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# BIPOLE3 TUTORIAL GUIDE

for BIPOLE3 Version 5.3

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This Tutorial Guide contains worked examples for the Bipole3 software. The relevant files are included with the distribution software. This guide should be used in conjunction with the Bipole3 Reference Manual.

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## 1. INTRODUCTION

This tutorial is aimed at new users of the Bipole3 software. It takes simple examples of discrete and integrated bipolar transistors (and MOSFETs) and shows the new user how to build input files to simulate new devices. It illustrates how to inspect the terminal electrical characteristics of the device and also how to study the internal physical behaviour. A section is devoted to illustrating a typical BJT design scenario where it is required to design a new improved transistor from an existing design. This tutorial covers double and single base contact integrated BJTs, oxide isolation, buried layer design, SiGe HBT design, basic MOSFET simulation. Simplicity is a key objective of the tutorial and reference is made where relevant to the comprehensive Bipole3 Users Manual for further information.

## 2.INPUT FILE CONSTRUCTION AND DEFAULT VALUES

### 2.1 Input file format

Bipole3 requires the construction of an input file as shown below (Users Manual sect 2.1). This file will in general contain details of the device (including vertical impurity profiles and lateral mask layout), the physical model parameters, numerical control parameters.

```
&TITLE
  tex0: Input file with all default parameter values
&PARAM
# comment lines
&END
```

The parameters are entered using a text editor and saved in this example as TEX0.BIP. If no parameters are defined, the default values are used in the simulation. The default device has junction depths: emitter-base **XJ1**=0.6E-04 (0.6 um), base-collector **XJ2**=1.0E-04 (1.0 um) (Users Manual sect 4.2.1); the collector epitaxial layer doping is **NEPI** = 1.5E15 (1.5x10<sup>15</sup> cm<sup>-3</sup>) (Users Manual sect 4.1) with a thickness (above the heavy doped substrate) **XEND** = 10.E-04 (10 um), an emitter stripe width **ELEM** = 4.E-04 (4 um) and a total emitter stripe length **B** = 1.0 (1.0 cm) (Users Manual sect 5.1.1). Note that cm and cm<sup>-3</sup> are used throughout for input values.

In the UNIX or non GUI PC version the simulation is performed by typing:

```
bip tex0
```

For the PC GUI version use the GUI execute option or when in Command Prompt type:

```
bip tex0.bip
```

The results of the simulation may be examined in the lst output file using a text editor. In the UNIX version the output graphs are available using the BIPGRAPH post processor. In the PC GUI version the output graphs are available within the GUI. In either case it is often convenient to keep the graph window open and perform separate simulations using the Command Prompt.

### 2.2 Physical model parameters

A full range of physical models is available for mobility versus doping and temperature, carrier velocity versus electric field and temperature, band-gap, band-gap narrowing, carrier recombination lifetimes. The default values are adequate for all preliminary design, with the possible exception of low current emitter-base recombination (see below).

### 2.3 Numerical control parameters

There are a number of control parameters which determine both bias ranges and numerical precision for the simulation. We will introduce only the most basic and useful of these parameters in this tutorial.

## 3. BJT EXAMPLES

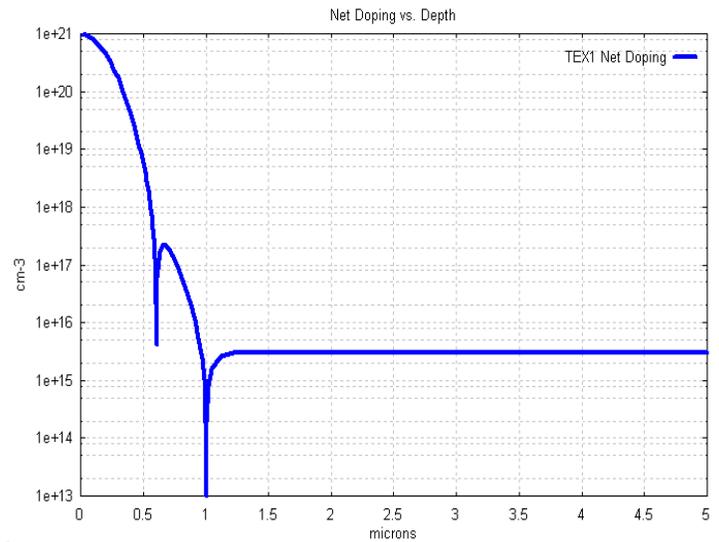
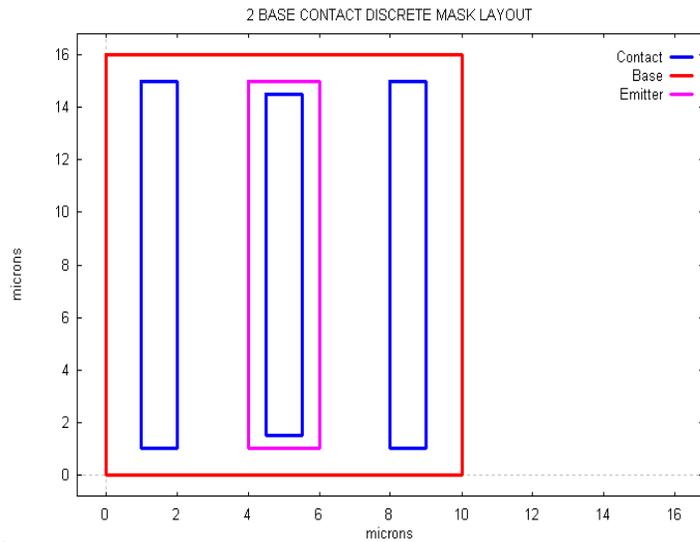
### 3.1 A simple discrete BJT

A few input parameters have been added to the default file to define a discrete BJT structure as a file tex1.bip. Specifically, we have added the epitaxial layer doping **NEPI** and thickness **XEND** and mask parameters **ELEM** (emitter diffusion width), **B** (emitter stripe length), **ECB** (base contact width), **ESB** (base contact to emitter diffusion spacing), **BPB** (length of base diffusion).

```

&TITLE
tex1: Largely default parameters
&PARAM
# Epitaxial layer data
  NEPI=3.e15,XEND=5.E-04,
#Emitter mask data
  ELEM=2.E-04,B=14.E-04,ECB=1.e-04,
# Base mask data
  ELPB=10.E-04,BPB=16e-04,ESB=2.E-04,
  mask=1,
# parameter to reduce Ic current increase step
  crlat=1.2,
&END

```



The above mask layout is obtained by typing:

```
plmask tex1
```

Alternatively, in the PC GUI version, the mask plots are available in the graph menu.

The impurity profile plot is available in both versions from the GRAPH menu. It corresponds to the default junction depths described above with a simple double gaussian profile, but with the new **NEPI** and **XEND** values. Note that additional parameters may be used to define completely a substrate with an up-diffusion into the epitaxial layer as explained in Users Manual sect 4.1

### 3.1.1 Examining lst file output

The tex1.lst file may be examined with a text editor or using Bipgraph (type bgwin to start this graphics post processor). The details of the output are given in the Users Manual sect 9. Of some particular interest are the following quantities:

```

RB-OHM/SQ RE-OHM/SQ RBE-OHM/SQ
1.55E+02 3.73E+00 7.90E+03

```

These are the sheet resistance values of the emitter, base and base under emitter diffusions. They are particularly useful: (a) as a verification that the impurity profile has been correctly defined (RBE-OHM/SQ is particularly important since it relates directly to base resistance and to current gain); (b) to compare with technology data on a real device; (c) to compare with technology data from a process simulator. The actual values of base resistance RBB and extrinsic base resistance are then printed.

```
RBB = 1.18E+02 RBEXT = 1.03E+01
```

Then follow the values of zero bias emitter-base and base-collector junction capacitances per unit of junction perimeter and per unit

junction area; the final line contains the total values of each capacitance. These results are obtained from numerical solution of Poisson's equation for the various regions and are valuable for comparing with experimental data and/or when attempting to improve the device design by reducing the capacitance values.

CJE(PERIPHERY)= 1.83E-11 F/CM. CJE(PLANE)= 1.10E-07 F/SQ.CM, FOR VBE=0

CJC(PERIPHERY)= 2.84E-12 F/CM. CJC(PLANE)= 1.69E-08 F/SQ.CM, FOR VCB=0

ZERO BIAS CAPACITANCES: CJE0 = 8.96E-14 CJCO = 4.18E-14

The Vertical Simulation table gives results of the simulation for the specified value of collector-base bias voltage **VCIN**, for a range of base-emitter bias conditions. Of particular interest are the values of delay times TEM (emitter), TSCL (base-collector space charge layer), TBASE (base transit time) and the value of the quasi-neutral base width WB.

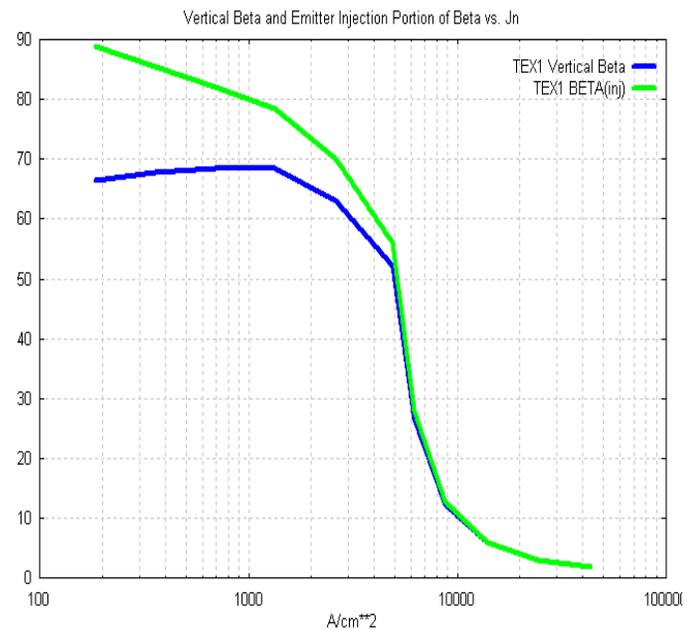
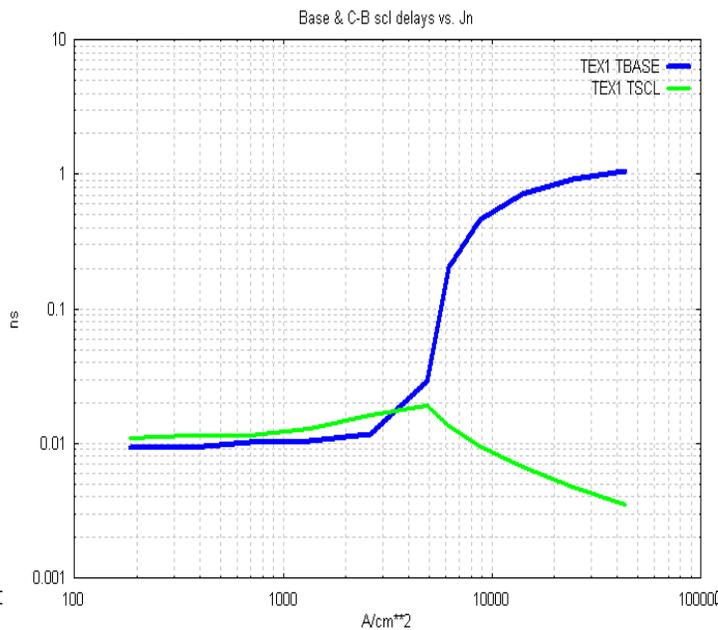
VERTICAL SIMULATION (1-D) RESULTS: VCIN = 10.00

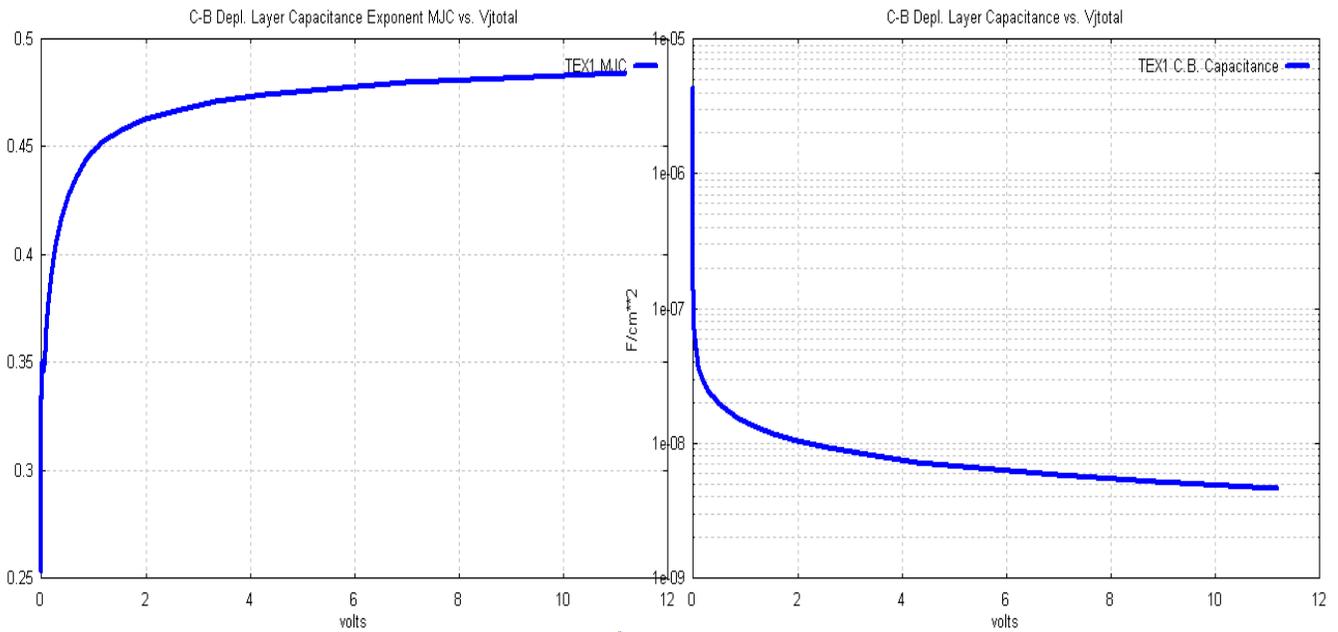
NJ	JN	BETA E	VBE	TRE	TEM	TSCL	FTOT	WB
NJ	JP	BETA T	M	TQBE	TBASE	TRC	FTMAX	VCB
1	1.84E+02	8.88E+01	7.20E-01	3.28E-11	1.02E-11	1.09E-11	1.92E+09	1.59E-05
1	-2.07E+00	6.66E+01	1.00E+00	1.80E-11	9.36E-12	1.62E-12	4.96E+09	1.06E+01

The final two tables contain details of the terminal characteristics (which are best studied with the Bipgraph menus) and a useful summary of these values for d.c. bias corresponding to : (a) low current, (b) peak current gain, (c) peak  $f_t$ .

### 3.1.2 Examining simulation results using graphics plots

Of probably more interest are the large number of graphics plots obtainable using Bipgraph. The Impurity Profile Menu may be used to study the various profiles, useful when fitting to experimental or process simulation data. The Vertical Analysis Results vs Bias Menu contains plots of various quantities vs vertical current density  $J_n$ , such as: vertical current gain vs current density  $J_n$ , delay times vs  $J_n$ ,  $J_n$  and  $J_b$  Gummel plots vs  $V_{BE}$ . Shown below are plots vs  $J_n$  of (a) base delay time and base-collector space charge layer delay time; (b) vertical beta and emitter injection limited beta.

