# NPN Bipolar Transistor Examples

## Example Specifications

The use of Medici is illustrated by going through some of the analysis that might be performed on an NPN bipolar transistor. The analysis is divided into six parts.

- The input file *mdex2* develops the simulation structure.
- The input file *mdex2f* then simulates the forward current characteristics for the device.

  The results of this simulation are examined with the input file *mdex2fp*.
- The input file *mdex2p* modifies the emitter region of the device and specifies different material properties for the modified region.
- The forward current characteristics are then repeated for the modified device.
- The results of the simulation with the modified emitter are examined with the input file *mdex2pp*.
- The input file *mdex2m* illustrates a one-dimensional analysis of a bipolar transistor.

## Generation of the Simulation Structure

The input file *mdex2* creates the simulation structure for an NPN bipolar device. The output associated with the execution of Medici for the input file *mdex2* is shown in Figures 5-1 through 5-5.

### Defining the Initial Mesh

As with the MOS example in Chapter 4, the first step in creating a device structure is to generate an initial mesh. Since this initial mesh will be refined, it needs to be adequate for defining the structure, but does not need to be fine enough to perform a solution on.

The mesh generation is initiated with the **MESH** statement at line 4 of the input file shown in Figure 5-1.

```
 1... TITLE     Avant! MEDICI Example 2 - NPN Transistor Simulation
 2... COMMENT   Grid Generation and Initial Biasing

 3... COMMENT   Specify a rectangular mesh
 4... MESH
 5... X.MESH    WIDTH=6.0  H1=0.250
 6... Y.MESH    DEPTH=0.5  H1=0.125
 7... Y.MESH    DEPTH=1.5  H1=0.125  H2=0.4

 8... COMMENT   Region definition
 9... REGION    NAME=Silicon  SILICON

10... COMMENT   Electrodes
11... ELECTR    NAME=Base  X.MIN=1.25  X.MAX=2.00  TOP
12... ELECTR    NAME=Emitter  X.MIN=2.75  X.MAX=4.25  TOP
13... ELECTR    NAME=Collector  BOTTOM

14... COMMENT   Specify impurity profiles
15... PROFILE   N-TYPE  N.PEAK=5e15  UNIFORM     OUT.FILE=MDEX2DS
16... PROFILE   P-TYPE  N.PEAK=6e17  Y.MIN=.35  Y.CHAR=.16
  ... +                 X.MIN=1.25  WIDTH=3.5   XY.RAT=.75
17... PROFILE   P-TYPE  N.PEAK=4e18  Y.MIN=0    Y.CHAR=.16
  ... +                 X.MIN=1.25  WIDTH=3.5   XY.RAT=.75
18... PROFILE   N-TYPE  N.PEAK=7e19  Y.MIN=0    Y.CHAR=.17
  ... +                 X.MIN=2.75  WIDTH=1.5   XY.RAT=.75
19... PROFILE   N-TYPE  N.PEAK=1e19  Y.MIN=2    Y.CHAR=.27

20... PLOT.2D   GRID  TITLE="Example 2 - Initial Grid"  SCALE  FILL

21... COMMENT   Regrid on doping
22... REGRID    DOPING  LOG  RATIO=3  SMOOTH=1  IN.FILE=MDEX2DS
23... PLOT.2D   GRID  TITLE="Example 2 - 1st Doping Regrid" SCALE FILL

24... REGRID    DOPING  LOG  RATIO=3  SMOOTH=1  IN.FILE=MDEX2DS
25... PLOT.2D   GRID  TITLE="Example 2 - 2nd Doping Regrid" SCALE FILL

26... COMMENT   Extra regrid in emitter-base junction region only.
27... REGRID    DOPING  LOG  RATIO=3  SMOOTH=1  IN.FILE=MDEX2DS
  ... +         X.MIN=2.25  X.MAX=4.75  Y.MAX=0.50  OUT.FILE=MDEX2MS
28... PLOT.2D   GRID  TITLE="Example 2 - 3rd Doping Regrid" SCALE FILL

29... COMMENT   Define models
30... MODELS    CONMOB  CONSRH  AUGER  BGN

31... COMMENT   Solve for Vce=3 volts
32... SYMB      CARRIERS=0
33... METHOD    ICCG  DAMPED
34... SOLVE     V(Collector)=3.0

35... COMMENT   Switch to Newton and two carriers - save solution
36... SYMB      NEWTON  CARRIERS=2
37... SOLVE     OUT.FILE=MDEX2S
```

Figure 5-1 Output of the simulation input file *mdex2*

## Mesh Specifications

The **X.MESH** and **Y.MESH** specify how the initial rectangular mesh is generated.

- The **X.MESH** statement that follows creates a grid section extending from $x$=0 microns (the default starting location) to $x$=6 microns.
- A uniform spacing of 0.25 microns is specified with the **H1** parameter.
- The first **Y.MESH** statement creates a 0.5 micron grid section at the top of the device that has a uniform spacing of 0.125 microns.

- The next **Y.MESH** statement adds a 1.5 micron grid section beneath this with a grid spacing that increases from 0.125 microns at *y*=0.5 microns to 0.4 microns at the bottom of the structure (*y*=2.0 microns).

## Device Regions

The entire structure is defined as silicon with the **REGION** statement. The **ELECTR** statements are used to place the contacts. The base and the emitter are placed on the surface, and the collector is placed along the entire bottom of the structure.

## Impurity Profiles

The impurity profiles for the device were specified using analytic functions, although they could also have been read from Avant! SUPREM-3, TSUPREM-4, or 1D and 2D formatted files.

The first **PROFILE** statement specifies a uniform n-type background concentration. The next two **PROFILE** statements specify p-type impurities for forming the base. High concentration n-type profiles are then used to form the emitter and buried collector for the structure.

The specification of an output file on the first **PROFILE** statement saves the profiles to be used whenever the grid is refined. This should always be done to avoid having to interpolate impurity concentrations from the nodes of an unrefined grid to the nodes of a refined grid.

## Regrid

In lines 22 and 24, the grid is refined based on impurity concentration. During the regrids, a triangle is subdivided into four congruent triangles whenever the impurity concentrations at the nodes of the triangle differ by more than three orders of magnitude.

In line 27, a third refinement based on impurity concentration is performed. This regrid is confined to the vicinity of the emitter-base junction. Confining the regrid in this manner allows a fine grid to be placed in this important region and at the same time keeps the total node count from becoming excessive.

The final mesh is saved in a file for use in later simulations.

The various stages of the mesh refinement are shown in Figures 5-2 through 5-5.

## Models and Initial Solution

The **MODELS** statement at line 30 is used to select various physical models that are included during the solution phase.

At this point it is desired to obtain a solution with $V_{ce}$=3V and $V_{be}$=0V which can be used as a starting point for subsequent simulations. Under these bias conditions, current flow is not expected to be significant.

The desired solution can then be obtained most efficiently by first performing a zero-carrier solution with 3V applied to the collector. This can then be used as the initial guess for a full two-carrier solution.

Following this approach, a zero-carrier solution is performed at line 34. The two-carrier solution (using Newton's method as the most efficient solution technique) is performed at line 37. Since no biases were specified here, they are defaulted to those used during the previous solution. The **OUT.FILE** parameter causes the solution to be saved in a file for later use.

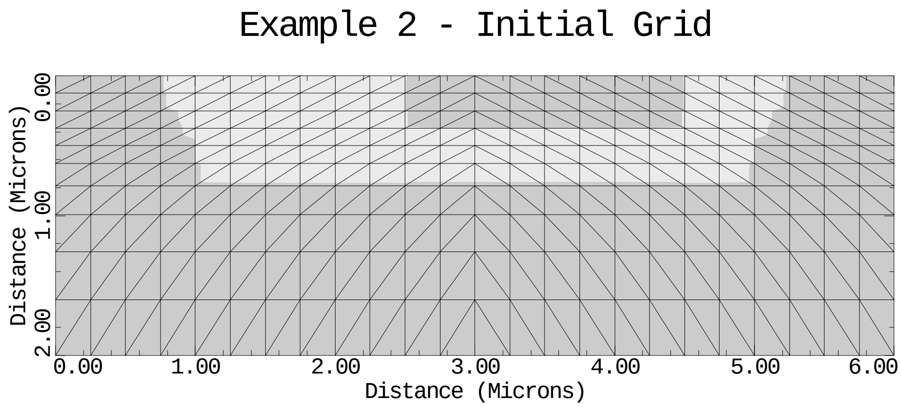


Figure 5-2 Initial grid from **PLOT.2D** at line 20 in file *mdex2*, Figure 5-1

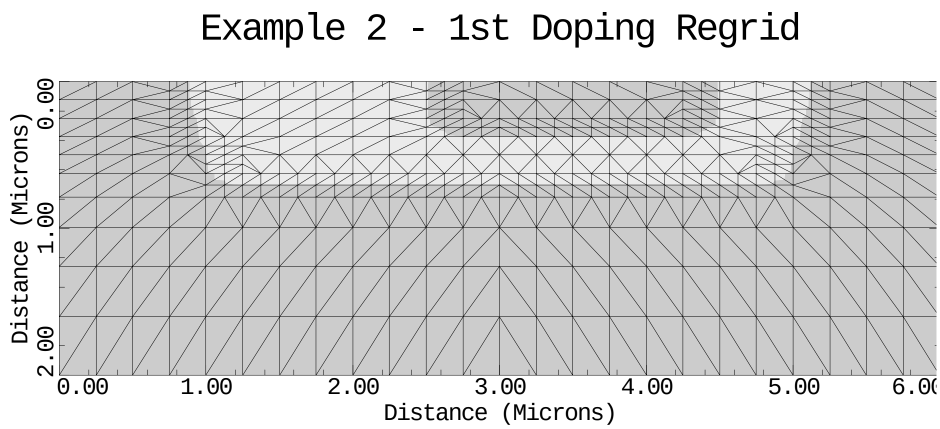


Figure 5-3 First doping regrid from **PLOT.2D** at line 23 in file *mdex2,* Figure 5-1

