC	2.345f	2.205f	6%
NC	1.111	1.104	1%
VAF	76.54	68.70	10%
VAR	19.87	20.40	3%
RB	8.765	4.250	52%
RE	1.234	1.610	30%
RC	8.765	11.70	33%

7. Give the results in the form of a table showing:
- the SPICE parameter you have extracted in part 2,
  - the optimized SPICE parameter you developed in part 6,
  - the NRE error (as defined in part 5) for each setup with the optimized parameter values.

**See the results tabulated in Table 2. The NRE can be optimized to less than 0.1% or even as low as 0.005%.**