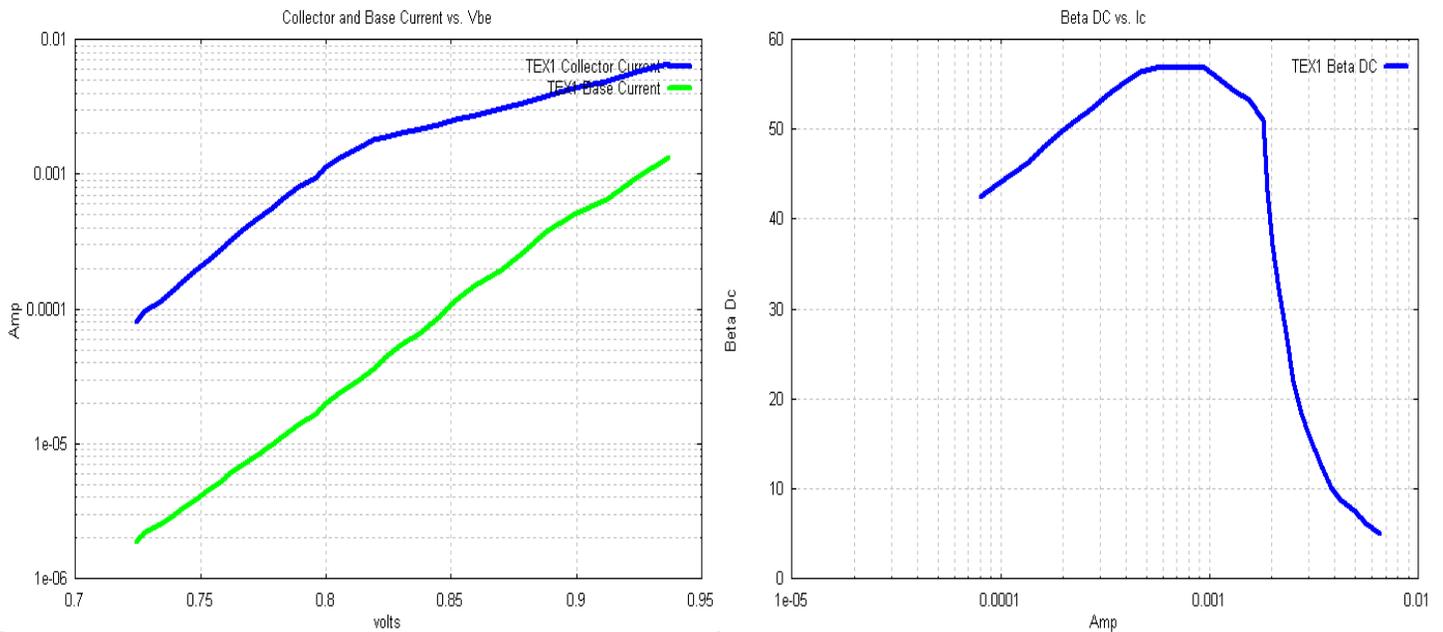




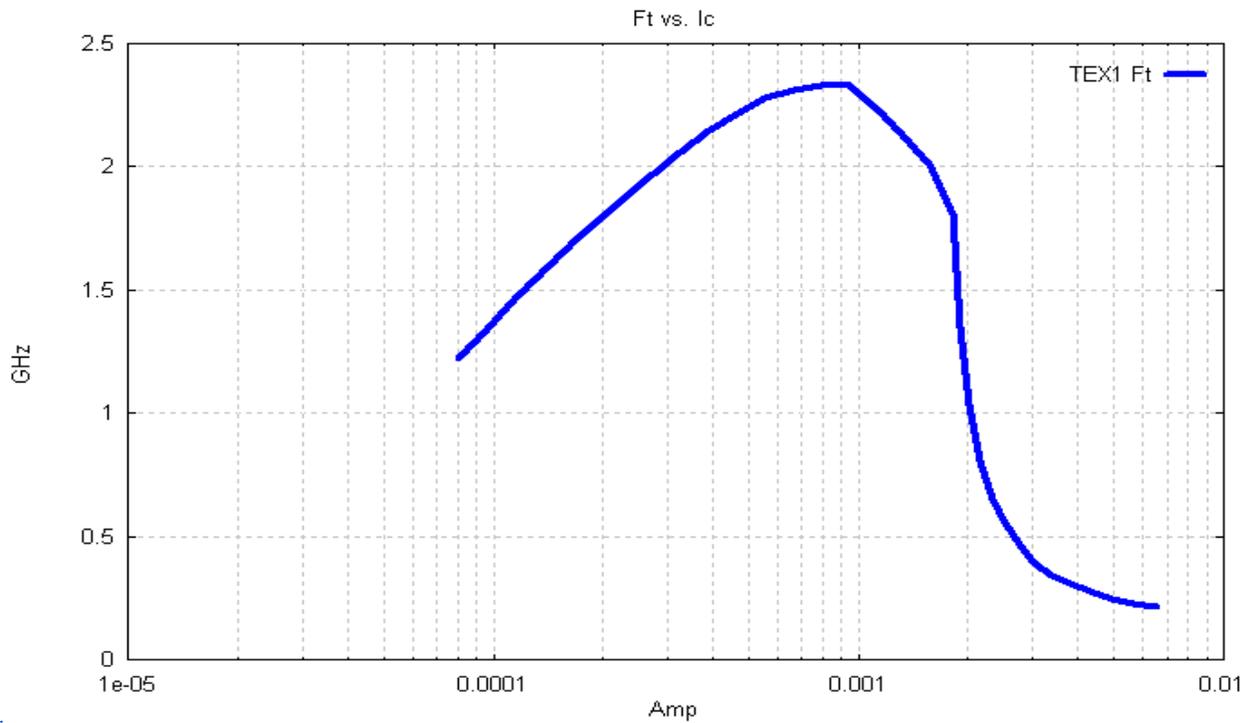
The depletion layer capacitances per unit area may also be plotted vs total junction voltage as shown above.

The MJC capacitance vs bias exponent is available as a separate plot as shown versus total junction voltage and may be observed to vary from the value of 1/3 for forward bias (i.e. towards zero total junction voltage) to almost 1/2 for reverse bias.

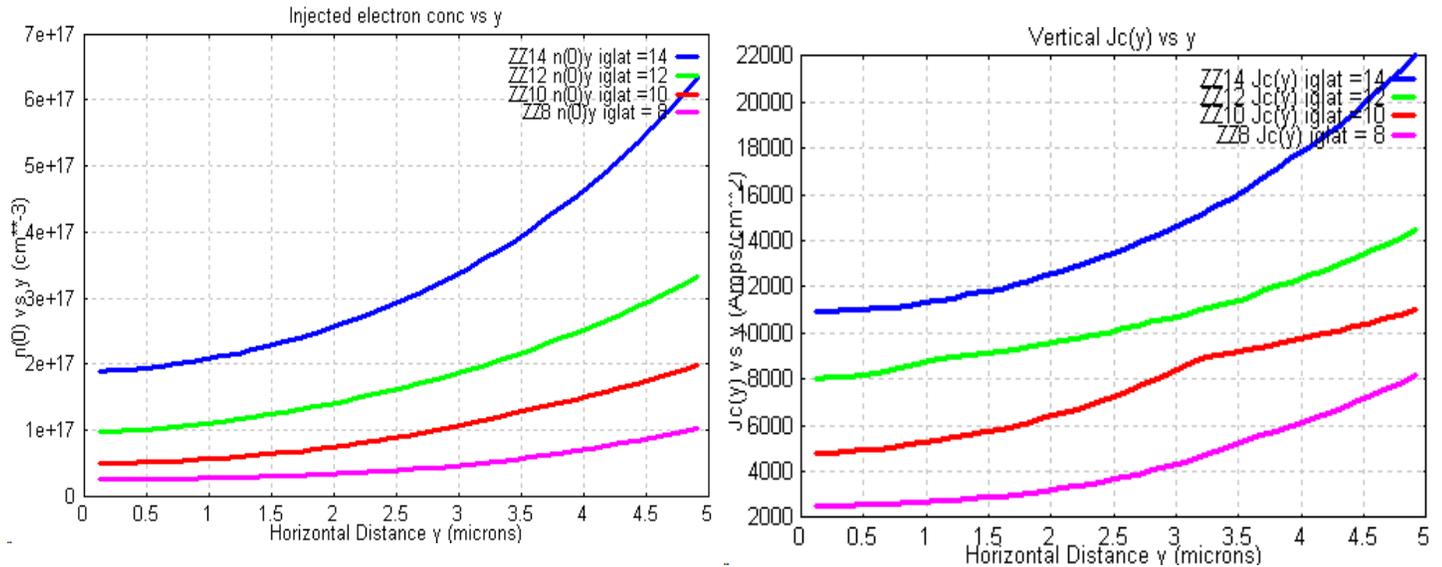
The Terminal Characteristics Menu provides the electrical characteristics of the complete device. Shown below are the Gummel plots for  $I_C$  and  $I_B$  versus  $V_{BE}$  and the plot of d.c.gain versus  $I_C$ . Note that log or linear plots may be selected from the Bipgraph menu.



Perhaps the most important terminal characteristic,  $f_t$  versus  $I_C$ . It should be noted that this is obtained from a rigorous small signal simulation at each bias point assuming a frequency in the 6 dB fall-off region between the current cut-off  $f$  and  $f_t$  frequencies.



Other graph menus are available using the Bipgraph interactive menu. For example, variables related to internal lateral potential difference in the active base region may be observed by specifying **IGLAT** equal to the  $n^{\text{th}}$  value of  $I_C$  in the Lateral Simulation table in the .lst file. For the TEX1 transistor with **ELEM** = 10E-04 (in order to highlight the lateral potential difference) we add **IGLAT** = 8, 10, 12, 14 to this file making ZZ8, ZZ10, ZZ12, ZZ14 bip files to generate the following plots:



These variations are particularly significant for large area power BJT structures.

### 3.1.3 Avalanche multiplication and breakdown voltage simulation

Of crucial importance in any real BJT design is the value of avalanche breakdown voltage for the collector-base junction and also the  $BV_{ceo}$  breakdown voltage. These are directly available from the numerical simulations by specifying a value for the input parameter **ION**. By adding **ION** = 1 in the tex1.bip file some additional information appears in the output lst file and additional plots are available. On the first page of the lst file, the following lines appear:

VBR = 9.95E+01 +/- 5.%, X = 4.98E-04 IONIZ. INTEGRAL: PLANE JUNCTION 2

VBR = 5.29E+01 +/- 1.%, X = 4.36E-04 IONIZ. INTEGRAL: SIDEWALL JUNCTION 2

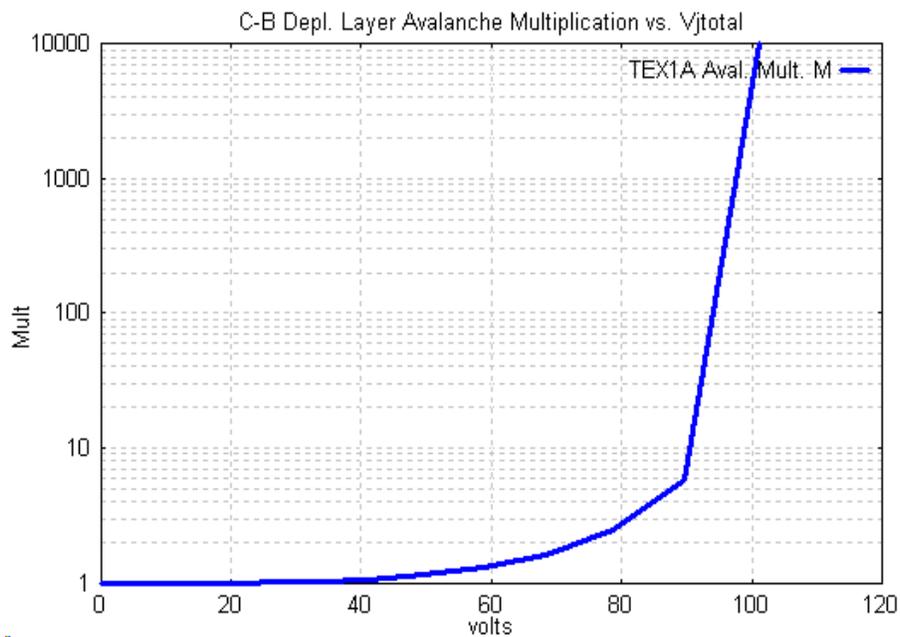
These are the values of c-b breakdown voltage for the plane and peripheral regions respectively. The peripheral breakdown value will ultimately limit the operating bias.

At the end of the lst file the following additional line now appears.

BVceo = 3.3E+01 volt; Figure of Merit: BVceo\*f<sub>t</sub> = 7.66E+01 GHz

This gives the BVceo value and also the useful figure of merit - the product of peak f<sub>t</sub> and BVceo.

The additional graph using **ION=2** consists of plots of multiplication coefficient 'M' and 'M-1'. Shown below is an example. Note that smoother curves may be obtained by reducing the value of the input step size parameter **RA** (from 1.2 to 1.1) as explained in the Users Manual sect 7.1.



Several models exist for impact ionization coefficients as described in Users Manual sect 7.3

In sect 3.6 of this Tutorial Guide, we discuss Breakdown simulation using a Non Equilibrium Transport model for shallow junction devices.

### 3.1.4 Automated mask layout

There are two options to be mentioned with reference to discrete BJTs using the **IC** parameter.

#### 3.1.4.1 One dimensional BJT using **IC = -1**

A quasi one dimensional BJT (a vertical slice) may be simulated using **IC = -1**. This may be useful to determine only impurity profile related electrical performance; it may also be used to compare results with other 1D simulator results. In Bipole3, setting **IC = -1** sets the emitter width **ELEM** to 0.1 um and the total emitter length **B** to 10 um, i.e. an emitter area of 1 um<sup>2</sup>. File tex-1.bip illustrates this case.

```

&TITLE
tex-1: Quasi one dimensional simulation using IC = -1
&PARAM
# Epitaxial layer data
  NEPI=3.e15,XEND=5.E-04,
# quasi 1D simulation
  ic=-1,mask=1,
&END

```

### 3.1.4.2 Fixed layout design rule discrete BJT, IC= -10

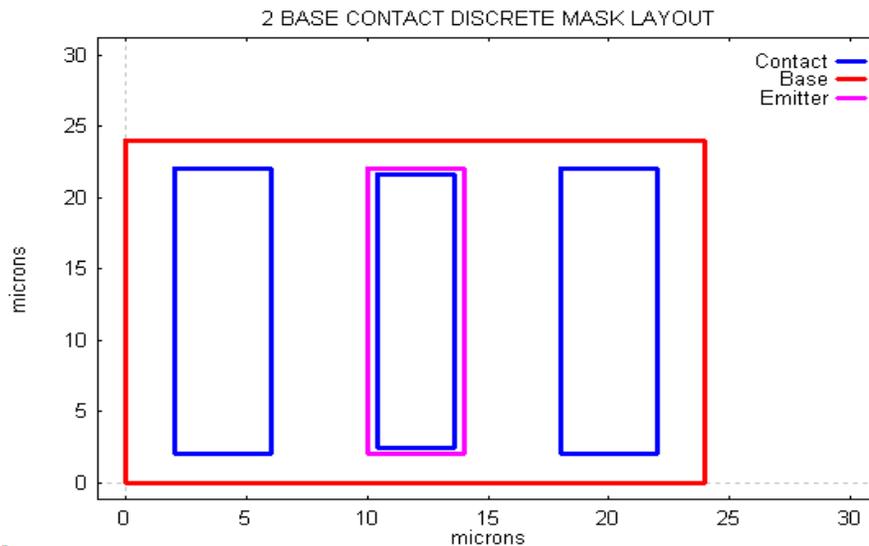
Using **IC** = -10, and specifying only the emitter width **ELEM** and length **B**, generates a BJT with automatic selection of the remaining mask dimensions. This can save time at the preliminary design stage. File tex-10.bip illustrates this case.

```

&TITLE
tex-10: Largely default parameters using internal design rules IC = -10
&PARAM
# Epitaxial layer data
  NEPI=3.e15,XEND=5.E-04,
# quasi 1D simulation
  ic=-10,mask=1,elem=4.e-04,b=20.e-04,
  vbemin=0.7,
&END

```

The mask layout (obtained by typing: plmask filename) is shown below



### 3.2 Integrated BJT using minimum extra input parameters

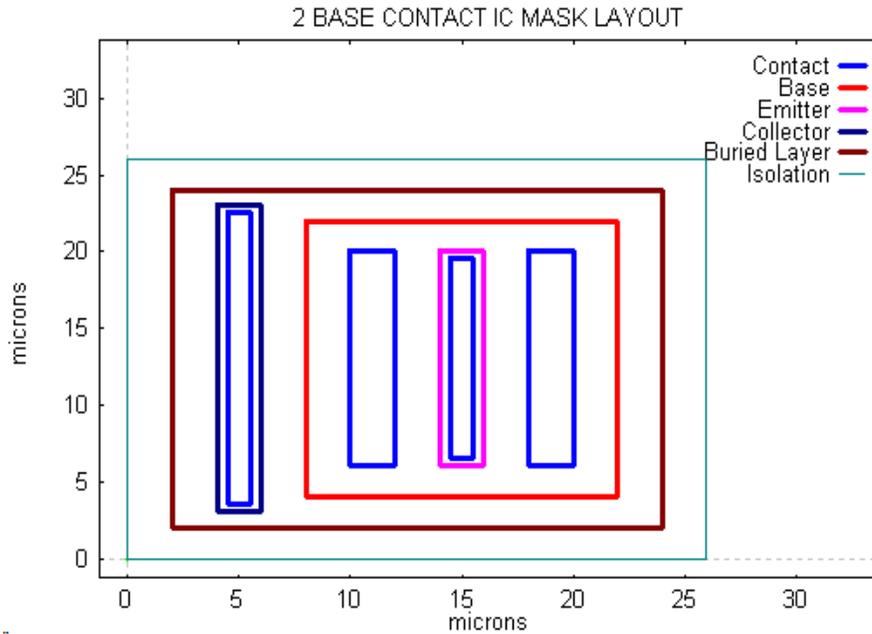
The additional key parameters required to simulate an integrated BJT, i.e. a transistor made on an epitaxial layer on a lightly doped P-substrate are as follows:

- **IC** (flag to select IC layout),
- substrate doping level,
- buried layer profile and mask parameters,
- P<sup>+</sup> isolation profile and mask parameters
- collector contact details

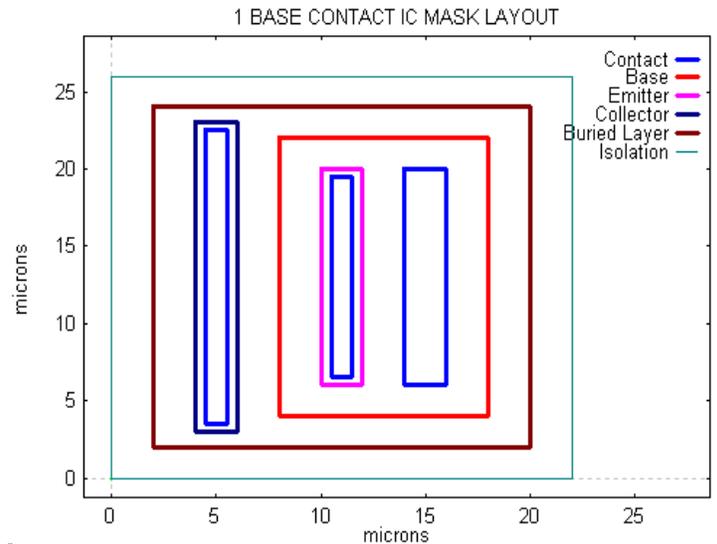
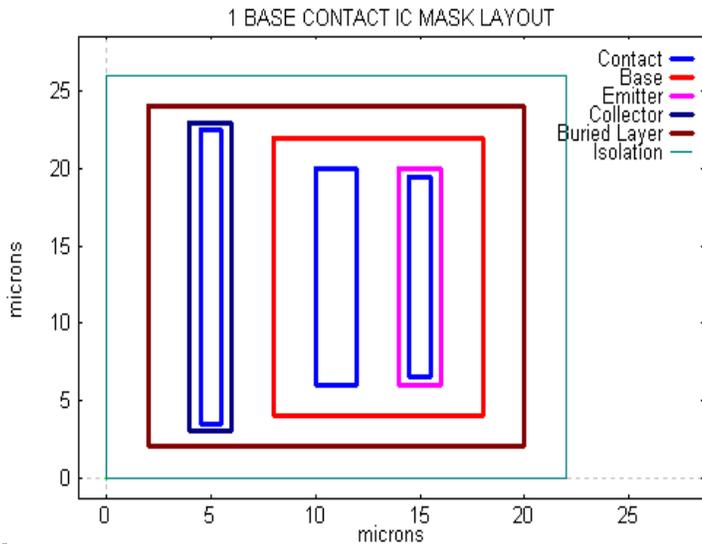
For a complete definition of a double base contact IC transistor, **IC=2** must be specified, together with all the extra mask dimensions for

the buried layer, isolation and collector contact regions as described in Users Manual sect 5.2. (at least 7 extra mask parameters).