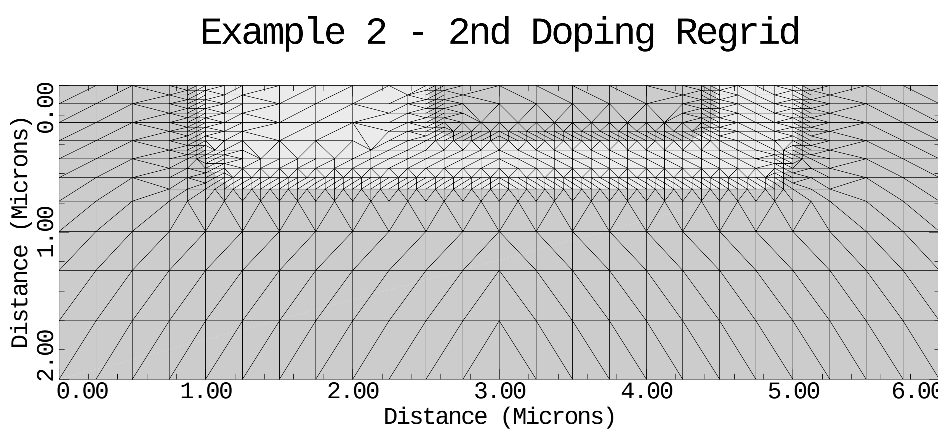


Figure 5-4 Second doping regrid from **PLOT.2D** at line 25 in file *mdex2*, Figure 5-1

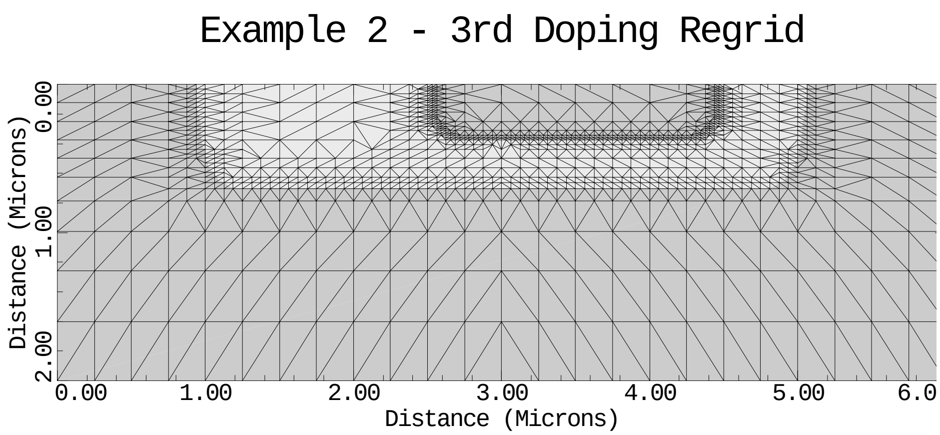


Figure 5-5 Third doping regrid from **PLOT.2D** at line 28 in file *mdex2*, Figure 5-1

## Simulation of Forward Characteristics

The device structure and initial solution that were created and saved by the input file *mdex2* are read by the input file *mdex2f*. Simulations are performed for:

- Base-emitter biases of 0.2V to 0.9V.
- For each bias, an AC small-signal analysis is performed at a frequency of $10^6$ Hz.

Figure 5-6 contains a portion of the output associated with the execution of Medici for the input file *mdex2f*.

```
 1... TITLE     Avant! MEDICI Example 2 - NPN Transistor Simulation
 2... COMMENT   Forward Bias Points

 3... COMMENT   Read in simulation mesh
 4... MESH      IN.FILE=MDEX2MS

 5... COMMENT   Load previous solution:  Vce=3.0 Vbe=0.0
 6... LOAD      IN.FILE=MDEX2S

 7... COMMENT   Use Newton's method with 2 carriers
 8... SYMB      NEWTON  CARRIERS=2

 9... COMMENT   Setup log file for I-V and AC data
10... LOG       OUT.FILE=MDEX2FI

11... COMMENT   Forward bias the base-emitter junction and
12... $         calculate the admittance matrix at 1.0 MHz

13... SOLVE     V(Base)=0.2  ELEC=Base  VSTEP=0.1  NSTEP=4
  ... +         AC.ANAL FREQ=1E6 TERM=Base
14... SOLVE     V(Base)=0.7  ELEC=Base  VSTEP=0.1  NSTEP=2
  ... +         AC.ANAL FREQ=1E6 TERM=Base OUT.FILE=MDEX2S7
```

Figure 5-6 Output of the simulation input file *mdex2f*

## Input Statements

Newton's method is chosen as the most efficient solution technique. Before performing any solutions, the I-V and AC log file is created in line 10 to store the I-V and AC data, for later plotting.

In this example, it is desired to plot the carrier concentrations for $V_{be}$ =0.7V. Since this is not the last bias, it is necessary to save the solution for this bias. To do this and not have to save the solutions for all the biases, two **SOLVE** statements are used.

- The first statement solves for biases through 0.6V and does not specify an output file.
- The second statement solves for the remaining biases and saves the solutions as a result of the output file specification.

Each solution on the second **SOLVE** statement is saved in a different file.

### AC Small-Signal

The **SOLVE** statements also requests that an AC small-signal be performed at a frequency of $10^6$ Hz after each DC solution is obtained. The parameter **TERM** is used to specify which electrode biases are to be perturbed when performing the AC small-signal analysis.

The default is to perturb all electrode biases, one at a time, so that a full admittance matrix is calculated. In this example, only the base voltage is perturbed by specifying **TERM**=Base.

# Post-Processing of Forward Bias Results

For performing a post-processing analysis of the simulation results, input file *mdex2fp* reads the following:

- The mesh file created and saved by the input file *mdex2*.
- The solution and log files that were created and saved by the input file *mdex2f*.

Figures 5-7 through 5-13 contain the output associated with the execution of Medici for the input file *mdex2fp*.

## Input Statements

The post-processing of forward bias results uses the following input statements.

### Collector and Base Currents

The input file *mdex2fp* is shown in Figure 5-7. The statements in lines 4 through 8 use the I-V log file *MDEX2FI* to plot the collector and base currents as a function of $V_{be}$. The **LABEL** statement uses the default settings from I-V log file *MDEX2FI*. The resulting plot is shown in Figure 5-8.

```
 1... TITLE     Avant! MEDICI Example 2FP - NPN Transistor Simulation
 2... COMMENT   Post-Processing of MDEX2F Results

 3... COMMENT   Plot Ic and Ib vs. Vbe
 4... PLOT.1D   IN.FILE=MDEX2FI  Y.AXIS=I(Collector)  X.AXIS=V(Base)
  ... +         LINE=1  COLOR=2  TITLE="Example 2FP - Ic & Ib vs. Vbe"
  ... +         Y.LOG  POINTS  BOT=1E-14  TOP=1E-3
 5... PLOT.1D   IN.FILE=MDEX2FI  Y.AXIS=I(Base)  X.AXIS=V(Base)
  ... +         Y.LOG  POINTS  LINE=2  COLOR=3  UNCHANGE
 6... LABEL     LABEL="Ic"  X=.525  Y=1E-8
 7... LABEL     LABEL="Ib"  X=.550  Y=2E-10
 8... LABEL     LABEL="Vce = 3.0v"  X=.75  Y=1E-13

 9... COMMENT   Plot the current gain (Beta) vs. collector current
10... EXTRACT   NAME=Beta  EXPRESS=@I(Collector)/@I(Base)
11... PLOT.1D   IN.FILE=MDEX2FI  X.AXIS=I(Collector)  Y.AXIS=Beta
  ... +         TITLE="Example 2FP - Beta vs. Collector Current"
  ... +         BOTTOM=0.0  TOP=25  LEFT=1E-14  RIGHT=1E-3
  ... +         X.LOG  POINTS  COLOR=2
12... LABEL     LABEL="Vce = 3.0v"  X=5E-14  Y=23
13... COMMENT   Plot the cutoff frequency Ft=Gcb/(2*pi*Cbb)
14... EXTRACT   NAME=Ft  UNITS=Hz
  ... +         EXPRESS="@G(Collector,Base)/(6.28*@C(Base,Base))"
15... PLOT.1D   IN.FILE=MDEX2FI  X.AXIS=I(Collector)  Y.AXIS=Ft
  ... +         TITLE="Example 2FP - Ft vs. Collector Current"
  ... +         BOTTOM=1  TOP=1E10  LEFT=1E-14  RIGHT=1E-3
  ... +         X.LOG  Y.LOG  POINTS  COLOR=2
16... LABEL     LABEL="Vce = 3.0v"  X=5E-14  Y=1E9

17... COMMENT   Read in the simulation mesh and solution for Vbe=0.9v
18... MESH      IN.FILE=MDEX2MS
19... LOAD      IN.FILE=MDEX2S9

20... COMMENT   Vector plot of total current for Vbe=0.9v
21... PLOT.2D   BOUND  JUNC  SCALE  FILL
  ... +         TITLE="Example 2FP - Total Current Vectors"
22... VECTOR    J.TOTAL   COLOR=2
23... LABEL     LABEL="Vbe = 0.9v"  X=0.4  Y=1.55
24... LABEL     LABEL="Vce = 3.0v"

25... COMMENT   Potential contour plot for Vbe=0.9v
26... PLOT.2D   BOUND  JUNC  DEPL  SCALE  FILL
  ... +         TITLE="Example 2FP - Potential Contours"
27... CONTOUR   POTEN  MIN=-1  MAX=4  DEL=.25  COLOR=6
28... LABEL     LABEL="Vbe = 0.9v"  X=0.4  Y=1.55
29... LABEL     LABEL="Vce = 3.0v"

30... COMMENT   Plot doping and carrier concentrations for Vbe=0.7v
31... LOAD      IN.FILE=MDEX2S7

32... PLOT.1D   DOPING  Y.LOG  SYMBOL=1  COLOR=2  LINE=1
  ... +         BOT=1E10  TOP=1E20
  ... +         X.STA=3.5  X.END=3.5  Y.STA=0  Y.END=2
  ... +         TITLE="Example 2FP - Carrier & Impurity Conc."

33... PLOT.1D   ELECTR  Y.LOG  SYMBOL=2  COLOR=3  LINE=2  UNCHANGE
  ... +         X.STA=3.5  X.END=3.5  Y.STA=0  Y.END=2

34... PLOT.1D   HOLES   Y.LOG  SYMBOL=3  COLOR=4  LINE=3  UNCHANGE
  ... +         X.STA=3.5  X.END=3.5  Y.STA=0  Y.END=2

35... LABEL     LABEL="Vbe = 0.7v"  X=1.55  Y=4E12
36... LABEL     LABEL="Vce = 3.0v"
37... LABEL     LABEL="Doping"     SYMBOL=1  COLOR=2
38... LABEL     LABEL="Electrons"  SYMBOL=2  COLOR=3
39... LABEL     LABEL="Holes"      SYMBOL=3  COLOR=4
```

Figure 5-7 Post-processing results for input file *mdex2fp*

## Beta

The **EXTRACT** statement is used in line 10 to define the symbol Beta (the collector current gain). This is then used in the **PLOT.1D** statement which follows, along with the I-V log file *MDEX2FI*, to plot current gain as a function of the collector current. The results are shown in Figure 5-9.

