

UNIVERSITY OF CALIFORNIA
College of Engineering
Department of Electrical Engineering and Computer Sciences

EE 130
Spring 2003

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Term Project
Due by 5 PM on Thursday, 4/24/03

NOTE: YOU MUST WORK ONLY WITH YOUR PARTNER ON THIS PROJECT

Part I: Manual Design of Ideal BJT Structure [75 points]

- A. Design an NPN bipolar junction transistor with uniformly doped emitter, base and collector regions to meet the stated performance specifications over the temperature range 300K to 360K, with the stated constraints on design. (Specify the thicknesses W_E , W_B and W_C of the emitter, base and collector regions, respectively, in addition to the doping concentrations N_E , N_B and N_C .)

Performance Specifications:

- $\beta_{dc, \text{ edge of saturation}} > 50 @ I_C = 1 \text{ mA}$
- $V_{A, \text{ edge of saturation}} > 10 \text{ V} @ I_C = 1 \text{ mA}$
- $V_{\text{punchthrough}} > 10 \text{ V}$
- $f_{T, \text{ edge of saturation}} > 20 \text{ GHz} @ I_C = 1 \text{ mA}$

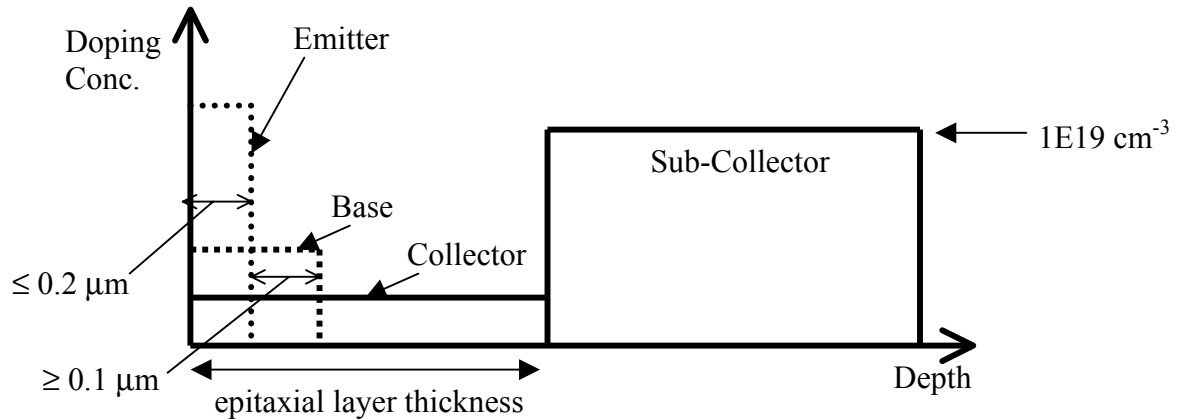
- Notes:
- i. Edge of saturation $\Rightarrow V_{BC} = 0 \text{ V}$
 - ii. $V_{\text{punchthrough}} = |V_{BC}|$ at which base width $W = 0$, for $V_{BE} = 0 \text{ V}$

Design Constraints:

- The BJT has a uniform cross-sectional area of $10\mu\text{m} \times 1\mu\text{m}$
 - Maximum emitter doping $N_E = 1\text{E}20 \text{ cm}^{-3}$
 - Maximum emitter thickness $W_E = 0.2 \mu\text{m}$
 - Minimum base width $W_B = 0.1 \mu\text{m}$
 - Minimum collector doping $N_C = 1\text{E}15 \text{ cm}^{-3}$
 - Epitaxial layer thickness $(W_E + W_B + W_C) \leq 4 \mu\text{m}$
 - Minimum collector thickness $W_C = 2.0 \mu\text{m}$
 - Sub-collector doping = $1\text{E}19 \text{ cm}^{-3}$
 - Sub-collector thickness = $1 \mu\text{m}$
 - minority-carrier lifetimes $\tau_E = \tau_B = \tau_C = 1\mu\text{s}$.
- B. Determine the impact of +/-10% changes in base width W_B and base doping N_B on your design. (You should vary W_B and N_B individually, *i.e.* you do not need to vary them simultaneously.) Your device design should be able to meet the performance specifications despite these variations, which can arise from typical variations in a transistor fabrication process.