The simplest way of starting the simulation is to use the option **IC=20**, in which case the user does not need to specify the additional mask dimensions. These are selected automatically based on the emitter and base mask dimensions. This is a convenient starting point. For the **TEX2A.BIP** file this yields the following mask layout (obtained from the Bipgraph mask menu).



To simulate the case of a single base contact IC transistor, specify **IC=10**, **TEX2B.bip**. This yields the following mask layouts. The second layout is obtained by adding the parameter **LOCAT=1** which locates the base contact to the far side of the collector - file **TEX2BL.BIP**.



It is frequently useful to be able to use the mask values from the above files to alter some of the values in a separate file using **IC=1** or **IC=2** which provides complete flexibility in specifying mask dimensions. The complete set is written in the **.lst** file and may be copied to a separate bip file for use with **IC=1** or **IC=2**.

To simulate an integrated BJT it is necessary to define a few extra parameters related to the impurity profiles.

**TEPI** The thickness of the epitaxial layer measured from the silicon surface to the P substrate

**XEND** The depth at which the simulation stops

**NPSUB** P<sup>-</sup> substrate doping level (default value 0.5E15)

The simplest simulation conditions use the same values for **TEPI** and **XEND**.

We shall use **TEPI**=3.E-04,**XEND**=3.E-04 in the input file tex2.bip.

It is also necessary to define the P<sup>+</sup> isolation and N<sup>+</sup> sinker impurity profile parameters (or at least to ensure that the default values are 'reasonable'). These are both defined by quasi gaussian functions as described in Users Manual sect 4.3.2, 4.3.3.

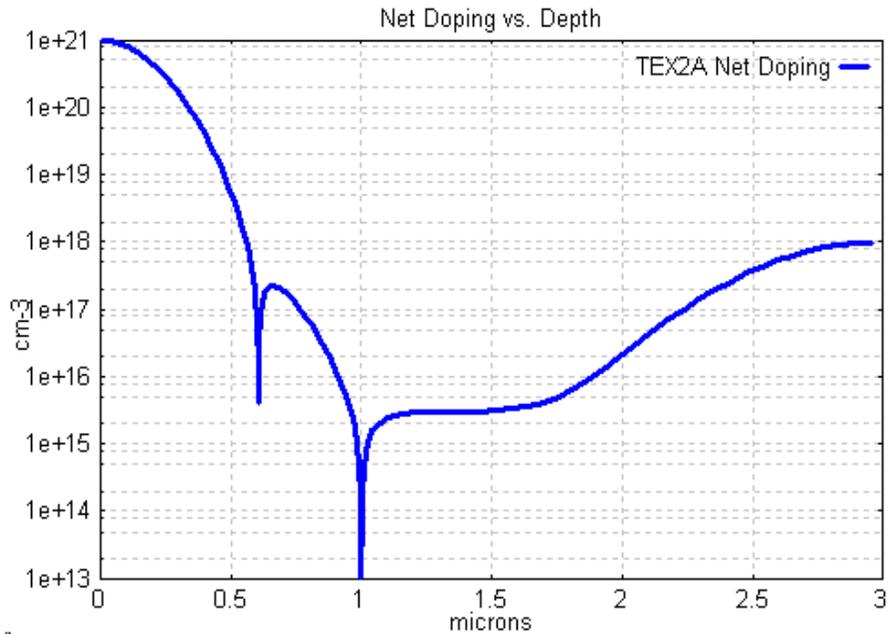
**NCOL** peak (surface) concentration of collector sinker diffusion/implant (1.E18)

**XNCOL** characteristic length of the sinker gaussian diffusion (1.E-04)

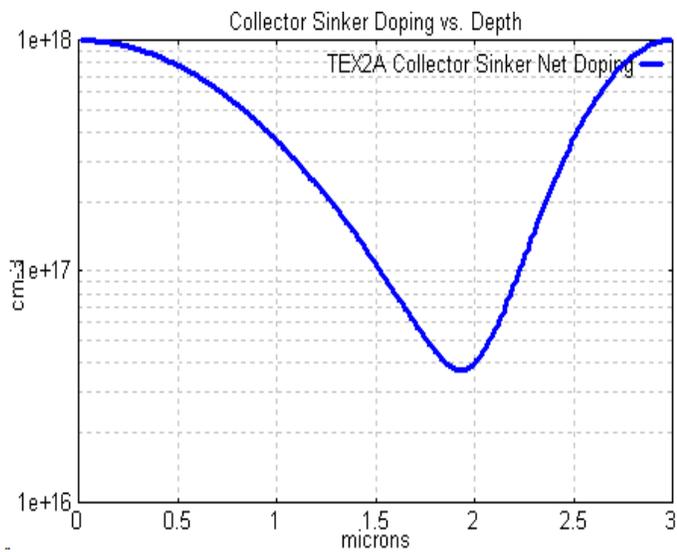
**NPWAL** peak (surface) concentration of P<sup>+</sup> isolation diffusion (1.E20)

**XPW** characteristic length of the isolation gaussian diffusion (2.E-04)

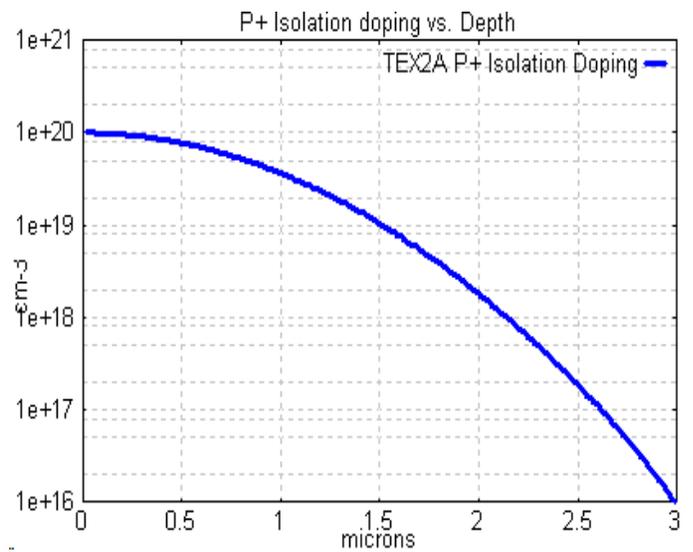
These values are compatible with the above parameters so we need not specify them in the tex2.bip file. The results of executing the tex2.bip simulation may be observed in the Bipgraph plots. Below are shown the impurity profiles in the active region followed by the collector sinker and isolation regions.



Active region impurity profile

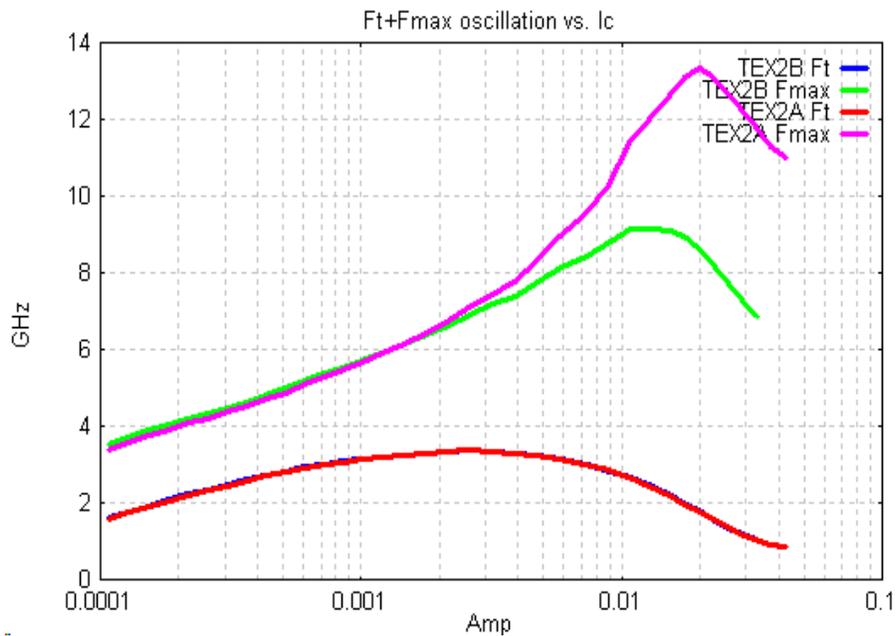


Collector sinker profile

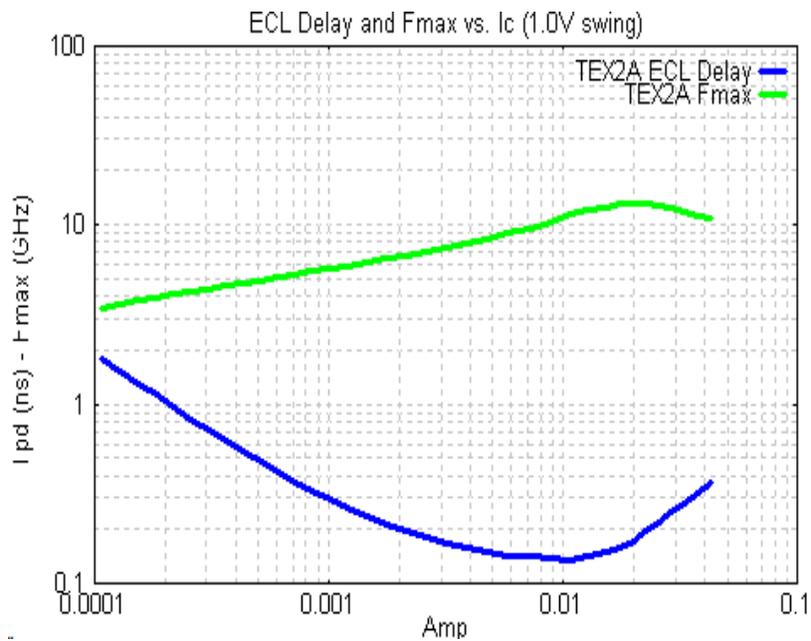


P<sup>+</sup> isolation profile

The terminal characteristics of these two transistors are very similar, except for the maximum oscillation frequency  $f_{\text{maxosc}}$  shown below. This is significantly different for the two base contact device because of the lower base resistance.



Of interest is the circuit performance of a BJT. The ECL delay time is extracted during simulations and available from the Bipgraph menu "ECL Delay Time Characteristics". Shown below is the plot for TEX2 showing delay time and  $f_{\text{maxosc}}$  vs  $I_C$  which illustrate the fact that a BJT designed to optimise  $f_{\text{maxosc}}$  also tends to approximately minimise ECL delay time.



### 3.3 Polysilicon emitter integrated BJT with oxide isolation

#### 3.3.1 Input file and related graph output

This section illustrates a polysilicon emitter BJT with oxide isolation. It also includes SPICE parameter generation. The input file TEX3.bip is as follows:

```
&TITLE
  TEX3 polysilicon emitter BJT with oxide isolation
&PARAM
# 1) polysilicon emitter data
  IPOLY=3,DELTA=7.,WPOL=.15E-04,
# 2) integrated device parameters
  IC=1,IPLUS=1,IEWAL=2,IBWAL=2,ICWAL=0,
  REXTSQ=375.,xpw=.85e-04,
# 3) impurity profile data
  XJ1=.18E-4,NE1=1.5E20,NXE1=6,XJ2=.35E-04,NB1=0.8E19,NXB1=4,
# 4) epi layer, buried layer
  NEPI=1.6E16, XSUB=.1E-04,NSUBO=3.E19,nbur=3,
  tepi=1.0e-04,xbl2=.7e-04, XEND=4.0E-04,
# 5) mask data
  B=5.E-4,ELEM=5E-4,BPB=5E-4,ELPB=11E-4,ESB=2E-4,ECB=3E-4
  ELEN=8E-4,ELCN=0.5E-4,BNS=7E-4,BPS=12E-4,ELNS=20E-4,ELPS=25E-4
  BPC=6E-4,ELC=5E-4,ESBX=2.0E-4,
  esbx=1.e-04, mask=1,
# 6) miscellaneous data
  vcin=2.0,vbemin=.5,
# 7) recombination/lifetime data
  TAUDE=10.E-09,PEE=1.5,XFS=5.E-04,
# 8) source resistance for noise figure
  rs=1000
# 9) avalanche multiplication for b-c junction
  ion=2,
# C-S junction contour plot
  look=99
&END
```

The following describes the input file using the numbered comment sections.

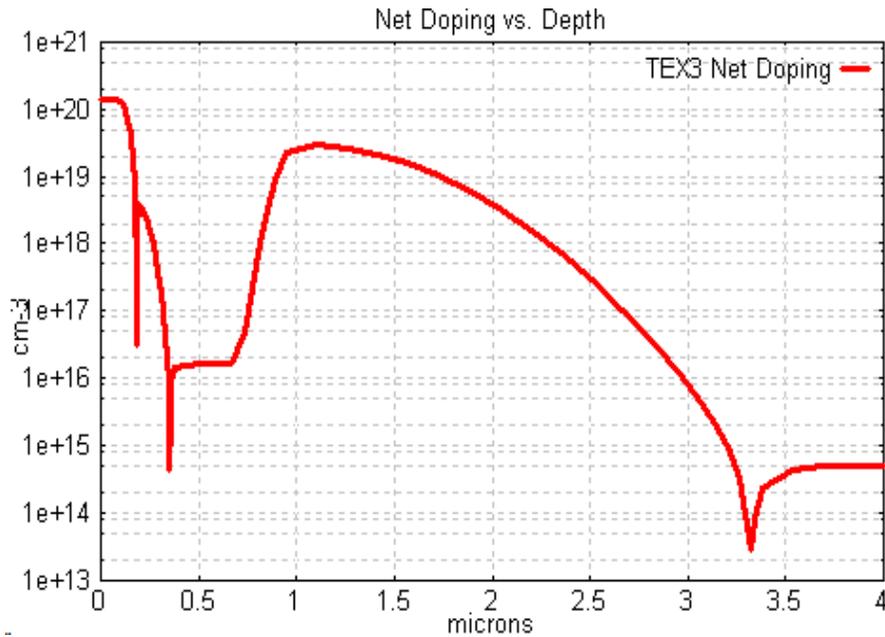
1) The polysilicon emitter option is selected using the **IPOLY** parameter. **WPOL** is the polysilicon thickness above the silicon surface; **DELTA** is the thin interfacial oxide thickness. Other parameters, such as the polysilicon doping level **NPOL** (1.E20) are given in the Reference Manual sect 7.3.

2) Here the device is defined to be a single base contact layout; **IEWAL**, **IBWAL**, **ICWAL** define the walled oxide as per Reference

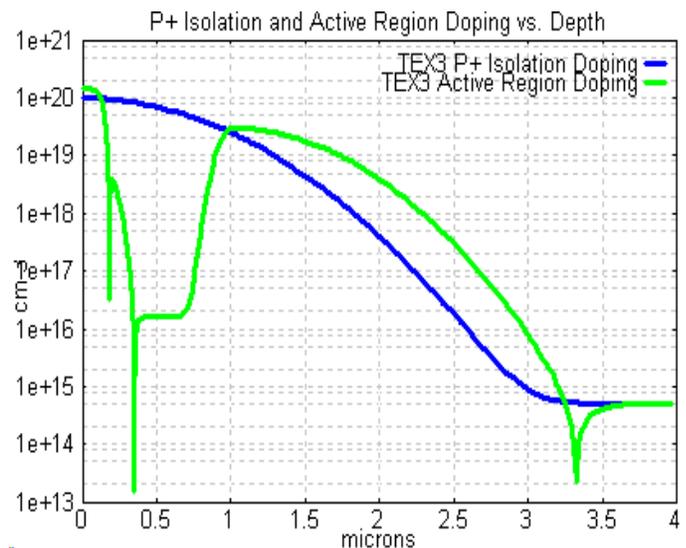
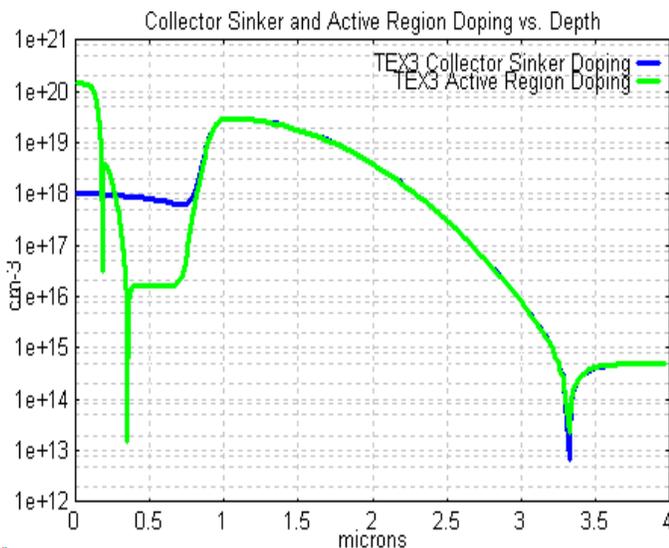
Manual sect. 7.1.2. **IPLUS** defines an extrinsic base with sheet resistance **REXTSQ** ending at a distance **ESBX** (5).

3) These lines define the impurity profile using the simplest method of specifying the two junction depths **XJ1**, **XJ2** and the surface concentrations of donors **NE1**, acceptors **NB1**. The quasi gaussian exponents are set to **NXE1=6**, **NXB1=4** (instead of values of 2 for ideal gaussians) to represent approximations to distributions obtained using a process simulator.