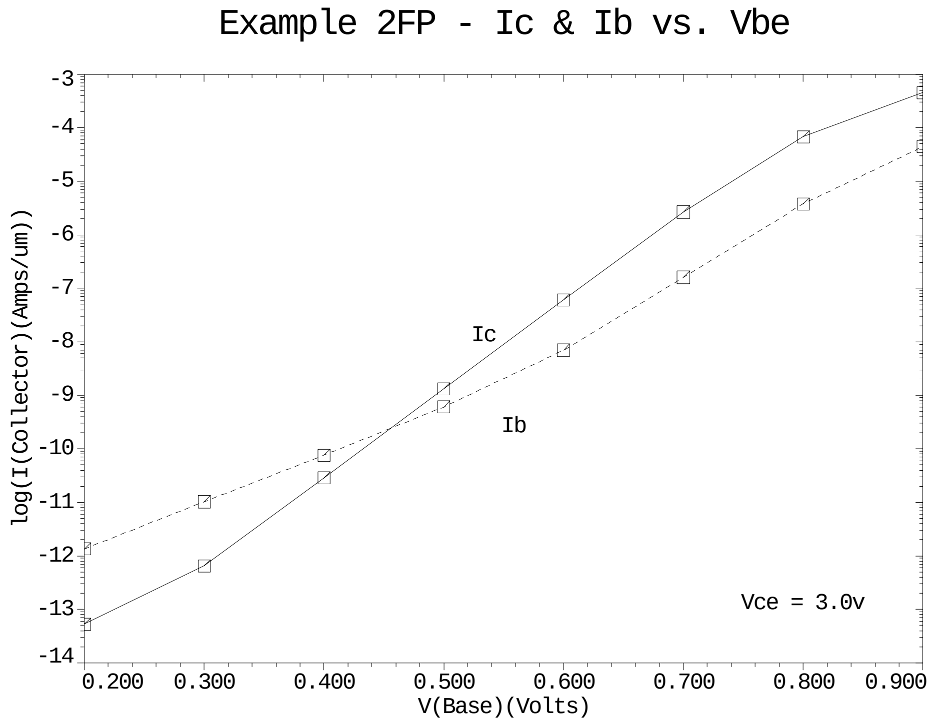


Figure 5-8 Ic and Ib vs. Vbe from **PLOT.1D** and **LABEL** at lines 4 through 8 in file *mdex2fp*, Figure 5-7

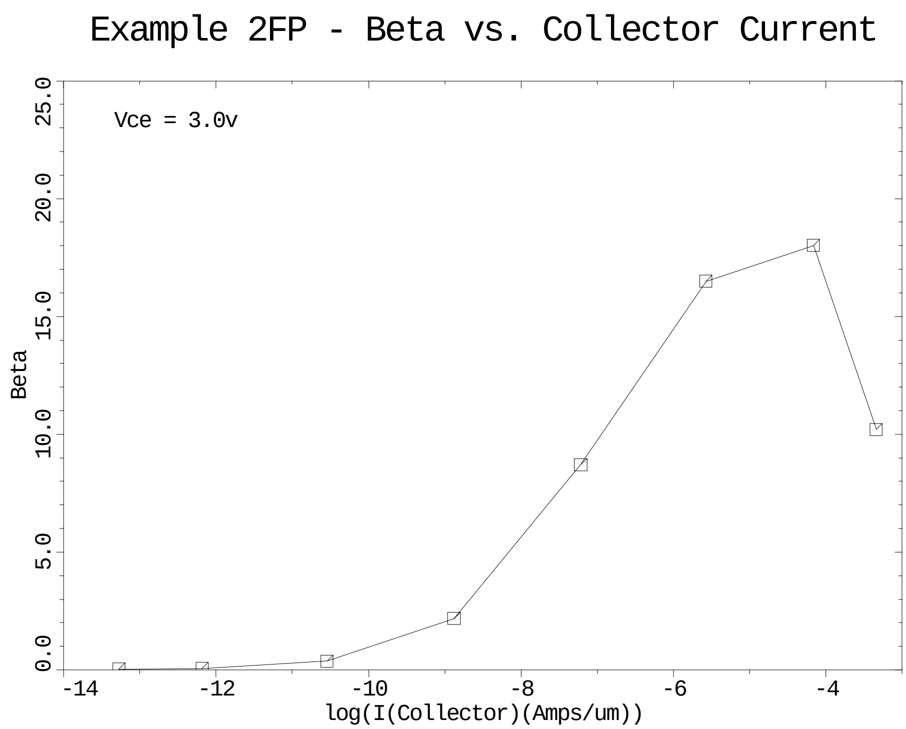


Figure 5-9 Beta vs. collector current **PLOT.1D** and **LABEL** at lines 11 through 12 in file *mdex2fp*, Figure 5-7

## Cutoff Frequency

In line 14, the **EXTRACT** statement is used in conjunction with the capacitance and conductance components obtained from the AC small-signal analysis. This to calculate an approximate expression for the cutoff frequency, Ft.

The **PLOT.1D** statement at line 15 uses this definition of Ft, along with the AC small-signal analysis data stored in the file *MDEX2FI*, to plot cutoff frequency as a function of collector current. The results are shown in Figure 5-10.

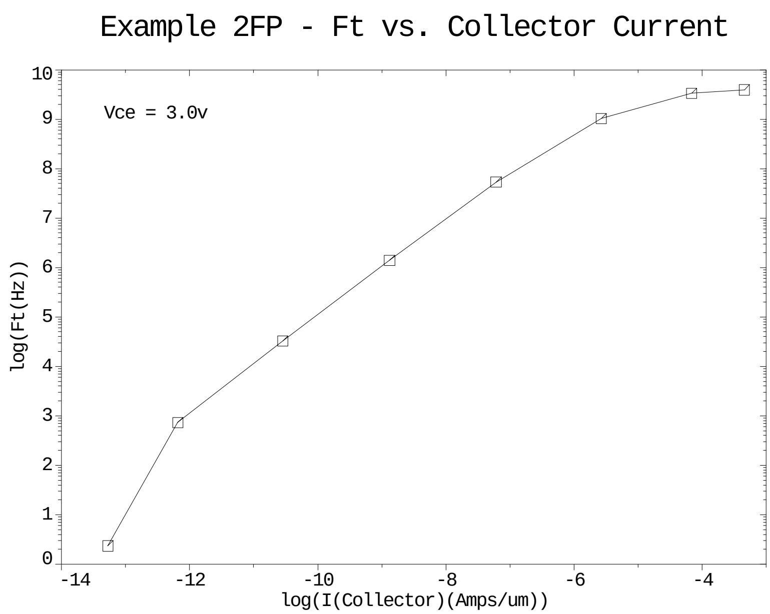


Figure 5-10 Ft vs. collector current from **PLOT.1D** and **LABEL** at lines 15 through 16 in file *mdex2fp*, Figure 5-7

## Current Vectors and Potential Contours

The **MESH** statement at line 18 reads the saved mesh and the **LOAD** statement at line 19 reads the saved solution corresponding to $V_{be}$ =0.9V. Current vectors and potential contours within the structure for this bias condition are illustrated in Figures 5-11 and 5-12.

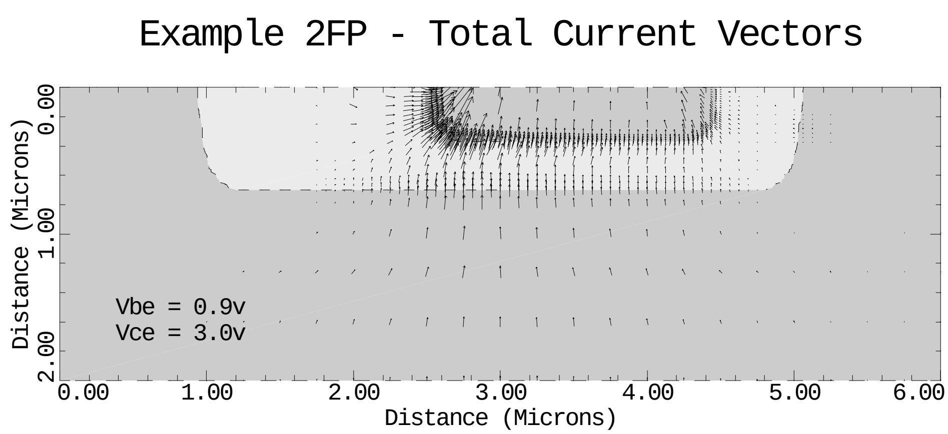


Figure 5-11 Total current vectors from **PLOT.2D**, **VECTOR**, and **LABEL** at lines 21 through 24 in file *mdex2fp*, Figure 5-7

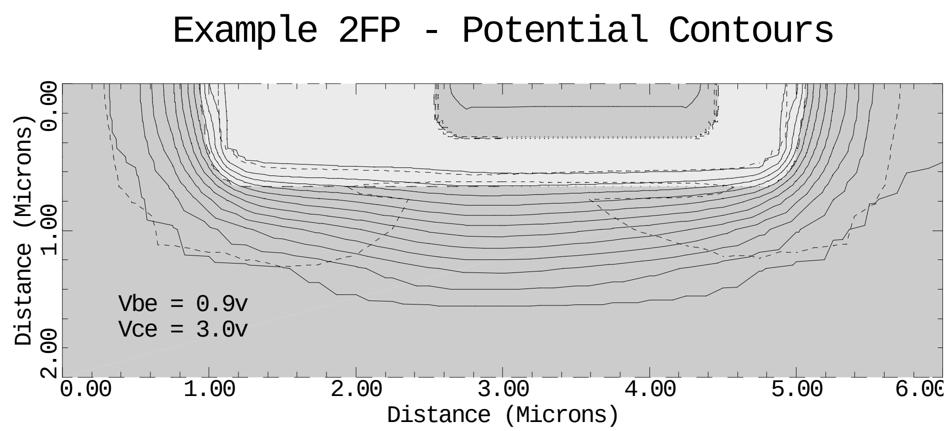


Figure 5-12 Potential contours from **PLOT.2D**, **CONTOUR**, and **LABEL** at lines 26 through 29 in file *mdex2fp*, Figure 5-7

## Impurity and Carrier Concentrations

The solution for $V_{be}$ =0.7V is read using the **LOAD** statement at line 31, and Figure 5-13 shows the impurity and carrier concentrations along a slice through the emitter for this bias.