Detailed Instructions/Guidance for Manual Design:

Assume that the collector, base, and emitter are formed using a combination of epitaxy (to grow a lightly doped n-type layer of Si on top of the heavily doped sub-collector) and ion-implantation and diffusion (to form the Base and Emitter doping profiles), resulting in the following ideal doping profiles:



Note that the emitter and base regions are compensated.

Setting Up:

First, determine the constants that apply within the various regions of the BJT.

- Use the empirical equations given on pages 83-84 of the textbook to determine the minority-carrier mobilities (dependent on the **total** doping concentration as well as the temperature), for each region (including the sub-collector) of the BJT. You will also need to determine the majority-carrier mobility in the collector, in order to calculate the resistivity of the collector r_C .
- Use the Einstein relationship to determine the minority-carrier diffusion coefficients for each region (including the sub-collector) of the BJT.
- Calculate the minority-carrier diffusion lengths for each region of the BJT.
- Use the following empirical equation (given on page 56 of the textbook) to determine the intrinsic carrier concentration for a moderately doped semiconductor:

$$n_i = 9.15 \times 10^{19} \left(\frac{T}{300} \right)^2 e^{-0.5928/kT}$$

- Determine the equilibrium carrier concentrations within each region of the BJT. Include the effect of bandgap narrowing (due to high dopant concentration) on n_i^2 when determining the minority-carrier concentration in the emitter:

$$n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT} \quad \text{where} \quad \Delta E_{gE} = 3.5 \times 10^{-8} (N_E)^{1/3} \sqrt{\frac{300}{T}}$$

- Determine the built-in potentials (V_{biE} , V_{biC}). (Assume that the Boltzmann approximation is valid for the base and collector regions, but that the emitter is degenerately doped.)

Next, define various parameters as functions of the applied biases (V_{BE} , V_{BC}):

- emitter-junction and collector-junction depletion widths
- emitter-junction and collector-junction depletion capacitances
- quasi-neutral-region widths (W_E' , W , W_C')
- Current components J_{Ep} , J_{En} , J_{Cp} , J_{Cn}

Then, you can calculate various performance parameters as follows:

- Terminal currents $J_E = J_{Ep} + J_{En}$ and $J_C = J_{Cp} + J_{Cn}$ and $J_B = J_E - J_C$
 - Find the value of V_{BE} which gives $I_C = 1$ mA; use this value for calculating β_{dc} , V_A and f_T .
- Common-emitter dc gain $\beta_{dc} = J_C / J_B$
- Early voltage $V_A = \frac{Q_B}{C_{dBC}} \bigg|_{V_{BC}=0}$ where $Q_B = q(N_B - N_C)W$ is the integrated dopant dose in the quasi-neutral base and C_{dBC} is the collector-junction depletion capacitance.
- Punchthrough voltage $V_{punchthrough}$

Notes:

- You may assume that the emitter, base and collector regions are “short”, *i.e.* $W_E' \ll L_E$, $W \ll L_B$, and $W_C' \ll L_C$.
- For the sole purpose of calculating the minority-carrier diffusion current in the collector, you should account for the boundary between the collector and sub-collector in your analysis, similarly as for a poly-Si emitter described in the text on page 428. (The bottom of the sub-collector can be considered as an ohmic contact.) As a result, W_C' should be replaced by $W_C' + t_{subcollector} \left(\frac{D_C}{D_{SC}} \right)$ in the equation for I_C , where $t_{subcollector}$ is the width of the sub-collector (1 μ m) and D_C and D_{SC} are the minority-carrier diffusion constants in the collector and sub-collector, respectively.