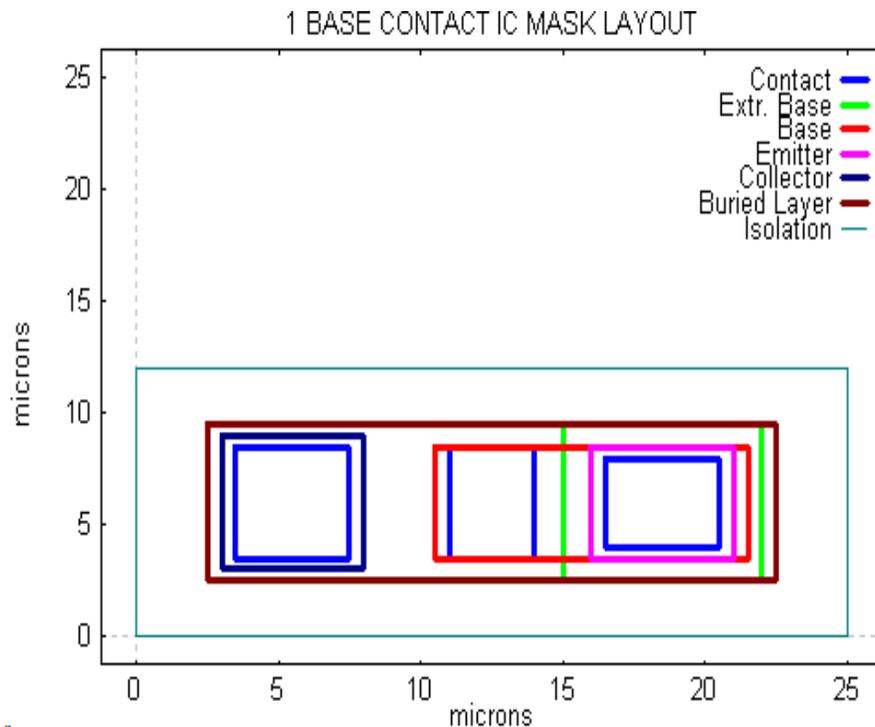
4) The epitaxial layer doping **NEPI** is  $1.6E16$ , the buried layer has a peak doping **NSUBO** =  $3.E19$  with an up-diffusion characteristic length **XSUB** =  $0.1E-04$ . **XEND** defines the depth at which the simulation stops. **TEPI** is the epitaxial layer thickness (from silicon surface to P<sup>-</sup> substrate) and **XBL2** is the characteristic length of the diffusion of the buried layer to the substrate. These parameters are defined in Reference Manual sect. 6.3.2 as is the parameter **NBUR** for which we here use the recommended value of 3. The resulting impurity profile from the Graphics View is shown below.



The impurity profile in the collector sinker and P<sup>+</sup> isolation regions are shown below (superimposed on the active region profile). These use default values (Reference Manual sects. 6.3.2 and 6.3.3) which are suitable for this transistor. It is worth while noting that these are often not critical in most BJTs, since they only partially determine the parasitic collector resistance and the sidewall component of collector-substrate capacitance.



5) The given mask dimensions are used to generate the following mask layout (type: plmask tex3).



6) **VCIN** the collector-base bias voltage and **VBEMIN** is the lowest value of  $V_{BE}$  used in the simulation.

7) All the physical model parameters may be altered from their default values given in Reference Manual Sect. 4. In many cases the default data is adequate. The exceptions are related to parameters which are strongly process dependent - mainly related to recombination in the emitter-base junction. For this device the values of **TAUDE**, **PEE** (bulk e-b recombination) and **XFS** (surface recombination) which determine low current gain fall-off have been defined as per Reference Manual Sect. 4.6.

8) The value of **RS** is the source resistance for noise figure extraction.

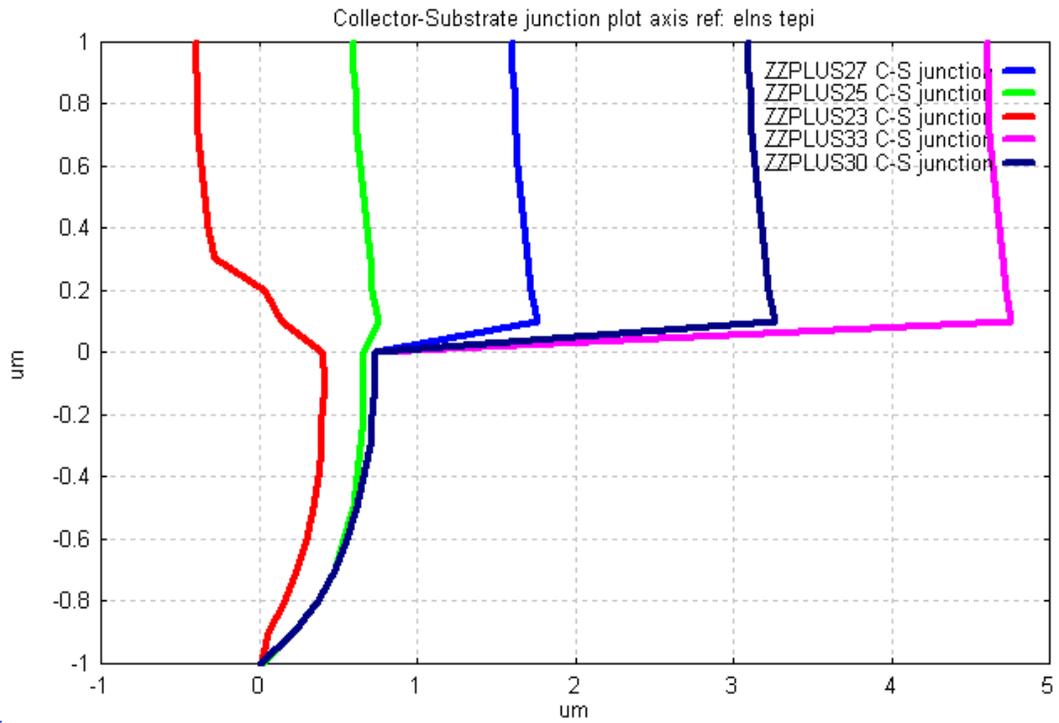
9) In order to simulate avalanche multiplication and compute  $BV_{ceo}$ , the input parameter **ION** has been set to 2 (see Reference Manual sect 8.9.1). The corresponding output in the tex3.lst file is given at the end of the Lateral Simulation - Summary of Terminal Characteristics table:

$BV_{ceo} = 8.7V$ , with a useful figure of merit  $BV_{ceo} * Ft = 38.5$  GHz

### 3.3.2 P<sup>+</sup> isolation sidewall space charge layer simulation

Of some interest in optimising the buried layer and P<sup>+</sup> isolation diffusions is the way in which these two regions overlap, thus increasing the value of the collector-substrate capacitance. Varying the spacing by progressively altering the P<sup>+</sup> isolation mask dimension **ELPS**, the effect on sidewall capacitance can be noted in the .lst file. Adding **LOOK = 99** in the input file generates C-S junction contour plots. Selecting the appropriate Bipgraph menu *C-S junction contour plot* shows the collector to isolation sidewall junction. Below we show results for TEX3.BIP varying the buried layer to isolation spacing; this is the difference  $(ELPS - ELNS)/2$ . In this case the buried layer mask has **ELNS** = 20  $\mu m$  and we run simulations for **ELPS** = 23, 25, 27, 30, 35 microns using filenames **ZZPLUS23**, **ZZPLUS25**, **ZZPLUS27**, **ZZPLUS30**, **ZZPLUS33**. The capacitance variation is confirmed in the table extracted from the .lst file data which indicates the expected minimum for a spacing of approximately 2.5  $\mu m$

The overlap of the P<sup>+</sup> isolation with the N<sup>+</sup> buried layer is clearly visible. By distancing the P<sup>+</sup> region (increasing the values of **BPS**, **ELPS** in the input file) this overlap is reduced and the value of the P<sup>+</sup> sidewall capacitance is lowered. The value of the sidewall capacitance decreases for an increased spacing then gradually increases again due to the increased total plane junction area. There is clearly an optimum spacing between the isolation sidewall and buried layer masks to obtain a minimum value of collector-substrate capacitance.



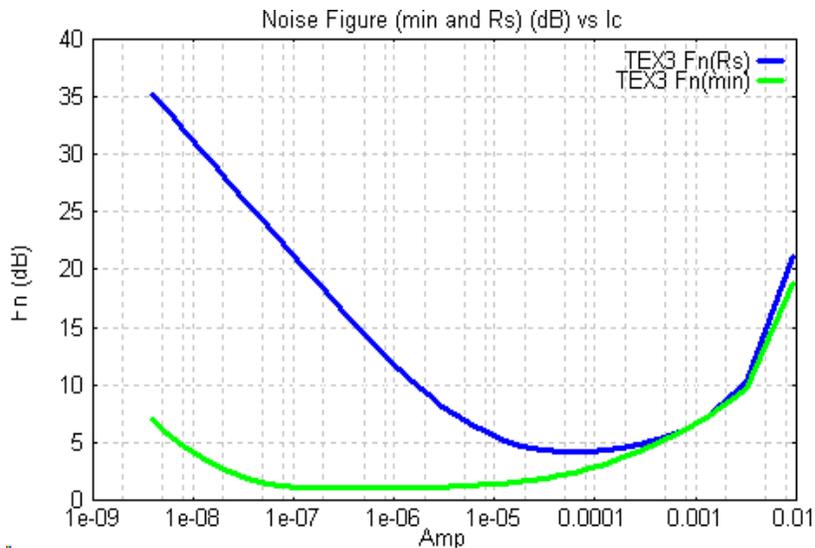
P<sup>+</sup> isolation to collector junction contour plots for TEX3.BIP with ELNS= 20 um using ELPS values from 23 um to 33 um

ELPS value (micron)	23	25	27	30	35
CJCS per (pF/cm)	23.6	9.9	13.0	17.0	21.2
CJCS total (fF)	138	64	81	103	125

Table of C-S sidewall and total C-S capacitance for the above values of ELPS.

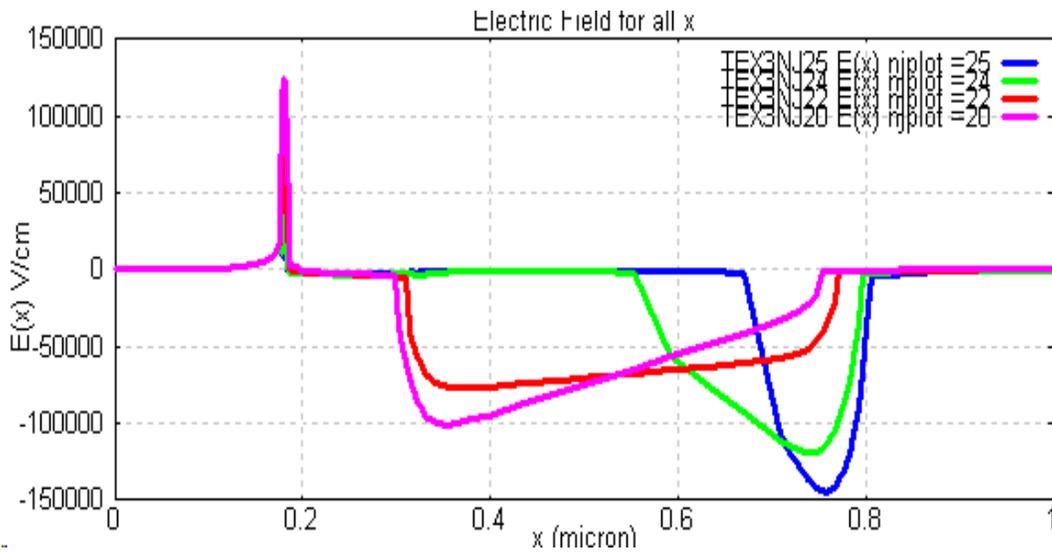
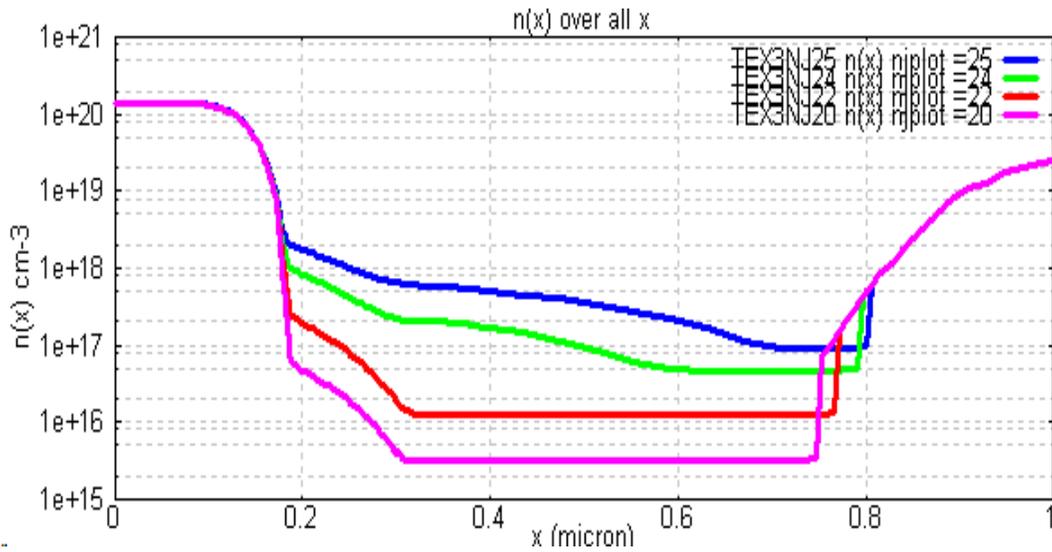
### 3.3.3 Noise Figure simulations

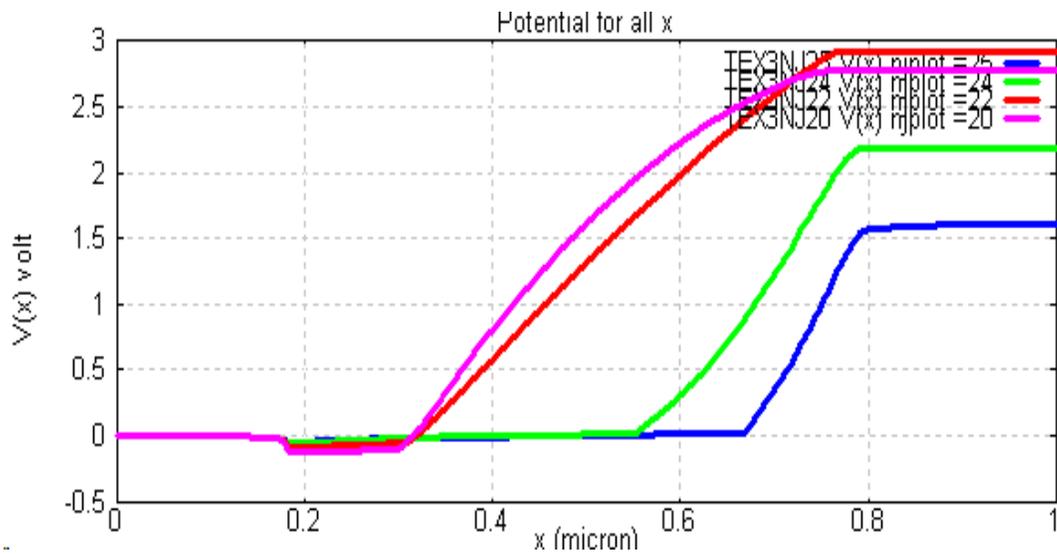
By selecting the Noise Figure menu in Bigraph, various plots of Noise Figure are generated. Here we reproduce F<sub>n</sub>(dB) versus collector current for (a) the specified source resistance of 1000 ohm, (b) the optimum noise figure for each current (the corresponding value of R<sub>S</sub> is also available in this menu).



### 3.3.4 Plots of results versus depth 'x'

By specifying a value **NJPLOT** for the  $n^{\text{th}}$  value of  $J_n$  or  $V_{BE}$  in the Vertical Simulation table (from the .lst file) plots of carrier distributions, electric field and potential may be obtained using the Bipgraph menu: "Plots vs all x". Below are shown results generated for the above tex3 transistor by specifying **NJPLOT**=20, 22, 24, 25 with filenames TEX3NJ20, TEX3NJ22, TEX3NJ24, TEX3NJ25 (corresponding to  $V_{BE}$  values of 0.842, 0.889, 0.969, 1.04 V). These values have been chosen to simulate behaviour from low level to high level conditions. Plots for a user defined value of  $V_{BE}$  may be obtained by specifying a value for **VBEMIN** and setting **NJPLOT**=1 (the  $V_{BE}$  value will only be approximate for high values).