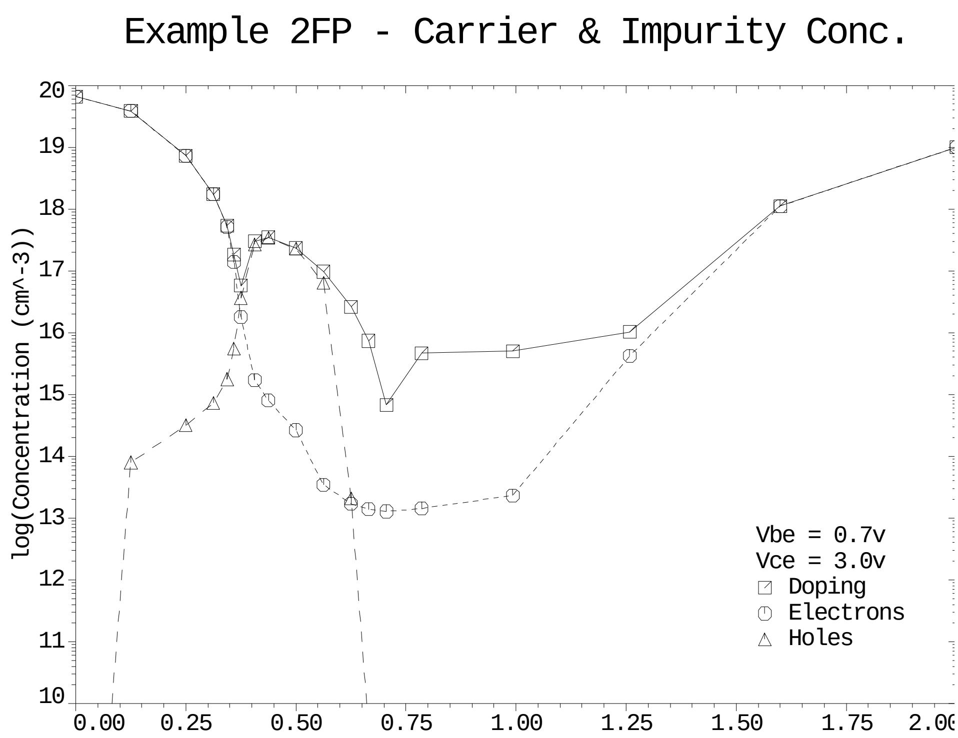


Figure 5-13 Carrier and impurity concentrations from **PLOT.1D** and **LABEL** at lines 32 through 39 in file *mdex2fp*, Figure 5-7

# Simulation with Modified Emitter Region

This section details the simulation with modified emitter region. This simulation requires numerous modifications. In this example, the emitter region of the NPN transistor considered in the previous examples is modified and the forward current characteristics are repeated. The modification is such that the emitter contact at $y$=0 is replaced by an additional 0.25 microns of silicon and the new contact location is placed at $y$=-0.25 microns.

```
  1... TITLE     Avant! MEDICI Example 2P - NPN Transistor Simulation
  2... COMMENT   Simulation with Modified Emitter Region

  3... COMMENT   Initial mesh specification
  4... MESH
  5... X.MESH    WIDTH=6.0  H1=0.250
  6... Y.MESH    Y.MIN=-0.25  Y.MAX=0.0  N.SPACES=2
  7... Y.MESH    DEPTH=0.5  H1=0.125
  8... Y.MESH    DEPTH=1.5  H1=0.125  H2=0.4

  9... COMMENT   Region definition
 10... REGION    NAME=Silicon  SILICON
 11... REGION    NAME=Oxide  OXIDE     Y.MAX=0
 12... REGION    NAME=Poly  POLYSILI  Y.MAX=0  X.MIN=2.75  X.MAX=4.25

 13... COMMENT   Electrodes
 14... ELECTR    NAME=Base  X.MIN=1.25  X.MAX=2.00  Y.MAX=0.0
 15... ELECTR    NAME=Emitter  X.MIN=2.75  X.MAX=4.25  TOP
 16... ELECTR    NAME=Collector  BOTTOM

 17... COMMENT   Specify impurity profiles
 18... PROFILE   N-TYPE  N.PEAK=5e15  UNIFORM  OUT.FILE=MDEX2DS
 19... PROFILE   P-TYPE  N.PEAK=6e17  Y.MIN=0.35  Y.CHAR=0.16
   ... +                 X.MIN=1.25  WIDTH=3.5  XY.RAT=0.75
 20... PROFILE   P-TYPE  N.PEAK=4e18  Y.MIN=0.0  Y.CHAR=0.16
   ... +                 X.MIN=1.25  WIDTH=3.5  XY.RAT=0.75
 21... PROFILE   N-TYPE  N.PEAK=7e19  Y.MIN=-0.25  DEPTH=0.25  Y.CHAR=0.17
   ... +                 X.MIN=2.75  WIDTH=1.5  XY.RAT=0.75
 22... PROFILE   N-TYPE  N.PEAK=1e19  Y.MIN=2.0  Y.CHAR=0.27

 23... COMMENT   Regrids on doping
 24... REGRID    DOPING  LOG  RATIO=3  SMOOTH=1  IN.FILE=MDEX2DS
 25... REGRID    DOPING  LOG  RATIO=3  SMOOTH=1  IN.FILE=MDEX2DS

 26... COMMENT   Extra regrid in emitter-base junction region only.
 27... REGRID    DOPING  LOG  RATIO=3  SMOOTH=1  IN.FILE=MDEX2DS
   ... +         X.MIN=2.25  X.MAX=4.75  Y.MAX=0.50  OUT.FILE=MDEX2MP

 28... PLOT.2D   GRID  SCALE  FILL
   ... +         TITLE="Example 2P - Modified Simulation Mesh"

 29... COMMENT   Modify properties of polysilicon-emitter region
 30... MOBILITY  POLYSILI  CONC=7E19  HOLE=2.3  FIRST  LAST
 31... MATERIAL  POLYSILI  TAUP0=8E-8
 32... MODEL     CONMOB  CONSRH  AUGER  BGN

 33... COMMENT   Initial solution
 34... SYMB      CARRIERS=0
 35... METHOD    ICCG  DAMPED
 36... SOLVE     V(Collector)=3.0
 37... SYMB      NEWTON  CARRIERS=2
 38... SOLVE

 39... COMMENT   Setup log files, forward bias base-emitter junction, and
   ... +         calculate the admittance matrix at 1.0 MHz
 40... LOG       OUT.FILE=MDEX2PI
 41... SOLVE     V(Base)=0.2  ELEC=Base  VSTEP=0.1  NSTEP=4
   ... +         AC.ANAL  FREQ=1E6  TERM=Base
 42... SOLVE     V(Base)=0.7  ELEC=Base  VSTEP=0.1  NSTEP=2
   ... +         AC.ANAL  FREQ=1E6  TERM=Base  OUT.FILE=MDEX2P7
```

Figure 5-14 Output of the simulation input file *mdex2p*

The mobility and lifetime of the minority carrier in this additional region are modified from their default silicon values to approximately represent this region as a material other than silicon.For example, this region may represent n+ polysilicon in a real device. Figures 5-14 and 5-15 contain the output associated with the execution of Medici for the input file *mdex2p*.

## Modification of Mesh

To include an additional 0.25 microns of emitter material without altering the rest of the structure, it is necessary to make some modifications to the input file *mdex2* shown in Figure 5-1 for creating the device structure. This is done with the following statements:

- Two additional lines of nodes are added to the top of the initial simulation mesh by including an additional **Y.MESH** statement that places the first line of nodes at $y$=-0.25 microns.
- Two additional **REGION** statements are necessary.
  - The first additional **REGION** statement defines the top 0.25 microns of the structure to be silicon dioxide.
  - The second additional **REGION** statement redefines the portion of this region that is to be part of the emitter as polysilicon.
- The base electrode is modified by replacing "**TOP**" with "**Y.MAX**=0.0" so that contact is made to the silicon.
- The **PROFILE** statement that defines the emitter doping (line 21) is modified so that the additional emitter material has a uniform n-type concentration of $7 \times 10^{19}\ \text{cm}^{-3}$.

The modified simulation mesh after three regrids on impurity concentration is shown in Figure 5-15.

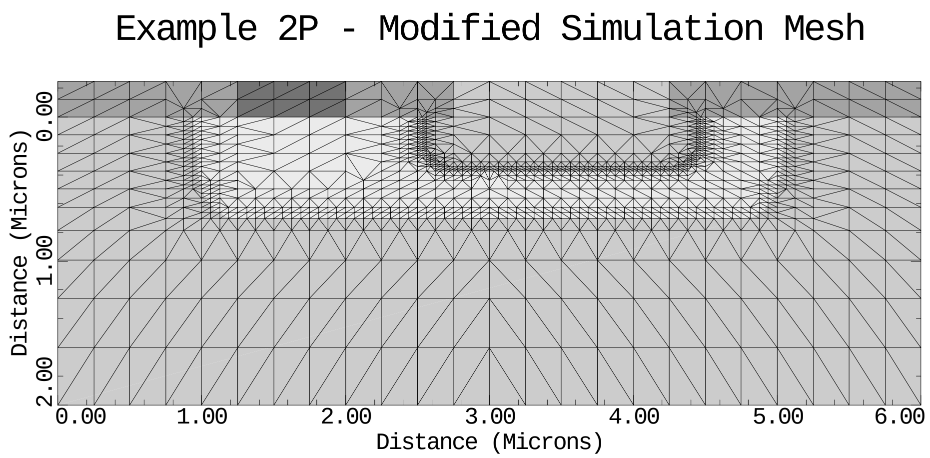


Figure 5-15 Modified simulation mesh from **PLOT.2D** at line 28 in the file *mdex2p*, Figure 5-14

## Hole Mobility and Lifetime

The minority carrier (hole) mobility in the Poly region is adjusted at line 30 by specifying an entry for the concentration-dependent hole mobility table. The parameters **FIRST** and **LAST** cause this entry to be the only value in the table for the polysilicon region. This is so that the specified hole mobility will in fact apply to any impurity concentration value in this region. The hole lifetime is also modified (line 31).