- f_T : Calculation of this parameter is a little more involved:
 - Calculate the base transit time τ_t .
 - Determine the base-emitter voltage V_{BE} at which $I_C = 1$ mA at the edge of saturation, *i.e.* $V_{BC} = 0$ V.
 - Calculate the total excess minority charge in the quasi-neutral base

$$Q_{nB} = q \int_0^W \Delta n_B(x) dx \cong \frac{1}{2} q W \Delta n_B(x_{pBE})$$

where x_{pBE} is the location of edge of the emitter-junction depletion region in the base.

- Calculate the total excess minority charge in the quasi-neutral emitter

$$Q_{pE} = q \int_0^{W_E'} \Delta p_E(x) dx \cong \frac{1}{2} q W_E' \Delta p_E(x_{nBE})$$

where x_{nBE} is the location of edge of the emitter-junction depletion region in the emitter.

- Calculate $\tau_F \approx [(Q_{nB} + Q_{pE}) / Q_{nB}] * \tau_t$.
- Calculate the collector resistance r_c :

$$r_c = \frac{1}{q\mu_{nC}N_C} \left(\frac{W'_C}{A} \right)$$

where μ_{nC} is the majority-carrier mobility in the collector, and W'_C is the width of the quasi-neutral collector region. (Note that the series resistance of the sub-collector is considered to be negligible.)

- Use the following equation to calculate f_T :

$$f_T = \frac{1}{2\pi(\tau_F + [(C_{dBE} + C_{dBC})kT/(qI_C)] + r_c C_{dBC})}$$

where C_{dBE} and C_{dBC} are the equilibrium (zero applied bias) emitter-junction and collector-junction depletion capacitances, respectively.

Design Process:

Using your intuitive knowledge of the dependences of BJT performance parameters on the design, select some initial values for W_E , W_B , W_C , N_E , N_B and N_C and determine the resulting device performance parameters. Vary the design until you find one that meets the specifications over the temperature range 300K to 360K. Then, perturb the base doping by +/- 10% to see the effect on the performance parameters; likewise, perturb the base width by +/- 10% to see the effect.

- C. Write a high-quality, clearly written report detailing your design. Your report should contain the following information:

1. **[20 pts]** Summary specifications for your design (W_E , W_B , W_C , N_E , N_B and N_C), and resulting performance parameters (β_{dc} , V_A , $V_{punchthrough}$ and f_T) in tabulated format:
 - List values of β_{dc} , V_A , $V_{punchthrough}$ and f_T in separate columns. Each parameter should have two columns: one for values at $T = 300K$, the other for values at $T = 360K$.
 - Row 1: nominal values
 - Row 2: values with 10% increase in N_B
 - Row 3: values with 10% decrease in N_B
 - Row 4: values with 10% increase in W
 - Row 5: values with 10% decrease in W
2. **[10 pts]** Common-emitter output characteristics (plot of I_C vs. V_{CE} , for multiple values of I_B : 10 μA , 20 μA , 30 μA , 40 μA and 50 μA)
3. **[20 pts]** Description/details of design process. (You MUST show the procedure by which you set up the equations and obtained the final results.)
4. **[20 pts]** Perturbation analysis -- provide brief qualitative explanations of the observed changes in performance parameters:
 - β_{dc} : effect of increasing N_B , effect of increasing W
 - V_A : effect of increasing N_B , effect of increasing W
 - $V_{punchthrough}$: effect of increasing N_B , effect of increasing W
 - f_T : effect of increasing N_B , effect of increasing W
5. **[5 pts]** Ideas for design improvement

Part II: Computer-Aided Design of More Realistic BJT Structure [25 points]

Note: The entire MEDICI manual is available on mingus in the file
/share/instsw/pkg/tcad/tcad-medici_v2002.4/manuals_pdf/medici_2002.4.0/MD_2002.4.pdf
Relevant excerpts from the manual will be posted on the EE130 website.