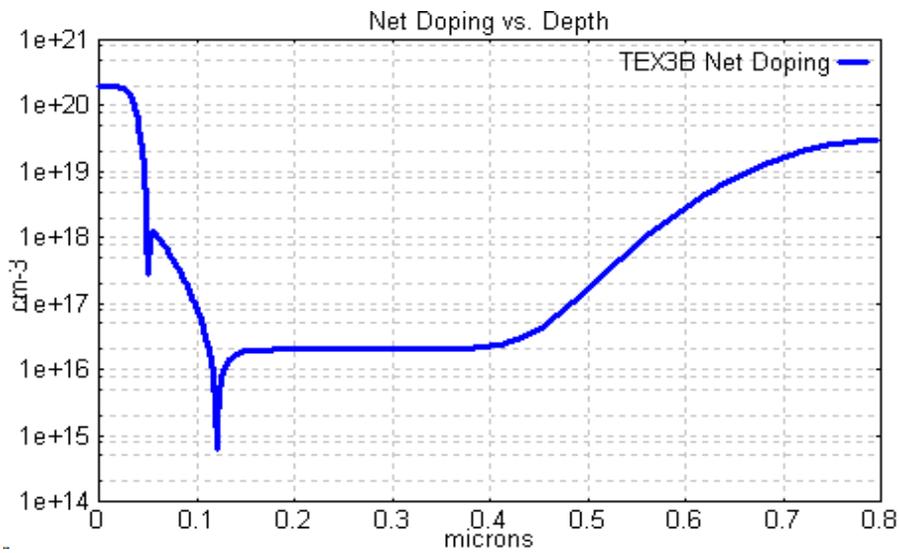
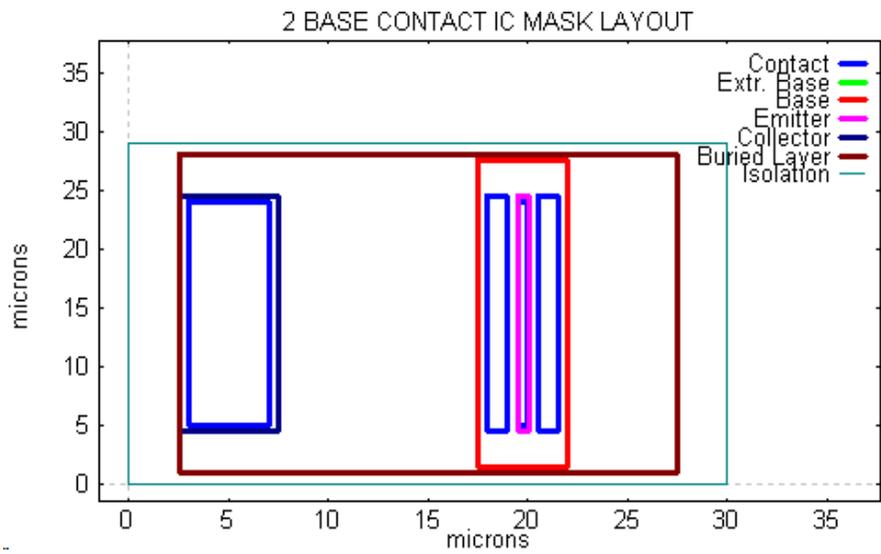


### 3.4 High performance 25 GHz silicon BJT

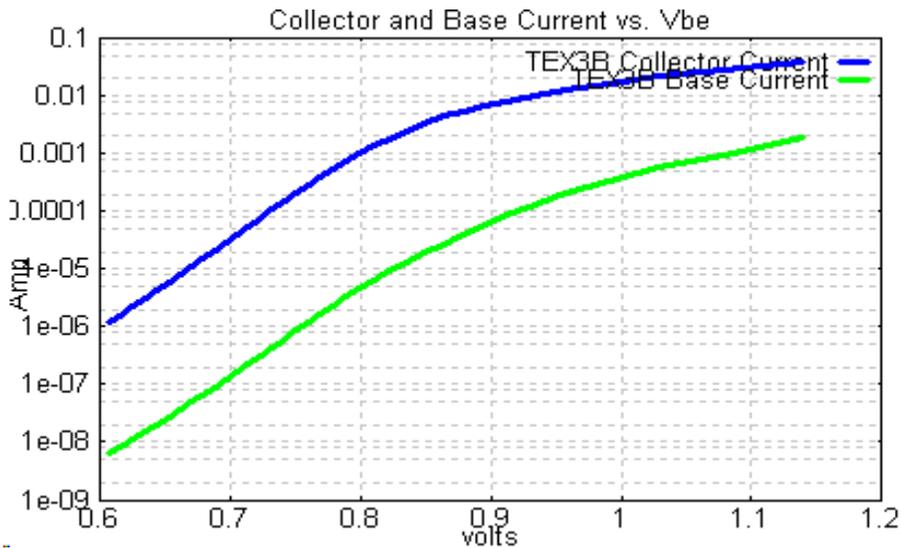
#### 3.4.1 Basic simulation

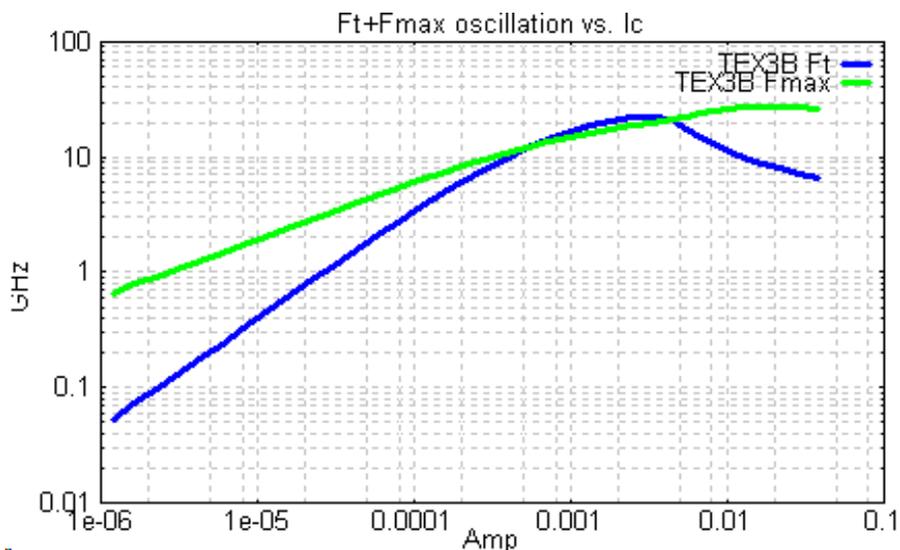
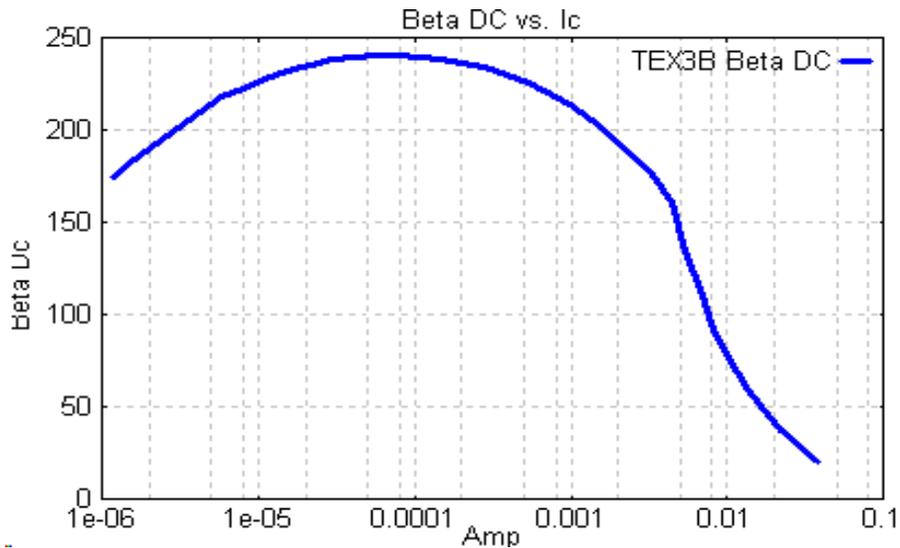
This example is based on a paper in Sept. 1990 BCTM paper pp114-117. The input file TEX3B.BIP is given below, followed by the corresponding mask layout and impurity profile.

```
&TITLE
  TEX3B: file based on Sept. 1990 BCTM paper pp114-117 (HP device)
&PARAM
# Impurity profile data
  nepi=2.e16,xend=.8e-04,tepi=0.8e-04,
  nel=.2e21,nxel=6,xj1=.50e-05,
  nbl=.4e19,nxb1=2,xj2=.12e-04,
# buried layer
  xsubo=0.,xsub=.13e-04,nsubo=3.e19,
# polysilicon emitter parameters
  ipoly=-3,wpol=.2e-04,delta=7.0,npol=1.e20,
# mask data
  elem=.54e-04,b=20.e-04,esb=.5e-04,ecb=1.e-04,bpb=26.e-04,elpb=4.5e-04,
  elns=25e-04,bns=27e-04,elps=30e-04,bps=29e-04,
  iplus=1,rextsq=270.,ici=1,mask=1,
# recombination parameters
  taude=33.e-09,
# bias and current density increment data
  vcin=0.2,vbemin=0.6,vbemax=1.1,
  ra=1.1,arev=.01,
&end
```



The following Bipgraph plots show  $I_C$  and  $I_B$  vs  $V_{BE}$ , beta vs  $I_C$ ,  $f_t$  and  $f_{\text{maxosc}}$  vs  $I_C$ .



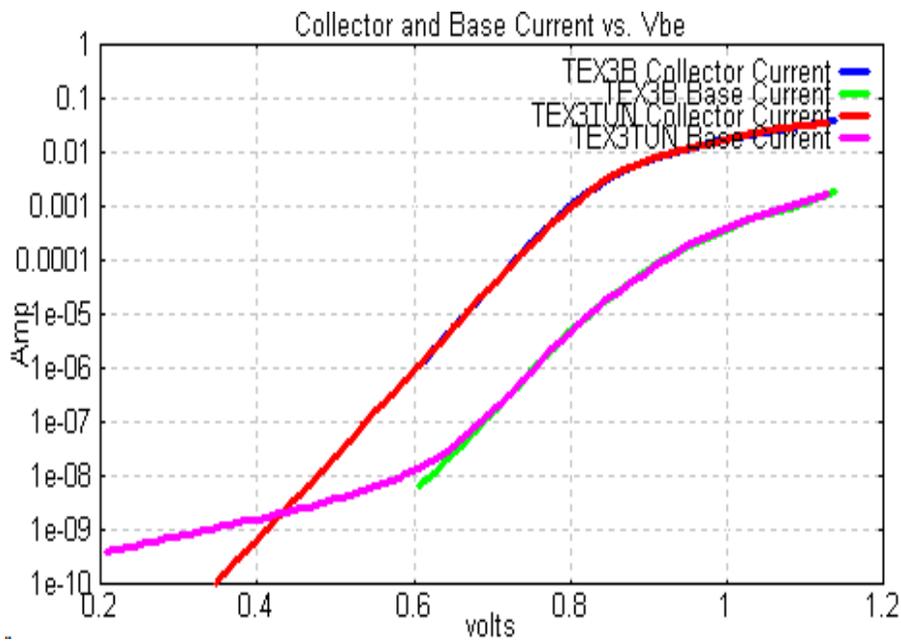


### 3.4.2 Simulation of e-b tunnel current

Tunnel current in the e-b junction is simulated using **ION=6**. We use the above TEX3B.BIP file and add heavily doped extrinsic base layer overlapping with the emitter to create conditions for tunnel current at low  $V_{BE}$  bias. The following lines are added:

```
# P++ extrinsic base overlap with emitter for tunnel current simulation
  esext=0, iplus=2, next=5.e19,
#select e-b tunnel simulation & set VBEMIN
  ION=6, VBEMIN=0.2, ntot=45,
```

The following graph is obtained which illustrates clearly the tunnel current due to the P<sup>++</sup> extrinsic base overlap.

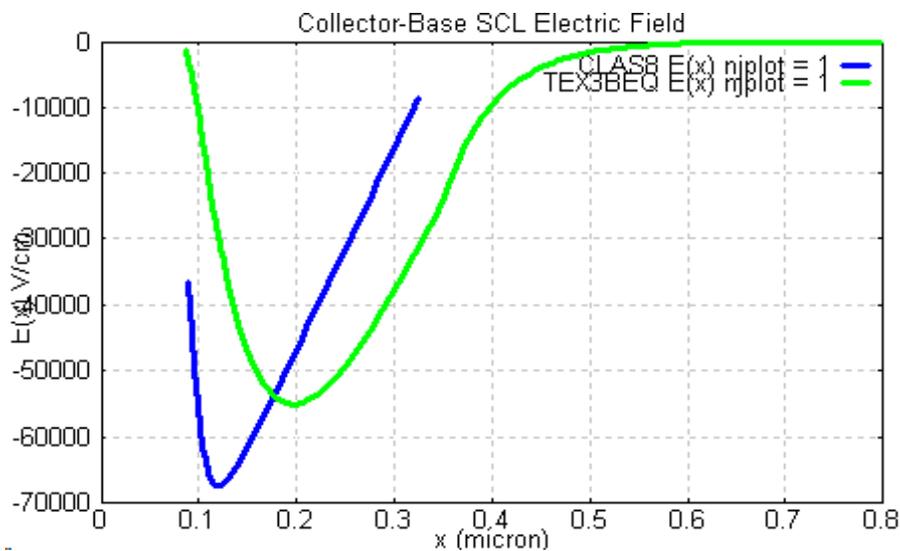


### 3.4.3 Non Equilibrium Transport model for avalanche breakdown simulation

We use the file TEX3B.BIP to illustrate a specific hydrodynamic model case using the Non Equilibrium Transport model invoked using  $ION=20$ . This model is important for high speed BJTs with narrow epitaxial layers. The epitaxial layer thickness is reduced from 0.8  $\mu m$  to 0.6  $\mu m$  to 0.5  $\mu m$  to create files TEX3BEQ, ZZQP6, ZZQP5 and the results compared with the classical avalanche multiplication model using  $ION = 2$  - files zsqp8, zsqp6, zsqp5. The following table shows the results for  $BV_{ceo}$ .

File	TEPI (m)	$BV_{ceo}$ classical (V)	$BV_{ceo}$ Non Eq. Transport (V)
TEX3BEQ	0.8	4.8	6.5
ZZQP6	0.6	3.2	4.3
ZZQP5	0.5	2.1	3.1

In addition, specifying  $ION=200$  the graph of effective electric field  $E(x)$  vs depth in the collector region can be viewed and compared with the actual (Classical)  $E(X)$  graph as shown in the following graph for the TEX3BEQ file.



### 3.4.4 $I_c$ - $V_{ce}$ characteristics

Multiple runs with different values of collector-base voltage  $V_{CIN}$  are simulated using  $NVCB=1$  (Reference Manual sect 5.2). We use the TEX3B.BIP file as an example and add the following lines to create a new file TEX3BIC.BIP.

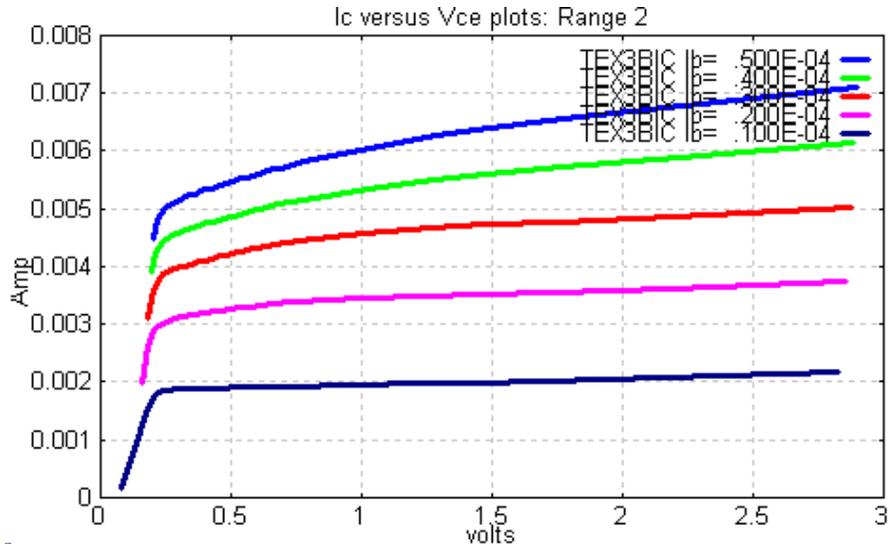
```
# ICVCE PLOT data
  IGRAPH=1, IPRIN2=0, IPRIN3=0,
  NVCB=1, VSTART=2., VSTOP=-0.84, vcinf=0.02, fvcin=1.5,
  NTOT=18,
```

**IGRAPH=1** generates  $I_c$ - $V_{ce}$  graph data. **IPRIN2=0, IPRIN3=0** are added to suppress results of vertical and lateral simulation results in the .lst file. The highest  $V_{cb}$  voltage is set by **VSTART**, and the maximum forward bias to a value **VSTOP**

**VCINF** is the **VCIN** increment in forward bias, **FVCIN** is the **VCIN** reduction factor in normal bias. **NTOT** is the total number of current steps used in the vertical simulation.

It is necessary to determine values of these parameters from initial runs without the above parameters in order to choose the voltage and current ranges. (using **ION=2**, or -2 or 20 to set a reasonable maximum **VSTART** limit below  $BV_{ceo}$ ).

The following is a typical set of  $I_c$ - $V_{ce}$  characteristics from Bipgraph.

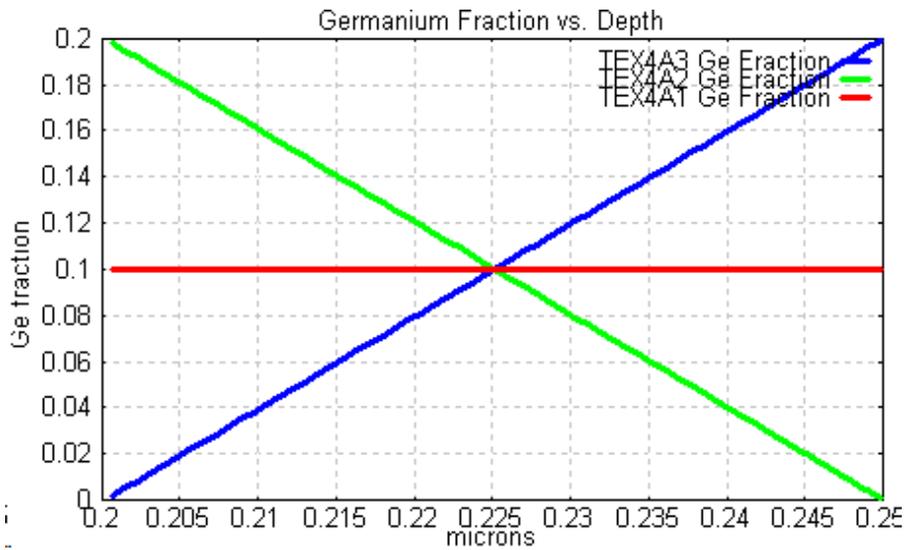


### 3.5 Constant doping SiGe HBT examples

The file **TEX4A1** is chosen to represent an SiGe HBT with constant doping in the emitter, base, collector regions using **IMPUR=4**. The  $Ge(x)$  fraction is constant at a value **XGE=0.1** in the base region as described in the Reference Manual sect 6.4. **NJPLOT=1** is specified to generate plots vs depth of various quantities. **ICON=1** is used to use the same values of injected electron concentration into the base region to facilitate comparisons with two similar devices **TEX4A2**, **TEX4A3**.

```
&TITLE
  EX13 Si-Ge HETEROJUNCTION, XGE = 0.1
&PARAM
# Profile and band-gap options
  IMPUR=4, IGAP=7, XGE=0.1,
# junction depths & doping levels
  XJ1=.2E-04, XJ2=.25E-04, XEND=0.5E-04, NEPI=5.E16, NE1=5.E17, NB1=1.E18,
# geometry
  elem=2.0e-04, b=4.e-04, esb=2.0e-04, ecb=2.e-04, elpb=10.e-04, bpb=4.e-04,
# recombination parameters
  TAUB=10.E-09, TAUDE=1.E-09,
# miscellaneous parameters
  VCIN=2.0, NTOT=12, IEDGE=-10, ICON=1,
  NJPLOT=1,
# ntot=9,
&END
```

The file **TEX4A2** is the same except that the  $Ge(x)$  distribution is graded from a value **XGE=0.2** at the e-b junction depth **XJ1** to a value **XGEP=0** at the b-c junction **XJ2**. A third file **TEX4A3** has the opposite gradient with **XGE=0** at the e-b junction to **XGEP=0.2** at the b-c junction. These  $Ge(x)$  profiles are shown below from the Bipgraph SiGe menu.