**Final Adjustments and Saves**

After making the above adjustments to the simulation structure, the forward current characteristics and AC small-signal analysis are repeated. The I-V and AC log file is saved, as well as the modified mesh and solutions for biases of $V_{be}$=0.7V, 0.8V, and 0.9V.

# Post-Processing of Device with Modified Emitter

The mesh, solution, and log files that were created and saved by the input file *mdex2p* are read by the input file *mdex2pp* for performing a post-processing analysis of the simulations results. Figures 5-16 through 5-23 contain the output associated with the execution of Medici for the input file *mdex2pp*.

## Metal Contact vs. Metal-Poly-Silicon

The input file *mdex2pp* shown in Figures 5-16 and 5-17 is similar to the input file *mdex2fp* shown in Figure 5-7. They differ in that the saved mesh, solution, and log files are read in from the simulations of the structure with the modified emitter.

```
 1... TITLE      Avant! MEDICI Example 2PP - NPN Transistor Simulation
 2... COMMENT    Post-Processing of MDEX2P Results

 3... COMMENT    Plot Ic and Ib vs. Vbe
 4... PLOT.1D    IN.FILE=MDEX2PI  Y.AXIS=I(Collector)  X.AXIS=V(Base)
  ... +          LINE=1  COLOR=2  TITLE="Example 2PP - Ic & Ib vs. Vbe"
  ... +          BOT=1E-14  TOP=1E-3  Y.LOG  POINTS
 5... PLOT.1D    IN.FILE=MDEX2PI  Y.AXIS=I(Base)  X.AXIS=V(Base)
  ... +          Y.LOG  POINTS  LINE=2  COLOR=3  UNCHANGE
 6... LABEL      LABEL="Ic"  X=.525  Y=1E-8
 7... LABEL      LABEL="Ib"  X=.550  Y=2E-10
 8... LABEL      LABEL="Vce = 3.0v"  X=.75  Y=1E-13

 9... COMMENT    Plot the current gain (Beta) vs. collector current
10... EXTRACT    NAME=Beta  EXPRESS=@I(Collector)/@I(Base)
11... PLOT.1D    IN.FILE=MDEX2PI  X.AXIS=I(Collector)  Y.AXIS=Beta
  ... +          TITLE="Example 2PP - Beta vs. Collector Current"
  ... +          BOTTOM=0.0  TOP=25  LEFT=1E-14  RIGHT=1E-3
  ... +          X.LOG  POINTS  COLOR=2
12... LABEL      LABEL="Vce = 3.0v"  X=5E-14  Y=23
```

Figure 5-16 First part of the simulation input file *mdex2pp*

The results shown in Figures 5-18 through 5-23, however are not significantly changed from those shown in Figures 5-8 through 5-13 where the emitter region was not modified. This indicates that replacing a metal contact with a metal-poly-silicon contact has a small effect on the device behavior for the structure under consideration.

You may anticipate this result by considering the diffusion length of the minority carrier holes in the quasi-neutral emitter region $y>0$. The diffusion length for holes is given by the square root of the product of the diffusion coefficient ($D_p = (KT/q)$ (hole mobility)) and the hole lifetime.

```
13... COMMENT   Plot the cutoff frequency Ft=Gcb/(2*pi*Cbb)
14... EXTRACT   NAME=Ft  UNITS=Hz
  ... +         EXPRESS="@G(Collector,Base)/(6.28*@C(Base,Base))"
15... PLOT.1D   IN.FILE=MDEX2FI  X.AXIS=I(Collector)  Y.AXIS=Ft
  ... +         TITLE="Example 2FP - Ft vs. Collector Current"
  ... +         BOTTOM=1  TOP=1E10  LEFT=1E-14  RIGHT=1E-3
  ... +         X.LOG  Y.LOG  POINTS  COLOR=2
16... LABEL     LABEL="Vce = 3.0v"  X=5E-14  Y=1E9

17... COMMENT   Read in the simulation mesh and solution for Vbe=0.9v
18... MESH      IN.FILE=MDEX2MS
19... LOAD      IN.FILE=MDEX2S9

20... COMMENT   Vector plot of total current for Vbe=0.9v
21... PLOT.2D   BOUND  JUNC  SCALE  FILL
  ... +         TITLE="Example 2FP - Total Current Vectors"
22... VECTOR    J.TOTAL   COLOR=2
23... LABEL     LABEL="Vbe = 0.9v"  X=0.4  Y=1.55
24... LABEL     LABEL="Vce = 3.0v"

25... COMMENT   Potential contour plot for Vbe=0.9v
26... PLOT.2D   BOUND  JUNC  DEPL  SCALE  FILL
  ... +         TITLE="Example 2FP - Potential Contours"
27... CONTOUR   POTEN  MIN=-1  MAX=4  DEL=.25  COLOR=6
28... LABEL     LABEL="Vbe = 0.9v"  X=0.4  Y=1.55
29... LABEL     LABEL="Vce = 3.0v"

30... COMMENT   Plot doping and carrier concentrations for Vbe=0.7v
31... LOAD      IN.FILE=MDEX2S7

32... PLOT.1D   DOPING  Y.LOG  SYMBOL=1  COLOR=2  LINE=1
  ... +         BOT=1E10  TOP=1E20
  ... +         X.STA=3.5  X.END=3.5  Y.STA=0  Y.END=2
  ... +         TITLE="Example 2FP - Carrier & Impurity Conc."

33... PLOT.1D   ELECTR  Y.LOG  SYMBOL=2  COLOR=3  LINE=2  UNCHANGE
  ... +         X.STA=3.5  X.END=3.5  Y.STA=0  Y.END=2

34... PLOT.1D   HOLES   Y.LOG  SYMBOL=3  COLOR=4  LINE=3  UNCHANGE
  ... +         X.STA=3.5  X.END=3.5  Y.STA=0  Y.END=2

35... LABEL     LABEL="Vbe = 0.7v"  X=1.55  Y=4E12
36... LABEL     LABEL="Vce = 3.0v"
37... LABEL     LABEL="Doping"     SYMBOL=1  COLOR=2
38... LABEL     LABEL="Electrons"  SYMBOL=2  COLOR=3
39... LABEL      LABEL="Holes"        SYMBOL=3   COLOR=4
```

Figure 5-17 Second part of the simulation input file *mdex2pp*

Using a concentration-dependent hole mobility value of 85 $cm^2$/V-s and a concentration dependent lifetime value of $2 \times 10^{-10}$ seconds (corresponding to an average impurity concentration of $3 \times 10^{19}\ cm^{-3}$), the hole diffusion length is found to be approximately 0.2 microns.

Since the distance from the emitter-base depletion edge to the location $y$=0 is approximately 0.34 microns, most of the excess holes recombine before reaching the modified emitter material ($y>0$). Therefore, the base current, and consequently the gain, for this device is not significantly affected by the presence of the modified emitter material.

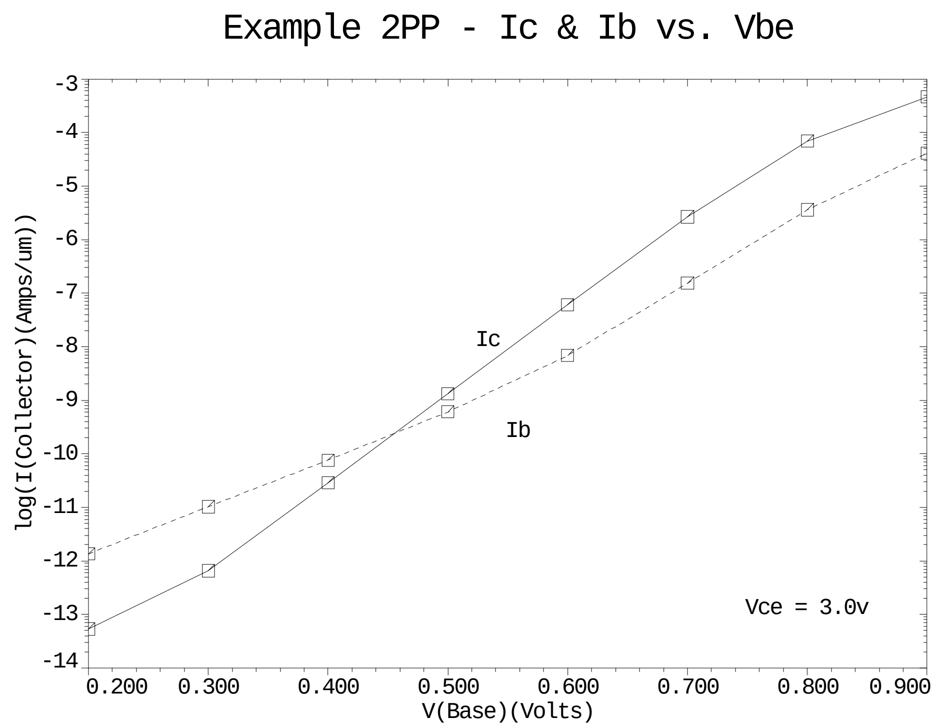


Figure 5-18 Ic and Ib vs. Vbe from **PLOT.1D** and **LABEL** at lines 4 through 8 in file *mdex2pp*, Figures 5-16 and 5-17