- A. Read the *NPN Bipolar Transistor Examples* section of the MEDICI manual (attached), which gives a detailed description of a 2-D BJT simulation input file and the resulting output generated by MEDICI, followed by an example of a 1-D BJT simulation. You will modify the input file for the 1-D simulation according to correspond to your manual design in Part I. Since you will be changing the doping profile specifications in the input file, the description of the PROFILE statement is also attached.
- B. Use MEDICI to simulate a more realistic NPN structure adapted from your manual design:
- Use the input file `mdex2m.inp` which you copied into your directory (Homework Assignment #8, Problem 5) as a starting point. Edit this file to specify BJT physical parameters similar to your manual design as follows:
 - Set the width of the device to $1\text{ }\mu\text{m}$ (Line 5).
 - Set the total depth of the mesh (DEPTH parameters in Lines 6-7) to be equal to the nominal thickness of the epitaxial layer in your manual design.
 - Set the location of the base contact in Line 12 by editing the Y.MIN and Y.MAX values. For example, if your manual design specifies an emitter width W_E of $0.2\text{ }\mu\text{m}$ and a base width W_B of $0.2\text{ }\mu\text{m}$, then the Y.MIN and Y.MAX value should fall between $0.2\text{ }\mu\text{m}$ and $0.4\text{ }\mu\text{m}$ (e.g. $0.25\text{ }\mu\text{m}$).
 - Set the peak concentration values (N.PEAK) for the collector (Line 16) and emitter (Line 19) to the nominal values N_C and N_E from your manual design.
 - Instead of specifying a value for the characteristic length (Y.CHAR), specify the junction depth (Y.JUNCTI) for the emitter in Line 19, to give the same emitter width W_E as in your manual design.
 - Use only a simple Gaussian doping profile for the base, by “eliminating” the first PROFILE statement for the base region (Line 17). You can do this by deleting Line 17, or by changing it to a COMMENT statement (by inserting ‘COMMENT’ at the beginning of the line).
 - In order to achieve a base doping profile (Line 18) which is comparable to that of your manual design, the following changes need to be made:
 - Specify the Y.MIN value to be equal to the emitter width W_E from your manual design.
 - Specify the Y.JUNCTI value to be equal to $W_E + W_B$ from your manual design.
 - Set N.PEAK to a value **higher** than that in your manual design, such that the peak acceptor doping concentration in the base region is **equal** to the base doping concentration N_B in your manual design. (You will need to run MEDICI and examine the dopant

concentration profile plot, then adjust the N.PEAK value and repeat the simulation, until you achieve this goal.)

- Delete the sub-collector doping profile (Line 20) altogether. For the simulation, we thus assume that there is an ohmic contact at the bottom of the collector.
- Run MEDICI on your modified input file and examine the output file and plots.

You can have MEDICI save the various plots to a postscript file (which you can then print out using the 'lpr' command) by specifying DEVICE=postscript and PLOT.OUT=<filename> in one of the PLOT.1D statements. For example, add one line to the PLOT.1D statement which begins on Line 40:

```
COMMENT  Plot Ic and Ib vs. Vbe
PLOT.1D  IN.FILE=MDEX2MI Y.AXIS=I(Collector) X.AXIS=V(Base)
+        Y.LOG POINTS LINE=1 COLOR=2
+        TITLE="Example 2M - Ic & Ib vs. Vbe"
+        DEVICE=postscript PLOT.OUT=curr.ps
```

C. Report your results and findings:

1. **[10 pts]** Include a printout of your output file (`<filename>.out`, generated by MEDICI when it is run using `<filename>.inp` as the input file)
2. **[5 pts]** Provide copies of the various plots generated by MEDICI
 - device structure
 - Gummel plot (I_C, I_B vs. V_{BE})
 - β_{dc} vs. I_C – Indicate the value of β_{dc} at $I_C = 1$ mA on the plot
 - f_T vs. I_C – Indicate the value of f_T at $I_C = 1$ mA on the plot
 - net doping concentration profile – Indicate the peak values of N_E , N_B and N_C , as well as the emitter width W_E and base width W_B , on the plot
3. **[10 pts]** Compare the simulation results with your nominal performance parameters from Part I. Discuss the differences and provide qualitative explanations for them, based on your intuitive understanding of the dependences of BJT performance parameters on the design (*e.g.* consider the base and emitter Gummel numbers).