The .lst files may be examined to observe the effects of the different Ge(x) gradients. Below are copied the first lines from the "VERTICAL SIMULATION (1-D) RESULTS" table for each device.

TEX4A1

NJ	JN	BETA E	VBE	TRE	TEM	TSCL	FTOT	WB
NJ	JP	BETA T	M	TQBE	TBASE	TRC	FTMAX	VCB
1	9.62E+02	3.07E+02	6.81E-01	1.35E-11	1.62E-13	1.27E-12	9.32E+09	3.04E-06
1	-3.13E+00	2.10E+02	1.00E+00	1.03E-12	1.08E-12	3.42E-15	6.32E+10	1.78E+00

TEX4A2

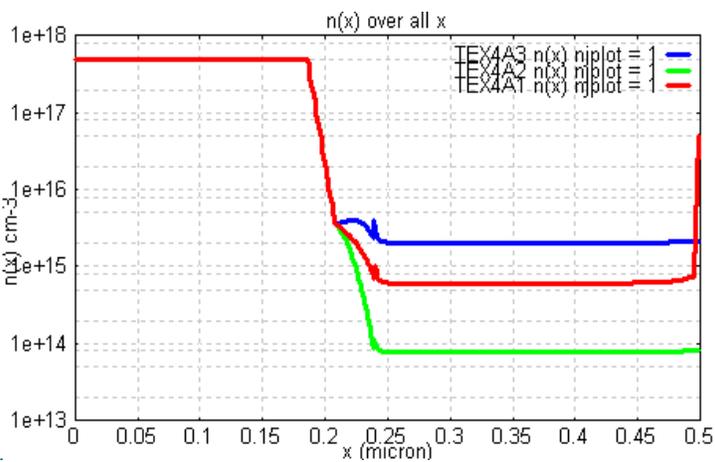
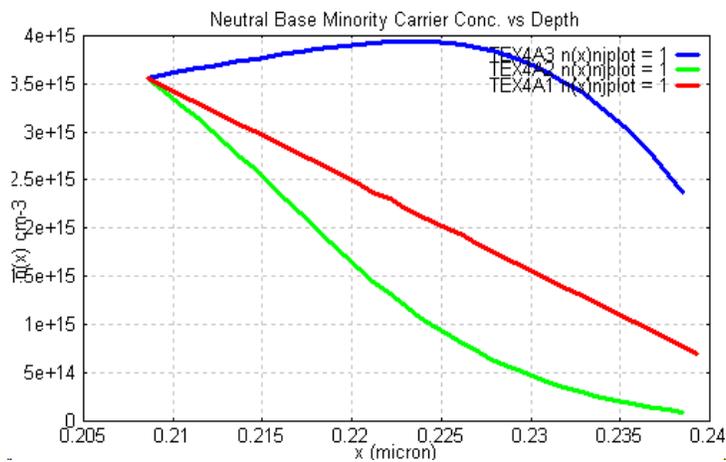
NJ	JN	BETA E	VBE	TRE	TEM	TSCL	FTOT	WB
NJ	JP	BETA T	M	TQBE	TBASE	TRC	FTMAX	VCB
1	1.22E+02	2.88E+02	6.29E-01	1.07E-10	1.75E-13	1.30E-12	1.37E+09	2.96E-06
1	-4.23E-01	1.20E+02	1.00E+00	3.02E-12	5.38E-12	1.25E-15	2.32E+10	2.24E+00

TEX4A3

NJ	JN	BETA E	VBE	TRE	TEM	TSCL	FTOT	WB
NJ	JP	BETA T	M	TQBE	TBASE	TRC	FTMAX	VCB
1	3.20E+03	1.36E+02	7.33E-01	4.05E-12	3.60E-13	1.31E-12	2.24E+10	2.96E-06
1	-2.36E+01	1.17E+02	1.00E+00	8.38E-13	5.46E-13	1.25E-15	7.19E+10	2.00E+00

Note particularly the three values for base delay time TBASE which varies from 1.08 ps (TEX4A1), to 5.38 ps (TEX4A2) to 0.546 ps (TEX4A3). This demonstrates clearly the fact that the positive Ge(x) gradient for TEX4A3 provides an accelerating electric field which reduces substantially the value of the base transit time. However, these comparisons have been made for the same value of injected electron concentration  $n(0)$ ; the values of  $V_{BE}$  and  $J_n$  are not the same, so care must be taken in generalising this comparison.

The  $n(x)$  distributions may be observed using the Bipgraph menu "Neutral base vars. Vs. Depth" and also from the menu "Vertical results for all x" as shown below.



### 3.6 High performance 70 GHz SiGe HBT with SIC implant

The input file is reproduced below. We will limit the discussion to parameters which have not already been used in the previous examples, or which are used in a different manner.

```

&TITLE
TEX4.bip 70 GHz SiGe HBT
&PARAM
#####
# 1) Layout definitions
mask=1,ic=2,
elem=0.25e-4,b=10.e-4
elpb=1.1e-4,bpb=12.e-4
esb=0.20e-4,ecb=0.2e-04,
elns=3.e-4,bns=15.e-4
elps=4.e-4,bps=16.e-4
bpc=12.e-4,elcn=0.5e-4,elc=0.5e-4,elen=1.0e-4
wps=0.02e-4
# 2) impurity profile
impur=1,
NEPI=2.0E+16
ne1=1.e20,nxel=4.0,xel=.01e-04,
nbl=1.e19,nxbl=4.0,xbl=.035e-04,
# 3) SIC for analytic fit profile
isic=1,ne3=2e18,xe3=.25e-04,xe3p=.5e-04,
# 4) Buried layer parameters
xend=1.2e-4,tepi=1.2e-04,nbur=3,nsubo=2e19,xsub=0.3e-04,xbl2=.5e-04,
# 5) Poly emitter
wpol=0.2e-4,npol=1e21,ipoly=3,
# 6) Contacts
rpcon=1.0e-7,rncon=1.e-7
# 7) collector Sink
ncol=1.e20,xncol=5.e-5,
# 8) Extrinsic base + Link base
iplus=1,rextsq=2,
# 9) P+ isolation
npwal=1.e20,xpw=0.7e-04,p3=0,
# 10) SiGe layer
igap=7,isige=1,xge=0.05,xgep=0.05,
xjlg=0.01e-4,xram1=0.005e-4,
xj2g=0.06e-4,xram2=0.005e-4
# 11) Peripheral injection
felat=4.,fqlat=1.0
# 12) Recombination
taude=20e-8,pee=4,xfs=1.e-06,taue=1e-8,
# 13) numerical precision
RA=1.1,arev=.001,
# 14) Bias
vcin=0.0,vbemin=0.7,vbemax=1.0,
&END

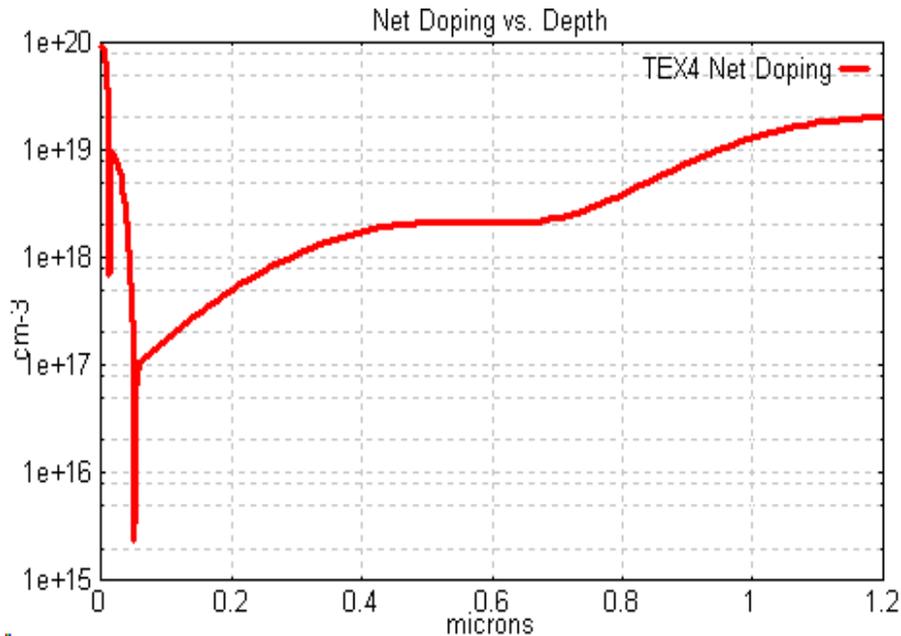
```

The impurity profile in this example is defined using **IMPUR=1** which requires input values for the donor and acceptor distributions (as opposed to specifying the junction depths as in the previous examples). Reference Manual sect 6.2.2 shows that two quasi gaussian functions may be used for each distribution; this enables excellent fits to any SIMS measured profiles or profiles obtained from a process simulator. In this example we use a simple representation for the two distributions defined by:

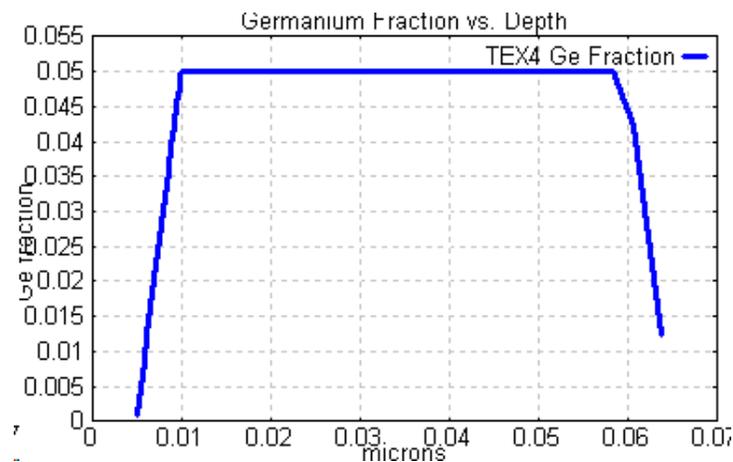
$ne1=1.e20, nxe1=4.0, xe1=.01e-04,$

$nb1=1.e19, nxb1=4.0, xb1=.035e-04,$

A selective implanted collector is incorporated using the **ISIC=1** with the extra parameters **NE3, XE3, XE3P** as defined in Reference Manual sect 6.2.5. The resulting impurity profile generated using Bipgraph is shown below:



The Ge(x) profile may be defined in several different ways as described in Reference Manual Sect 6.4 according to the values of input parameters **IGAP, ISIGE** used. In this file we have used **IGAP=7, ISIGE=1** with the Ge(x) distribution parameters as defined in the Manual Sect. 6.4 to provide the following profile (Bipgraph SiGe menu):



It may be noted that both the impurity profile and the Ge(x) profile may be appended to a Bipole3 input file as tabular values versus depth using **IMPUR = 3** or **-3** as described in Reference Manual sect 6.2.3. This is the preferred method when using profiles generated by a process simulator

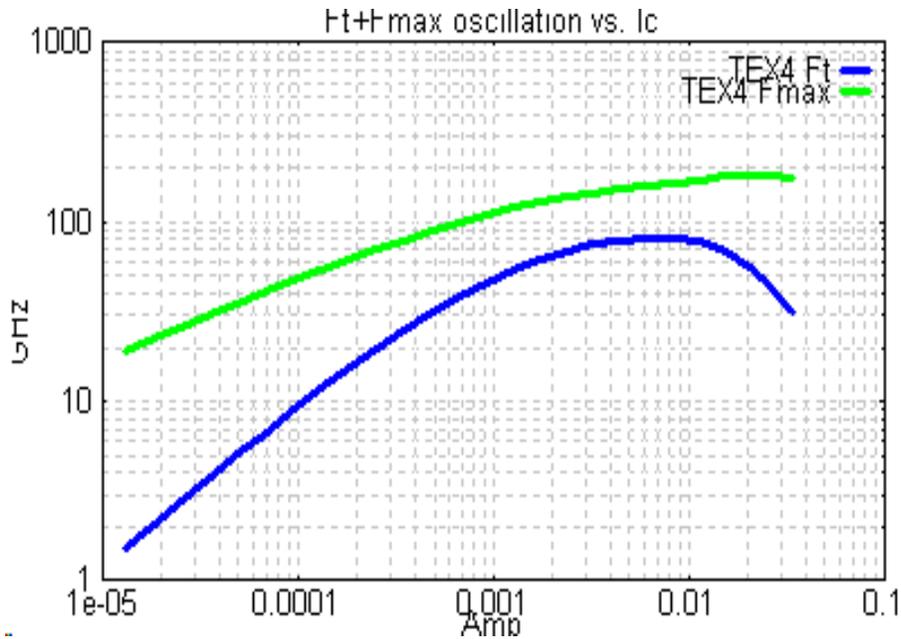
The file (7) contains values for contact resistance per square (Reference Manual sect 5.3) and uses a simple description for the extrinsic

base (9) **IPLUS=1** (Reference Manual sect 7.1.3).

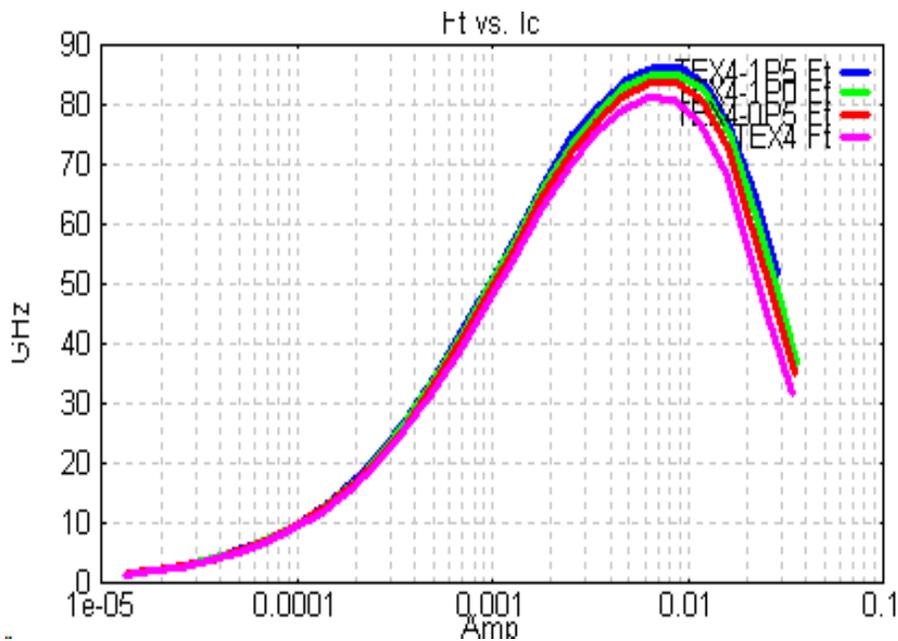
The Peripheral Injection parameters **FELAT**, **FQLAT** define the amount of minority carrier charge and current injected into the base along the emitter perimeter. The simulation results are not usually very sensitive to these values but as described below the Extension Module BIP2NEUT may be used to compute exact values of these two parameters using a full 2D simulation.

The precision of the numerical simulation is increased compared to the default case by using a smaller grid size (**RA=1.1** instead of the default value 1.2 see Reference Manual sect 10.1 and 3.5).

$f_t$  and  $f_{maxosc}$  vs  $I_C$  plots obtained for this device are shown below:



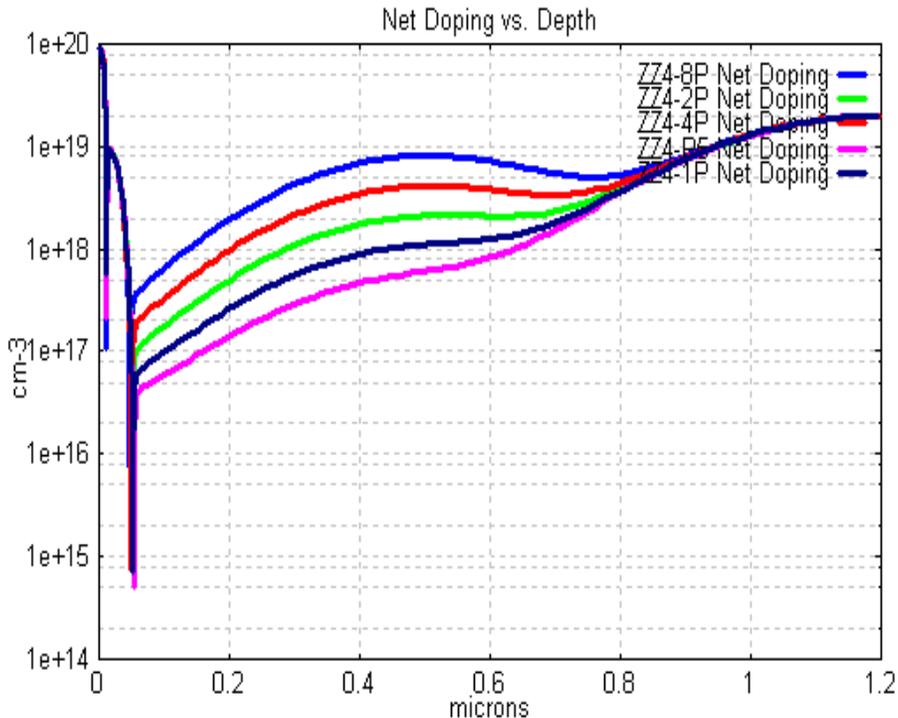
It is useful at the development stage of a device to study dependence of the terminal characteristics on  $V_{CB}$ . Below are shown plots obtained by making files TEX4-0p5, TEX4-1p0, TEX4-1p5 with values **VCIN** = 0.5, 1.0, 1.5 respectively.