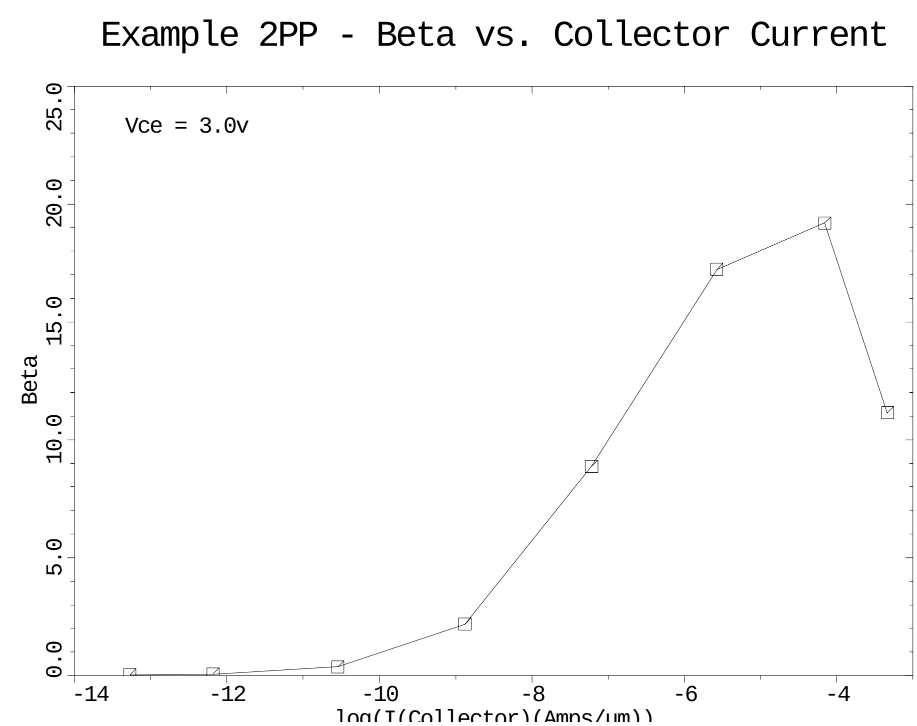


Figure 5-19 Beta vs. collector current from **PLOT.1D** and **LABEL** at lines 11 through 12 in file *mdex2pp*, Figures 5-16 and 5-17

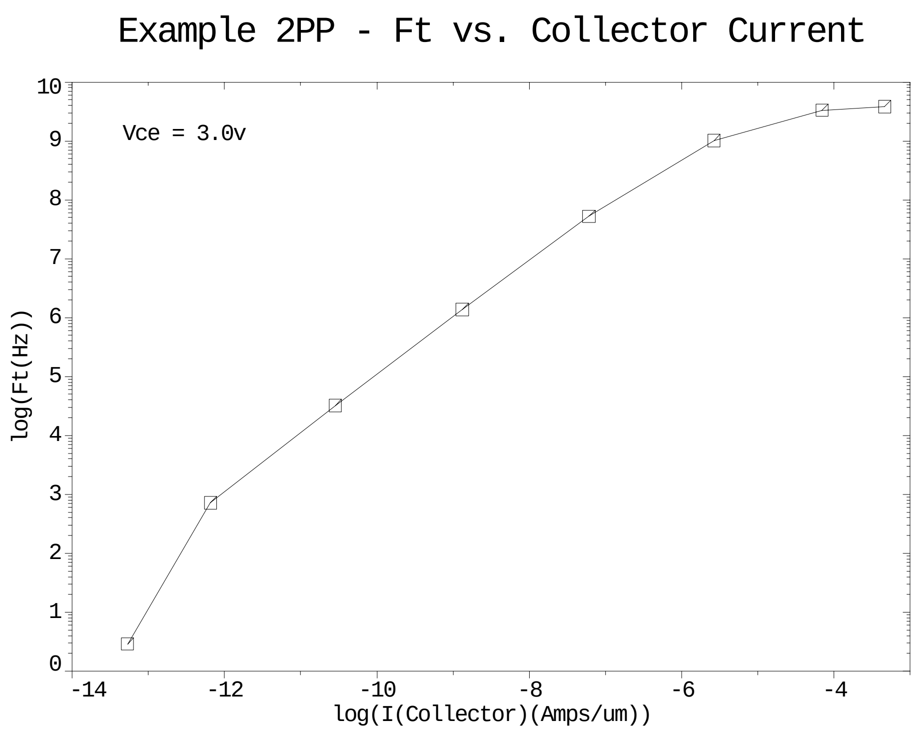


Figure 5-20 Ft vs. collector current from **PLOT.1D** and **LABEL** at lines 15 through 16 in file *mdex2pp*, Figures 5-16 and 5-17

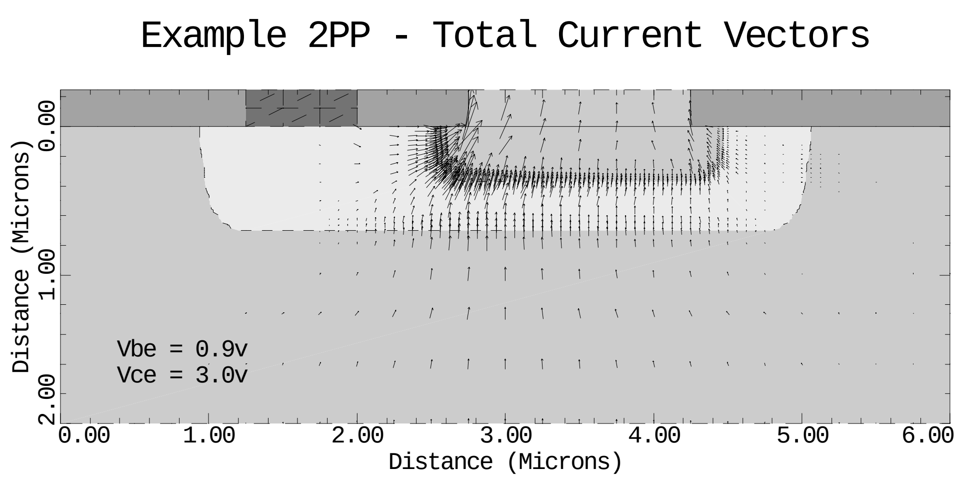


Figure 5-21 Total current vectors from **PLOT.2D**, **VECTOR**, and **LABEL** at lines 21 through 24 in file *mdex2pp*, Figures 5-16 and 5-17

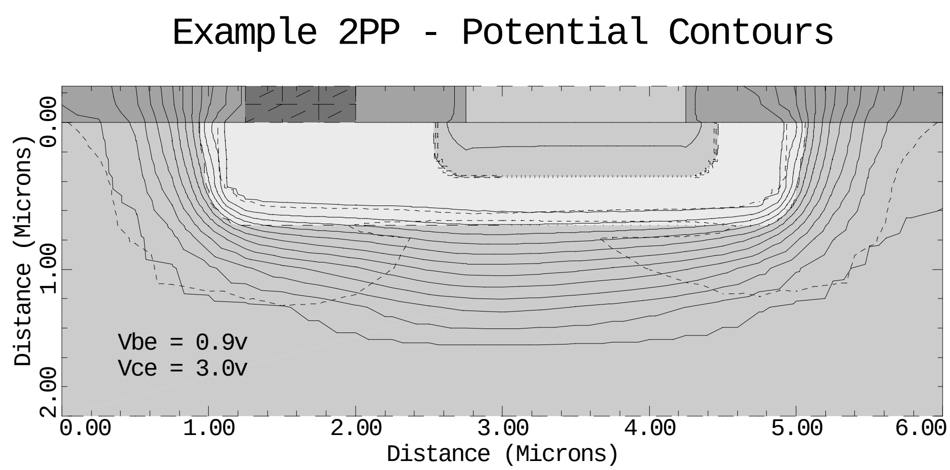


Figure 5-22 Potential contours from **PLOT.2D**, **CONTOUR**, and **LABEL** at lines 26 through 29 in file *mdex2pp*, Figures 5-16 and 5-17

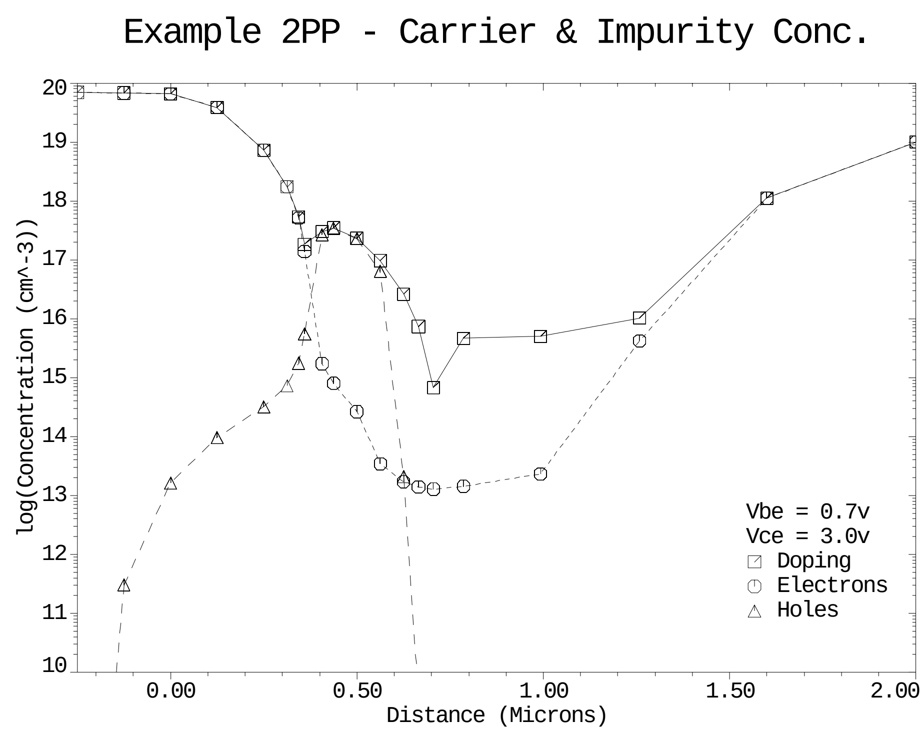


Figure 5-23 Carrier and impurity concentrations from **PLOT.1D** and **LABEL** at lines 32 through 39 in file *mdex2pp*, Figures 5-16 and 5-17

# Simulation of a One-Dimensional Bipolar Transistor

In this example, a one-dimensional simulation of a bipolar transistor is performed. One-dimensional analysis allows extremely rapid device simulation, but multi-dimensional effects like emitter current crowding or variations in the parasitic base resistance cannot be simulated.

Even with these limitations, quite accurate results can be obtained and a wide variety of physical effects can be accounted for. Some examples include:

- The Early effect and its effect on output conductance
- Base push-out and other high current effects
- Low current beta roll-off due to recombination in space charge regions
- Charge storage in the base and collector and various time-dependent effects

# Creating a One-Dimensional Device Structure

A one-dimensional device structure is created in Medici using a single column of triangular elements. This produces a structure with two columns of nodes. The resulting structure is not truly one-dimensional since there are two columns of nodes. A true one-dimensional structure would have only a single column of nodes.