### 3.7 Use of Bipole3 for design improvement of existing transistor

#### 3.7.1 Breakdown voltage dependence on SIC implant using Non Equilibrium Transport model

For BJTs or HBTs with peak ft values in excess of around 30 GHz it is essential to use a Non Equilibrium Transport model for correct simulation of avalanche multiplication. This is a special case of the generalized Hydrodynamic Model. In Bipole3 this option is selected by specifying **ION** = 20 (see Reference Manual Sect. 8.9.2). Using the TEX4 transistor as an example, we have varied the SIC layer parameters by altering the peak doping using values of **NE3** equal to 0.5E18, 1E18, 2E18, 4E18, 8E18 (file names zz4-p5, zz4-1p, zz4-2p, zz4-4p, zz4-8p) to generate the impurity profiles shown below. Note that for TEX4, using **ION**=2 (conventional ionization integral)  $BV_{ceo} = 1.1V$ , compared to  $BV_{ceo} = 2.6 V$  using the Non Equilibrium Transport model, **ION**=20.

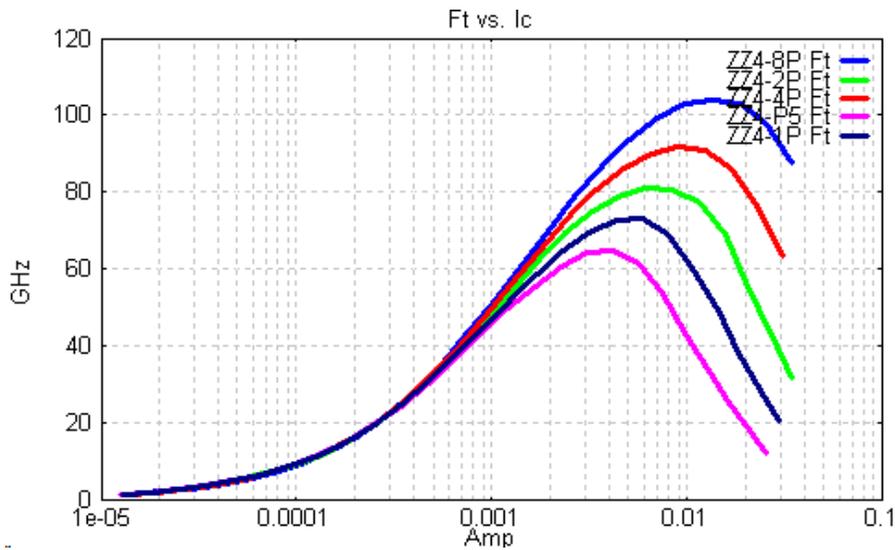


With **ION**=20 as input, from the corresponding lst files, we find the following results:

ne3x1.E18	$V_{BR}$	$BV_{ceo}$	$C_{jco}$ fF	$C_{jcsq} \times 1E7$ F/cm <sup>2</sup>
0.5	12.1	3.3	8.9	0.82
1.0	11.0	2.9	9.6	0.96
2.0	10.1	2.6	10.5	1.17
4.0	9.4	2.2	11.7	1.5
8.0	8.8	2.0	13.1	1.8

$V_{BR}$  is the C-B plane junction breakdown voltage,  $C_{jco}$  is the total C-B junction capacitance,  $C_{jcsq}$  is the junction capacitance per unit area in the active region (under the emitter).

The design trade-off is immediately apparent. As the SIC implant dose increases,  $BV_{ceo}$  decreases. At the same time the C-B capacitance rises; this has a deleterious effect on  $f_{maxosc}$ , specially at medium and low currents. The higher dose enables higher operating current densities, thus improving the  $f_t$  versus  $I_C$  curves as shown below.



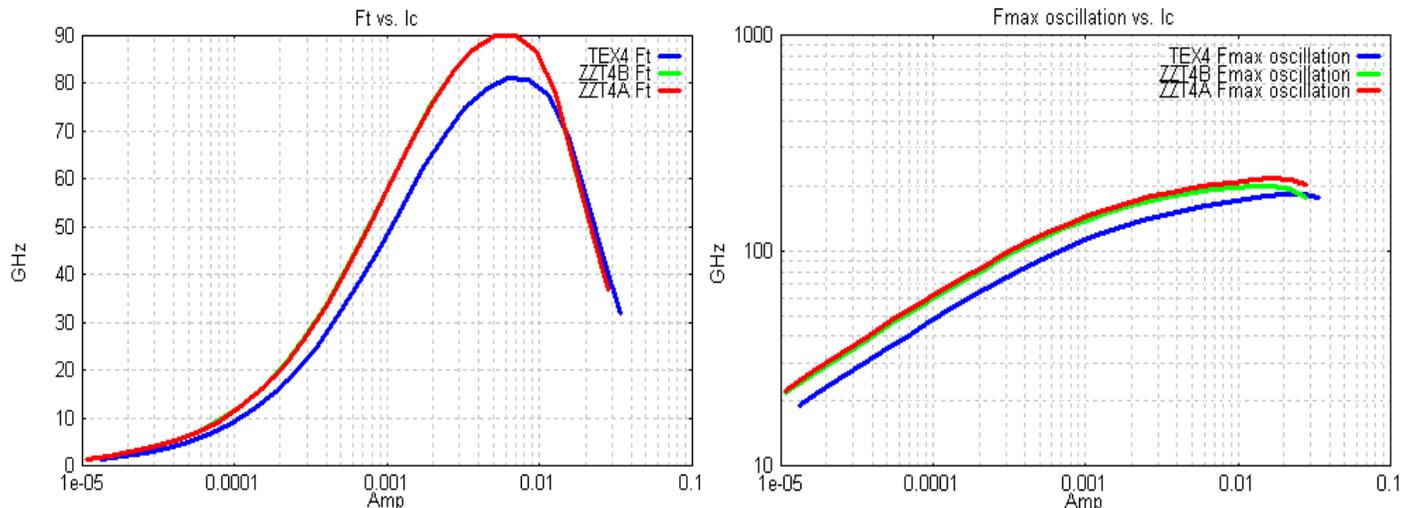
### 3.7.2 Design of transistor with improved $f_t$ and $f_{\max\text{osc}}$

Here we discuss briefly how Bipole3 may be used to take an existing device and use a systematic procedure for evolving a new device with improved characteristics.

The characteristics of most importance are usually breakdown voltage, current gain, maximum  $f_t$ , maximum  $f_{\max\text{osc}}$ . Let us take the TEX4 device and assume that we wish to rough out mask and impurity profile data for a device with a peak  $f_t$  of at least 100 GHz, and  $f_{\max\text{osc}}$  of 200 GHz at the same collector current and maintain a current gain of 200. Assume a minimum emitter width of 0.18  $\mu\text{m}$ .

We start by modifying the value of **ELEM** and the corresponding mask layout parameters.

The file ZZT4A.BIP has **ELEM** reduced from 0.25  $\mu\text{m}$  to **ELEM** = 0.18E-04. The file ZZT4B.BIP has all other mask dimensions reduced by comparable widths. The simulation results are shown below for  $f_t$  and  $f_{\max\text{osc}}$  where a visible improvement is seen in high frequency performance (with no alteration in impurity profile).

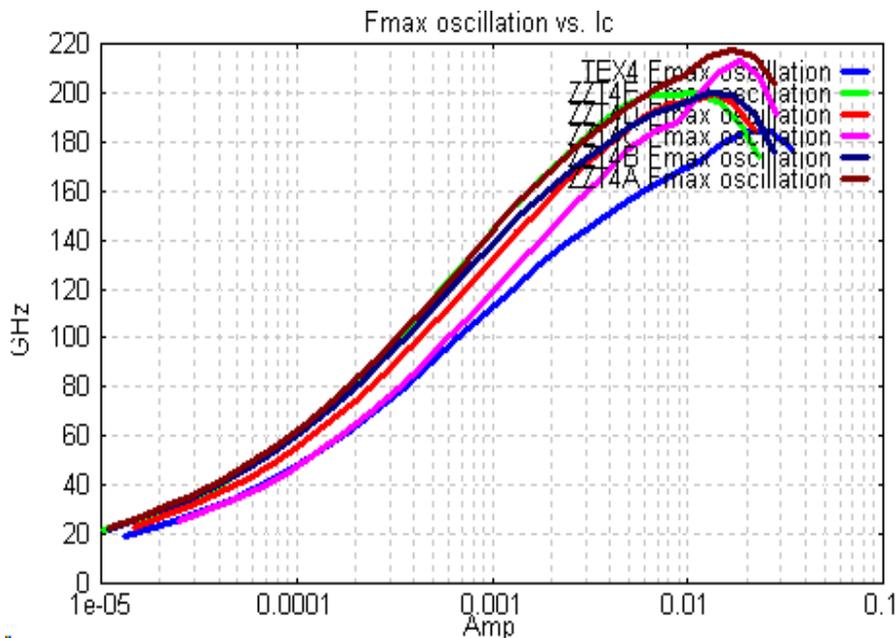
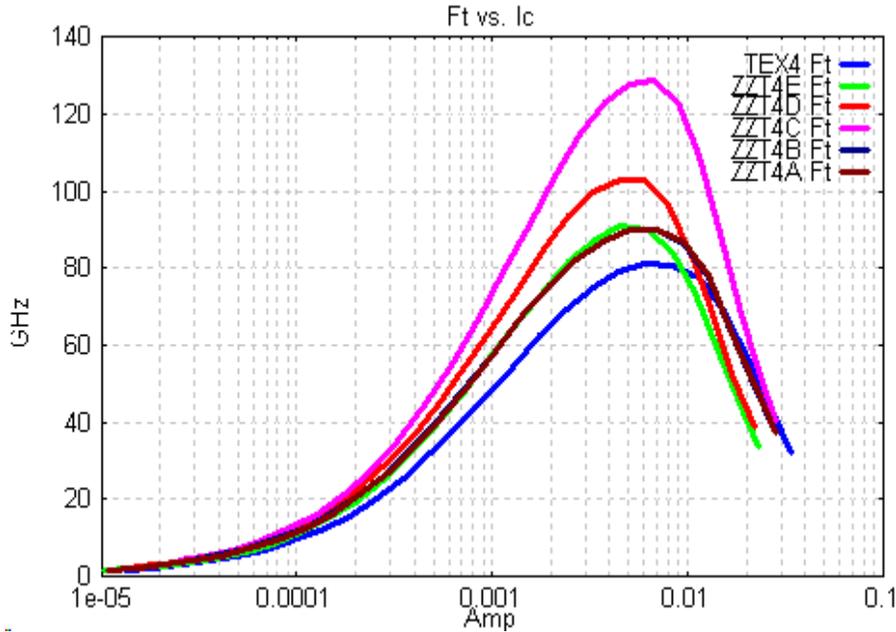


Let us now examine the effect of decreasing the junction depths. For the simulations this is best done gradually - if for example the base implant is altered to create too shallow a junction, the base region disappears completely. The following table shows the effect on base resistance for successive change in the impurity profile parameters.

File tex4:	RBB = 1.19E+01	original file
File zzt4a:	RBB = 8.57E+00	elem reduced from 0.25 to 0.18 $\mu\text{m}$
File zzt4b:	RBB = 8.57E+00	other widths reduced
File zzt4c:	RBB = 2.04E+01	xb1, xj2g reduced by x 0.7
File zzt4d:	RBB = 1.33E+01	Xe1, xj1g reduced by x 0.7
File zzt4e:	RBB = 6.12E+00	Nb1 increased from 1.E19 to 1.5E19

The plots below show the corresponding changes in  $f_t$  and  $f_{\text{maxos}}$ . The optimum device appears to be ZZT4D with a peak  $f_t$  above 100 GHz at  $I_C = 5$  mA and a corresponding  $f_{\text{maxosc}}$  of 200 GHz.

Clearly this approach can be continued for any desired specification (and the  $BV_{\text{ceo}}$  value checked using  $\text{ION}=20$ ).



### 3.8 TABULAR IMPURITY PROFILES

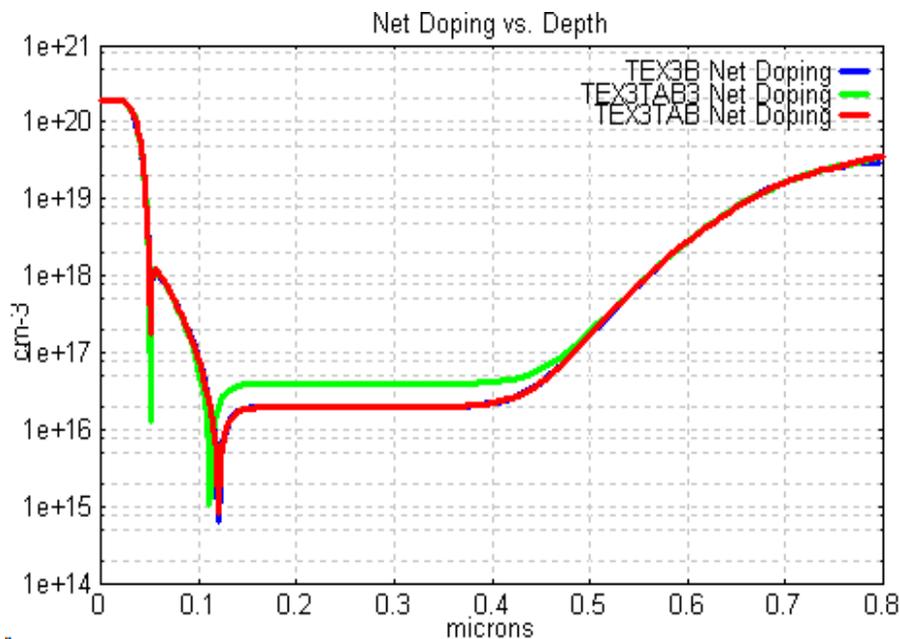
#### 3.8.1 Active region tabular profiles

For cases where the impurity profile can not be specified by quasi gaussian functions, tabular data may be added after an &DATA card before the &END card in the input file as described in Reference Manual Sect. 6.2.3 using  $\text{IMPUR}=3$  or  $\text{IMPUR} = -3$ . The tables may be obtained from measured SIMS data or from process simulation (e.g. using SUPREM or similar software). The following is an extract from a file identical to tex3b.bip except that the profile is given in tabular form.

```

&TITLE
TEX3TAB: TEX3B file with tabular impurity profile
&PARAM
# Tabular Impurity profile data
  nepi=2.e16,xend=.8e-04,tepi=0.8e-04,
  IMPUR=-3,
# polysilicon emitter parameters
  ipoly=-3,wpol=.2e-04,delta=7.0,npol=1.e20,
.....
.....
&DATA
80
.200E+21 .393E+19 .714E-06
.200E+21 .372E+19 .141E-05
.195E+21 .339E+19 .211E-05
.171E+21 .299E+19 .281E-05
.112E+21 .254E+19 .351E-05
.533E+20 .220E+19 .403E-05
.....
.....
.265E+20 .100E+01 .754E-04
.288E+20 .100E+01 .774E-04
.300E+20 .100E+01 .794E-04
.300E+20 .100E+01 .800E-04
&end

```



The output graph profile is shown above. We have added the case of **IMPUR=3** (TEXTAB3) to illustrate the effect of having **NEPI** added to the tabular data (the other two graphs are coincident).

### 3.8.2 Conversion of tabular profile input to analytic functions in non-active regions

Outside the active emitter-base region, Bipole3 uses analytic functions to describe the impurity profiles. To obtain the appropriate parameters for these functions the user can obtain the plots from the measured or simulated (e.g. using SUPREM3) data. For an improved procedure the user may use the available tabular data and convert it to the above Bipole3 input format for tabular profiles which consists of donor concentration  $N_D(x)$ , acceptor concentration  $N_A(x)$ , depth  $x$ , with dimensions in  $\text{cm}^{-3}$  for doping levels, cm for depth. By setting the input parameter **ID=50**, **IMPUR = +/- 3** and **XEND** to the maximum tabulated depth, the impurity profile may be plotted for each region. The procedure is then as follows:

Execute each of the files. We shall use as examples the files TNAISO.BIP, TNASINK.BIP, TNABASE.BIP with tabular data for the P+ isolation, N sinker, P+ extrinsic base regions respectively.

### Isolation profile:

From the Bipole3 TNAISO output graph plot for acceptor concentration  $N_A$  vs depth, estimate values for the acceptor profile  $N_A(x)$  parameters **NB1, XB1, NXB1, XB1P** and (optionally) **NB2, XB2, NXB2, XB2P**.

Construct a file TNAISOF.BIP with **ID=50, IMPUR=1** with the above profile parameters.

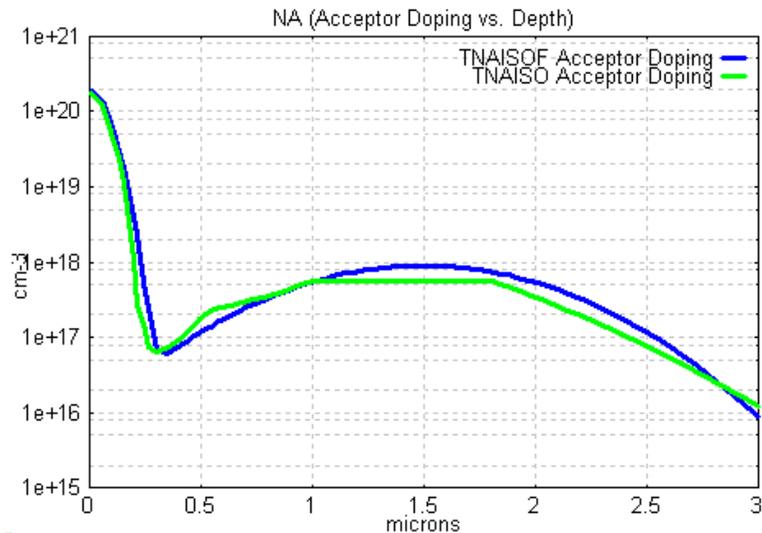
Run and plot  $N_A(x)$  for TNAISO and TNAISOF superimposed

Adjust values for the analytic profile parameters one at a time and save as a new file.

Run the new file and add to the output graph plot and compare.

Proceed iteratively until an acceptable profile fit is obtained (typically 5 runs)

The results is illustrated below using the files TNAISO and TNAISOF.