***Note:***

***The results of the analysis are the same as a true one-dimensional analysis as long as there is no variation in the device structure in the direction perpendicular to the column of nodes.***

## Base Contact

The simulation of a bipolar transistor requires that a contact be made to the base of the transistor. In a one-dimensional simulation this contact is placed across the device within the base of the transistor.

A normal electrical contact cannot be used since it would force the electron and hole concentrations to their equilibrium values with the result that no current could cross the base of the transistor from the emitter to the collector.

A **`MAJORITY`** carrier contact is used for the base contact. The **`MAJORITY`** contact only sets the quasi-Fermi potential of the majority carrier to the contact potential. (A normal electrode sets both the majority and minority carrier quasi-Fermi potentials to the contact potential.)

The result is that when the **`MAJORITY`** contact is used only majority carriers can leave the base via the contact. In addition, the concentration of both majority and minority carriers can deviate from the equilibrium levels within the **`MAJORITY`** contact.

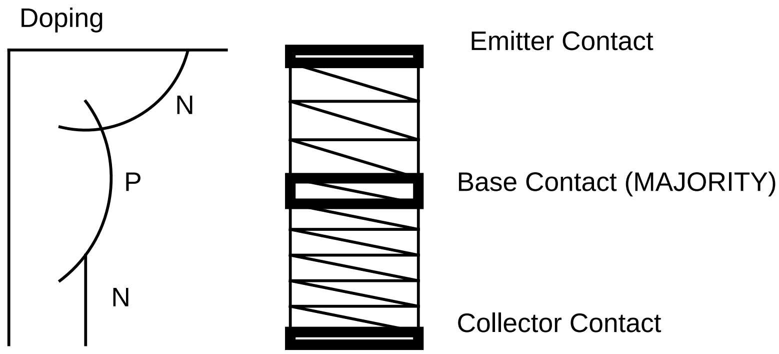


Figure 5-24 A one-dimensional bipolar transistor

## Grid

The simulation input file is shown in Figures 5-25 through 5-26. The grid is created by lines 5 through 7.

- A single column of elements is created in the *y* direction by specifying (at line 5) that **N.SPACES**=1.
- The **WIDTH** of device is set to 2 microns.

  This value was chosen to be the same as the emitter width in the previous example.

In both cases the emitter area is $2.0 \times 1.0 = 2.0$ square microns. The grid spacing for the first 0.8 microns of the device is 0.01 microns. Beyond 0.8 microns the grid is allowed to expand to a spacing of 0.04 microns. The total device is 2.0 microns high and the final grid has only 272 grid points.

## Electrodes

The electrodes are created by lines 12 through 14.

- The emitter is on top and covers the entire top edge of the device.
- The collector is on the bottom and covers the entire bottom edge of the device.
- The base covers a single row of nodes (i.e., 2 nodes) located at y=0.45 microns.

  The base is specified as a **MAJORITY** carrier contact. The **MAJORITY** contact is also be written as part of the mesh file and does not need to be re-specified when the mesh file is read.

## Doping Profiles

The doping profiles are specified at lines 16 through 20. These profiles are identical to the two-dimensional case with the exception that the *x* coordinate information (**X.MIN**, **WIDTH**) has not been specified.

No **REGRID** operations have been performed. While regrids can be used to refine the grid in the *y* direction, they also refine the grid in the *x* direction resulting in a rapid increase in the number of nodes. It is more efficient to simply specify a fine initial grid.

```
TITLE     Avant! MEDICI Example 2M - 1-D NPN Transistor Simulation
COMMENT   Grid Generation and Initial Biasing

COMMENT   Specify a rectangular mesh
MESH
X.MESH    WIDTH=2.0  N.SPACES=1
Y.MESH    DEPTH=0.8  H1=0.01  H2=0.01
Y.MESH    DEPTH=1.2  H1=0.01  H2=0.04

COMMENT   Region definition
REGION    NUM=1  SILICON

COMMENT   Electrodes
$         Use a majority carrier electrode for the base.
ELECTR    NAME=Base  Y.MIN=0.45  Y.MAX=0.45  MAJORITY
ELECTR    NAME=Emitter  TOP
ELECTR    NAME=Collector  BOTTOM

COMMENT   Specify impurity profiles
PROFILE   N-TYPE  N.PEAK=5e15  UNIFORM     OUT.FILE=MDEX2DS
PROFILE   P-TYPE  N.PEAK=6e17  Y.MIN=.35  Y.CHAR=.16
PROFILE   P-TYPE  N.PEAK=4e18  Y.MIN=0    Y.CHAR=.16
PROFILE   N-TYPE  N.PEAK=7e19  Y.MIN=0    Y.CHAR=.17
PROFILE   N-TYPE  N.PEAK=1e19  Y.MIN=2    Y.CHAR=.27

PLOT.2D   TITLE="Example 2M - 1-D Structure"  BOUND  FILL  SCALE
LABEL     LABEL="n-emitter"     X=0.87  Y=0.20
LABEL     LABEL="p-base"        X=0.91  Y=0.57
LABEL     LABEL="base contact"  X=0.87  Y=0.43  C.SI=0.2
LABEL     LABEL="n-collector"   X=0.85  Y=1.50

COMMENT   Specify some models
MODELS    CONMOB  CONSRH  AUGER  BGN

COMMENT   Use Newton's method with 2 carriers
SYMB      NEWTON  CARRIERS=2

COMMENT   Setup log file for I-V data
LOG       OUT.FILE=MDEX2MI

COMMENT   Find the base width (defined as p>1e15)
EXTRACT   NAME=w1  COND="@p>1e15"  EXPRESS="min(@w1;@y)" INIT=1000
EXTRACT   NAME=w2  COND="@p>1e15"  EXPRESS="max(@w2;@y)" INIT=-1000
EXTRACT   NAME=wb  EXPRESS="@w2-@w1"  UNITS=Microns
COMMENT   Forward bias the base-emitter junction

SOLVE     V(Collector)=3.0  V(Base)=0.2  ELEC=Base
+         VSTEP=0.05  NSTEP=9  AC.ANAL  TERM=Base  FREQ=1E6
SOLVE     V(Base)=0.70  OUT.FILE=MDE2MS7
+         AC.ANAL  TERM=Base  FREQ=1E6
SOLVE     V(Base)=0.75  ELEC=Base  VSTEP=0.05  NSTEP=3
+         AC.ANAL  TERM=Base  FREQ=1E6
```

Figure 5-25 First part of the simulation input file *mdex2m*

## Solutions

The remainder of the input file is very much like the files *mdex2f* and *mdex2fp* presented in the previous examples.

- The base voltage is ramped from 0.2V to 0.9V. Since this one-dimensional example runs significantly faster than its two-dimensional counterpart, more bias points have been requested.
- AC small-signal analysis is used to calculate the transconductance "gm" and the total base capacitance. These are used to estimate the cutoff frequency "Ft".

```
40... COMMENT   Plot Ic and Ib vs. Vbe
41... 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"
42... PLOT.1D   IN.FILE=MDEX2MI  Y.AXIS=I(Base)  X.AXIS=V(Base)
  ... +         Y.LOG  POINTS  LINE=2  COLOR=3  UNCHANGE
43... LABEL     LABEL="Vce = 3.0v"
44... LABEL     LABEL="Ic"  X=.525  Y=1.5E-8
45... LABEL     LABEL="Ib"  X=.550  Y=2.0E-10

46... COMMENT   Plot the current gain (Beta) vs. collector current
47... EXTRACT   Name=Beta  EXPRESS=@I(Collector)/@I(Base)
48... PLOT.1D   IN.FILE=MDEX2MI  X.AXIS=I(Collector)  Y.AXIS=Beta
  ... +         X.LOG  POINTS  COLOR=2
  ... +         TITLE="Example 2M - Beta vs. Collector Current"
49... LABEL     LABEL="Vce = 3.0v"

50... COMMENT   Plot cutoff frequency (Ft) vs collector current
51... COMMENT   Ft = Gcb/(2*pi*Cbb)
52... EXTRACT   NAME=Ft  UNITS=Hz
  ... +         EXPRESS="@G(Collector,Base)/(6.28*@C(Base,Base))"
53... PLOT.1D   X.AX=I(Collector)   Y.AX=Ft
  ... +         TITLE="Example 2M - Ft vs. Collector Current"
  ... +         X.LOG  Y.LOG  POINTS  COLOR=2  IN.FILE=MDEX2MI
  ... +         BOTTOM=1  TOP=1E10  LEFT=1E-14  RIGHT=1E-3
54... LABEL     LABEL="Vce = 3.0v"


55... COMMENT   Plot doping and carrier concentrations for Vbe=0.7v
56... LOAD      IN.FILE=MDE2MS7

57... PLOT.1D   DOPING  Y.LOG  SYMBOL=1  COLOR=2  LINE=1
  ... +         BOT=1E10  TOP=1E20
  ... +         X.STA=0  X.END=0  Y.STA=0  Y.END=2  C.SIZE=0.15
  ... +         TITLE="Example 2M - Carrier & Impurity Conc."

58... PLOT.1D   ELECTR  Y.LOG  SYMBOL=2  COLOR=3  LINE=2  UNCHANGE
  ... +         X.STA=0  X.END=0  Y.STA=0  Y.END=2  C.SIZE=0.15

59... PLOT.1D   HOLES   Y.LOG  SYMBOL=3  COLOR=4  LINE=3  UNCHANGE
  ... +         X.STA=0  X.END=0  Y.STA=0  Y.END=2  C.SIZE=0.15

60... LABEL     LABEL="Vbe = 0.7v"  X=1.55  Y=4E12
61... LABEL     LABEL="Vce = 3.0v"
62... LABEL     LABEL="Doping"     SYMBOL=1  COLOR=2
63... LABEL     LABEL="Electrons"  SYMBOL=2  COLOR=3
64... LABEL     LABEL="Holes"      SYMBOL=3  COLOR=4

65... COMMENT   Plot base width vs collector current
66... PLOT.1D   X.AXIS=I(Collector)  Y.AXIS=wb  X.LOG
  ... +         IN.FILE=MDEX2MI  COLOR=2  POINTS
  ... +         TITLE="Example 2M - Electrical Base Width"
67... LABEL     LABEL="Vce = 3.0v"
```

Figure 5-26 Second part of the simulation input file *mdex2m*

## Graphical Output

It is interesting to compare the results, shown in Figures 5-27 through 5-31 with the results of the two-dimensional analysis shown in Figures 5-8 through 5-13. The results with one- and two-dimensional analyses are very similar in this particular example.

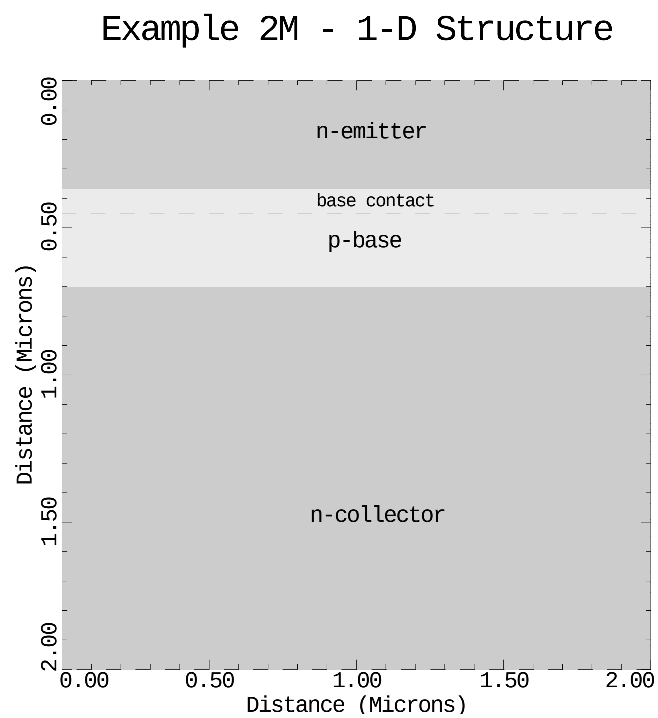


Figure 5-27 Device structure from **PLOT.2D** and **LABEL** at lines 21 through 25 in file *mdex2m*, Figure 5-25

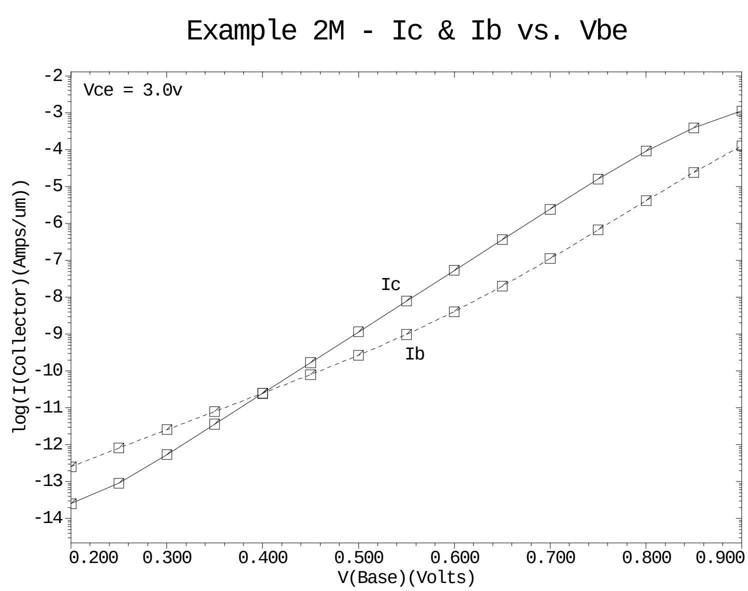


Figure 5-28 Base and collector current as a function of the base-emitter voltage from **PLOT.1D** and **LABEL** at lines 41 through 45 of the input file *mdex2m*

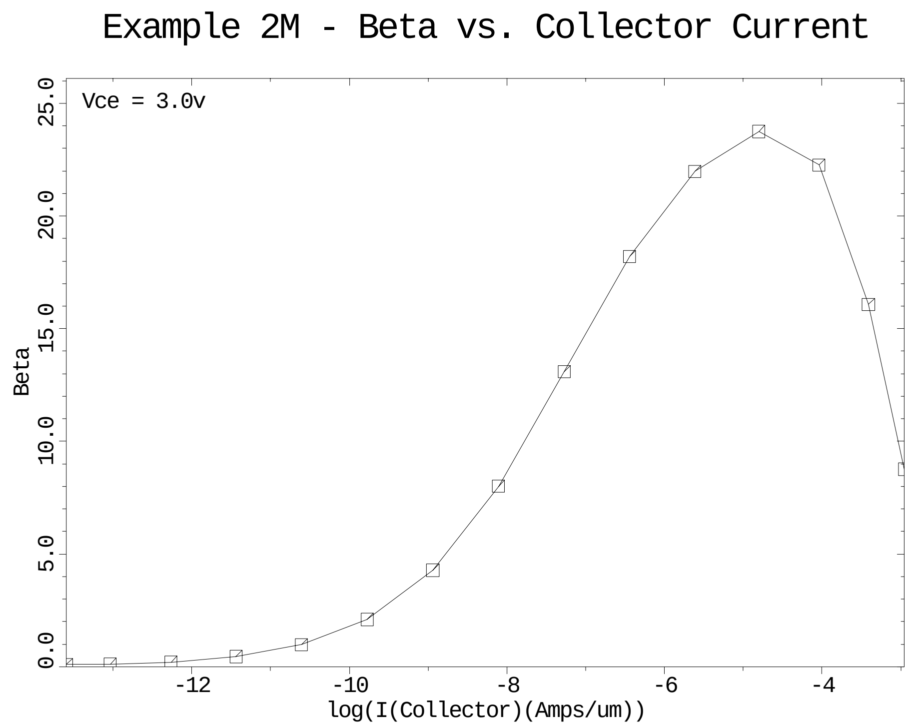


Figure 5-29 Current gain versus collector current from **EXTRACT**, **PLOT.1D**, and **LABEL** at lines 47 through 49 in file *mdex2m*

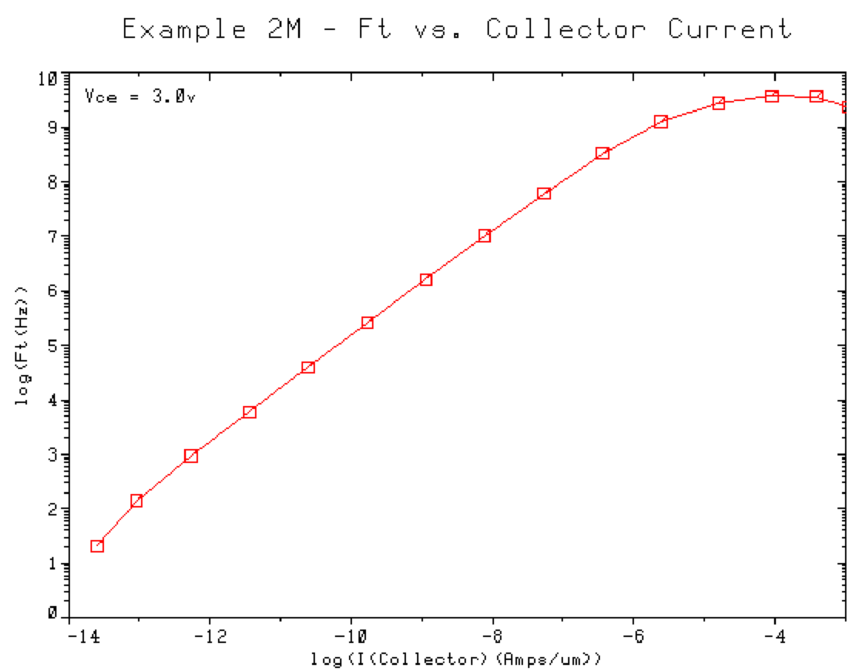


Figure 5-30 Cutoff frequency versus collector current from **EXTRACT**, **PLOT.1D**, and **LABEL** at lines 52 through 54 in *mdex2m*

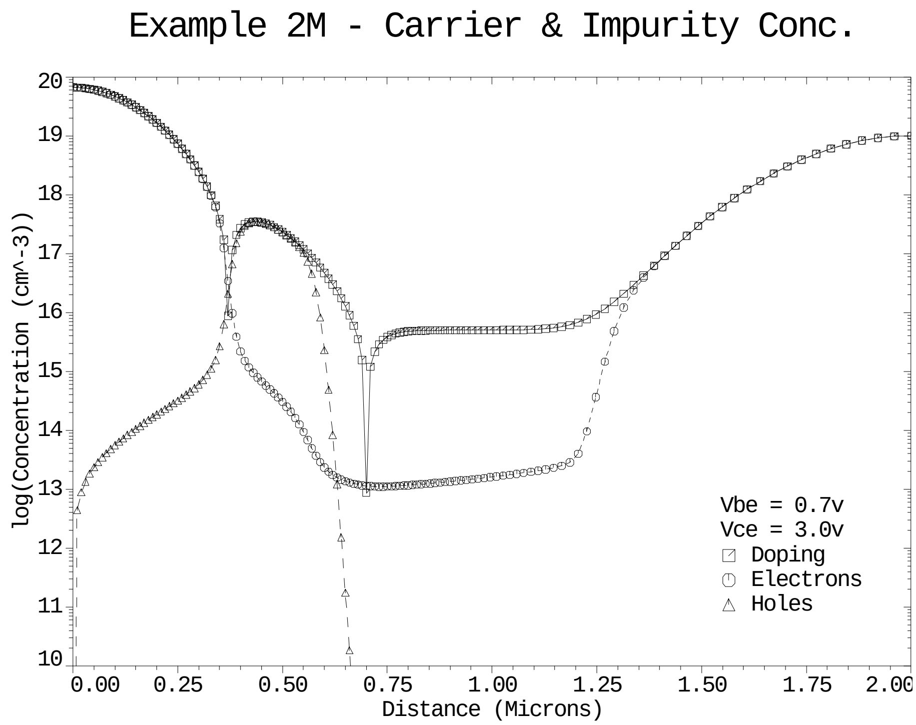


Figure 5-31 Electron, hole and doping concentrations from **PLOT.1D** and **LABEL** at lines 57 through 64 in file *mdex2m*