A complete input file may now be constructed using the active region tabular profile with **IMPUR = +/- 3** and the following isolation profile parameters obtained by substitution as follows: **NPWAL** from **NB1**

**XPW** from **XB1**

**NXPW** from **NXB1**

**XPWP** from **XB1P**

**P2** from **NB2**

**XP2** from **XB2**

**XP2P** from **XB2P**

**NXP2** from **NXB2**

### Collector sinker profile

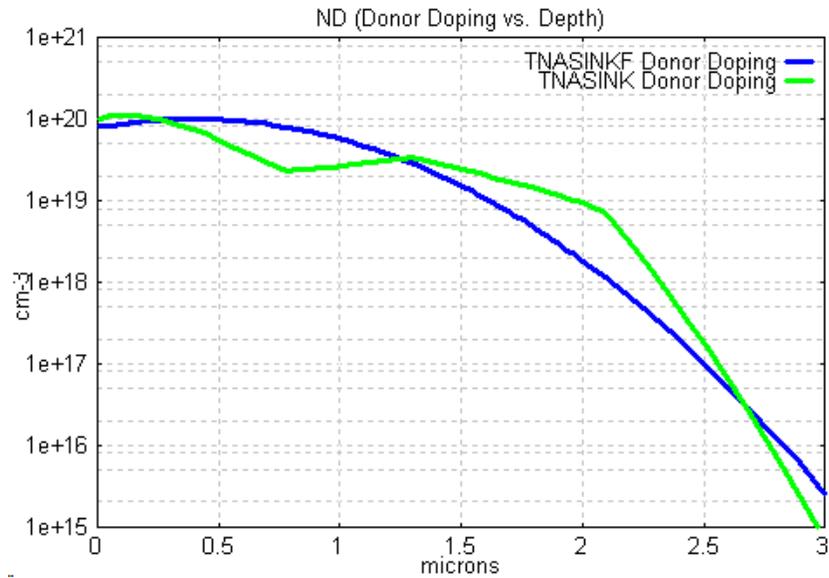
From the output graph plot for TNASINK estimate the donor profile  $N_d(x)$  parameter values **NE1, XE1, NXE1, XE1P** by inspection of the  $N_d(x)$  graph plot. Construct a file TNAISOF.BIP with **ID=50, IMPUR=1** with the above profile parameters and execute it. Using the output graph plot for  $N(x)$  load to superimpose with the original tabular profile TNASINK. Adjust values one at a time and run and add to the graph plot Iterate on values until satisfactory profile fit obtained. A complete input file may now be constructed using the active region tabular profile with **IMPUR = +/- 3** and the following collector sinker profile parameters obtained by substitution as follows:

**NCOL** from **NE1,**

**XNCOL** from **XE1, XNCOLP** from **XE1P,**

**NXNCOL** from **NEX**

The following result is obtained using TNASINK, TNASINKF



### Non active base region

From the output graph plot for TNABASE estimate the acceptor profile  $N_A(x)$  parameter values NB1, XB1, NXB1, XB1P (and optionally depending on the region, the parameters **NEXT, NXEXT, XEXT, XEXP**) by inspection of the  $N_A(x)$  graph plot.

Construct a file TNABASEF.BIP with **ID=50, IMPUR=1** with the above profile parameters and execute it. Using the output graph plot for  $N_A(x)$  load to superimpose with the original tabular profile TNABASE.

Adjust values one at a time and run and add to the graph plot

Iterate on values until satisfactory profile fit obtained

A complete input file may now be constructed using the active region tabular profile with **IMPUR = +/- 3** and the following non active base region profile parameters obtained by substitution as follows:

For the external base use:

**NB1, XB1, NXB1, XB1P**

or for iplus=2 substitute as follows:

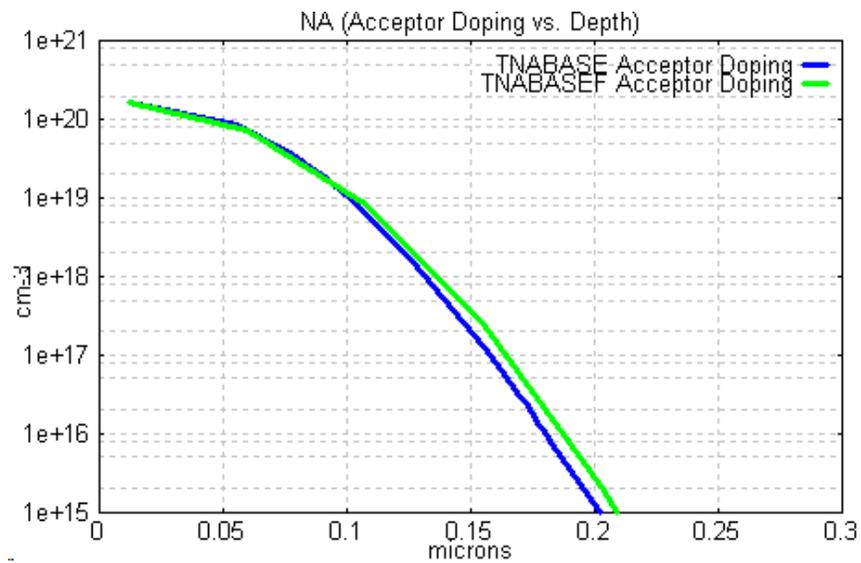
**NEXT** from **NB1**

**XEXT** from **XB1**

**NXEXT** from **NXB1**

**XEXP** from **XB1P**

The following example is obtained using TNABASE and TNABASEF.



### Notes on the effects of fitting errors for the above non-active region profiles

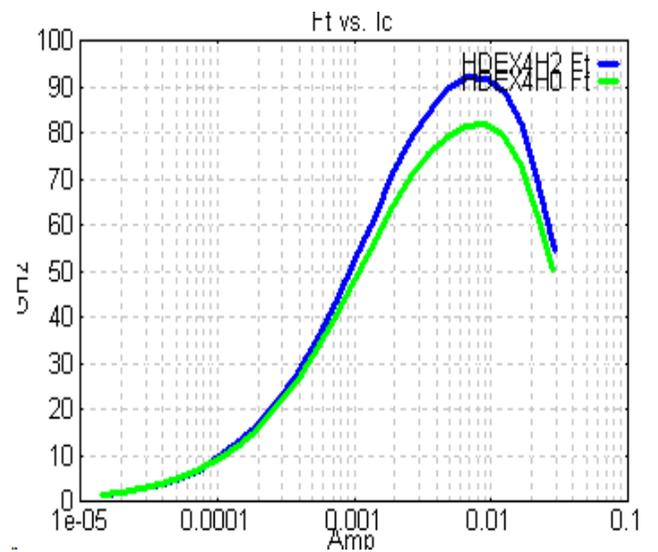
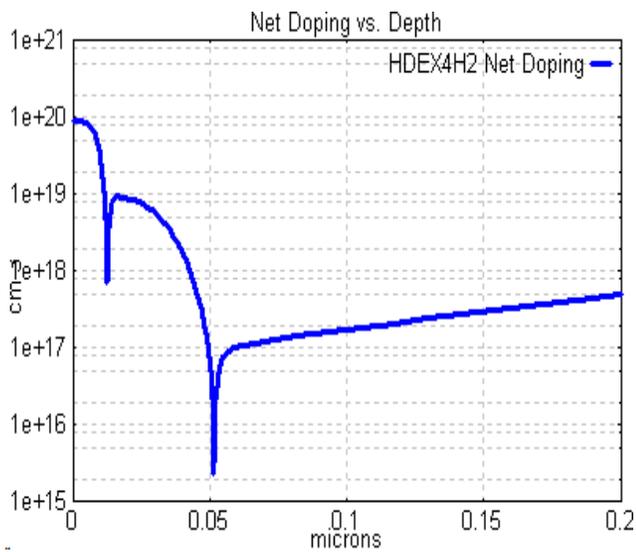
It should be noted that reasonable approximations to these profiles are normally sufficient for simulation of the complete device. The isolation profile affects only the sidewall component of the collector-substrate capacitance. The sinker profile determines only one component of the collector resistance; this component is normally a small fraction of the total.

The non active base profile determines the extrinsic base resistance which is normally less than the active region intrinsic base resistance; it also determines the non active value of base-collector capacitance. These terms represent a fairly small contribution to  $f_t$  but can be significant in the determination of the maximum oscillation frequency  $f_{max}$  - so care should be taken in obtaining the non active base parameters with adequate accuracy.

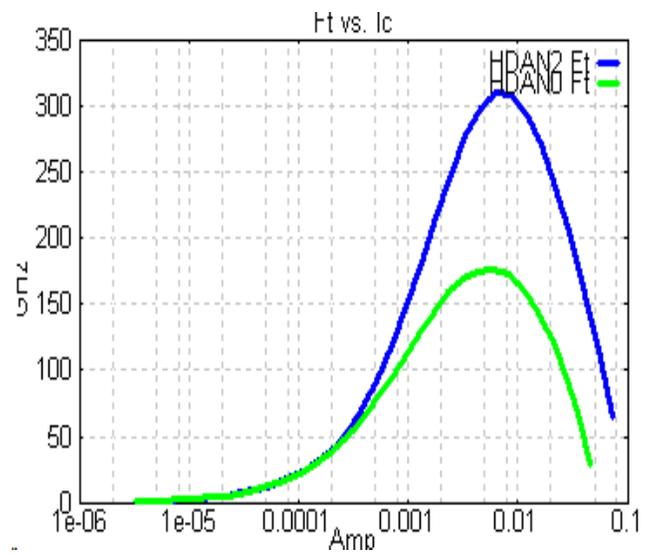
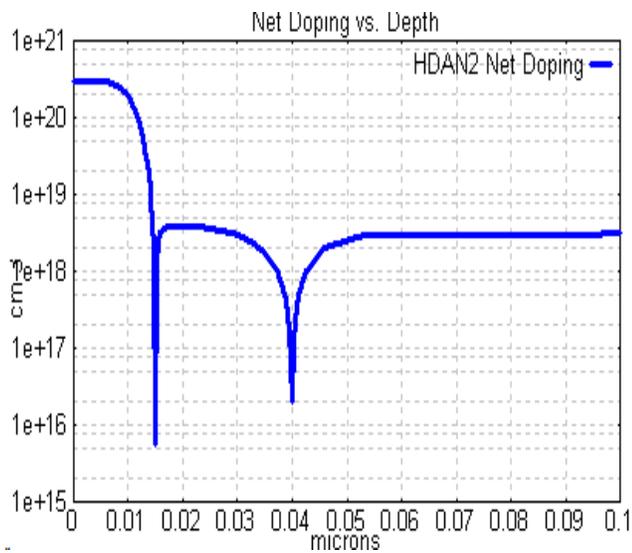
It should also be noted that it is not necessary to always include the above discussed non-active region impurity profiles. The appropriate parameter values for capacitance per unit area and per unit perimeter, plus the correct values of sheet resistance etc. may be used as input for all non-active regions.

### 3.9 Use of Hydrodynamic Model for very high frequency HBTs

For bipolar transistors or HBTs with  $f_t$  values in excess of 50 GHz, Hydrodynamic Model effects should be included. This is accomplished in Bipole3 release V5.2 and subsequent by the use of the **IHDM** parameter. Using the HBT of section 3.6 tex4.bip, with **VCIN** = 1.5, which has a nominal  $f_t$  of 80 GHz the following plots show the impurity profile and the effect of executing with **IHDM**=0 (no HDM included) and **IHDM**=2 (HDM included). There is a slight HDM effect. The magnitude of the effect depends on the vertical thicknesses of the various regions so one can not generalise about what transistor requires use of the Hydrodynamic Model; however it should not be necessary for devices with  $f_t$  values below about 25 GHz.

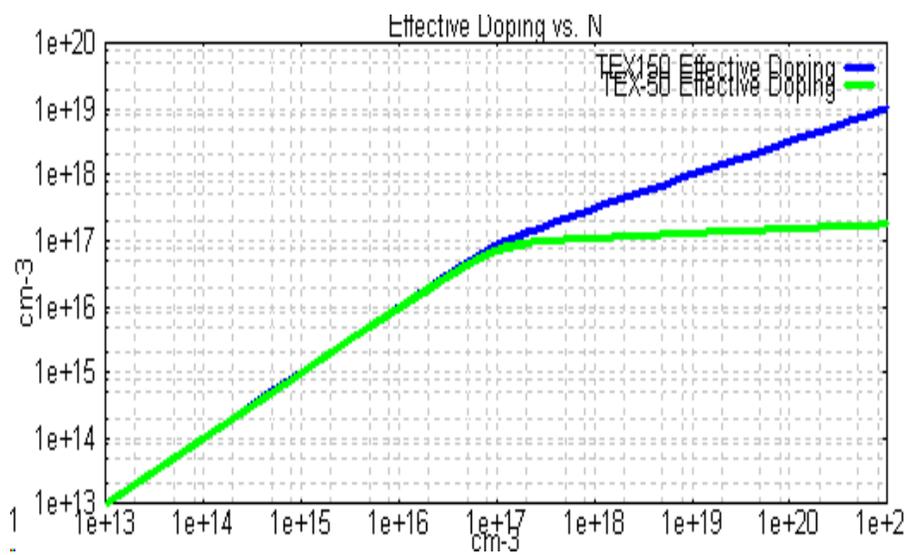
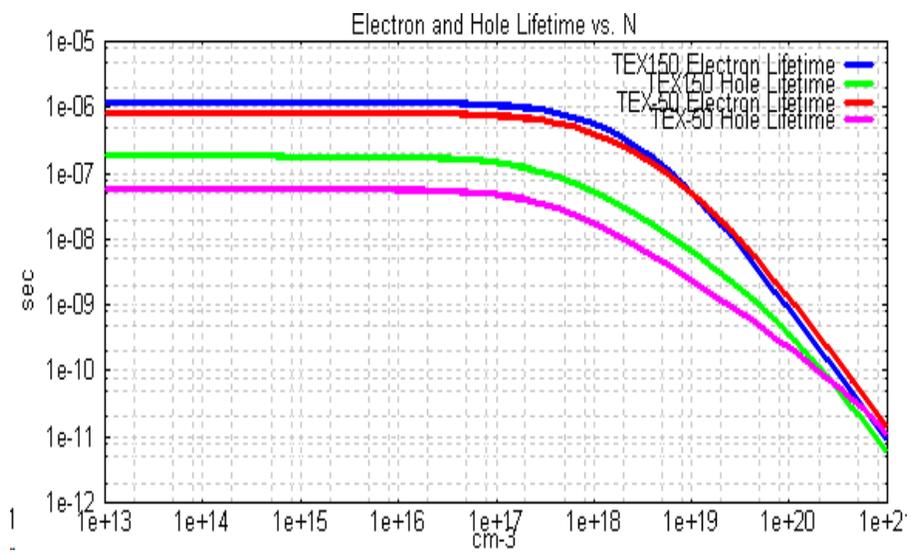
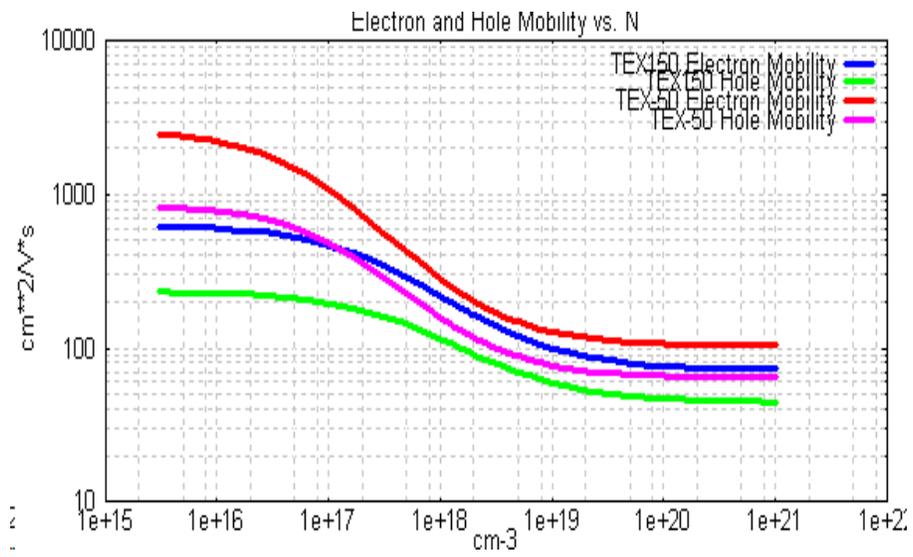


The next plot is for a transistor given by the file hdan0.bip (**IHDM=0**) and hdan2.bip (**IHDM=2**) with a peak  $f_t$  of 300 GHz. Results are again reproduced for both non HDM and HDM cases. In this case it is clearly essential to invoke the Hydrodynamic Model using **IHDM = 2** in order to obtain valid results.



#### 4.0 PHYSICAL MODEL PROPERTIES

The physical model parameters are described fully in the Reference Manual Sect. 4. The effect on the doping dependent physical parameters may be visualised using the Bipgraph menu. Below are shown plots of mobility, carrier lifetimes, and effective doping (i.e. including the effect of band-gap narrowing) for the default model parameters at **TE = -50 and +150 degrees C**.



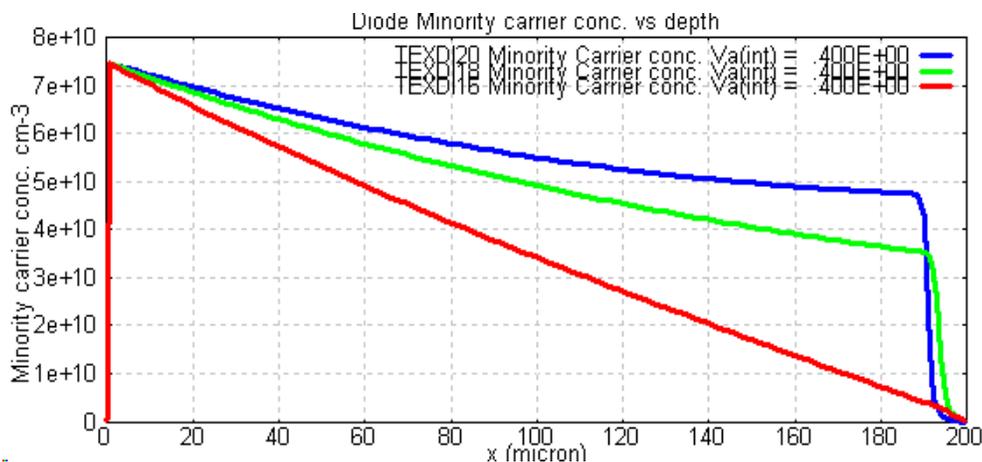
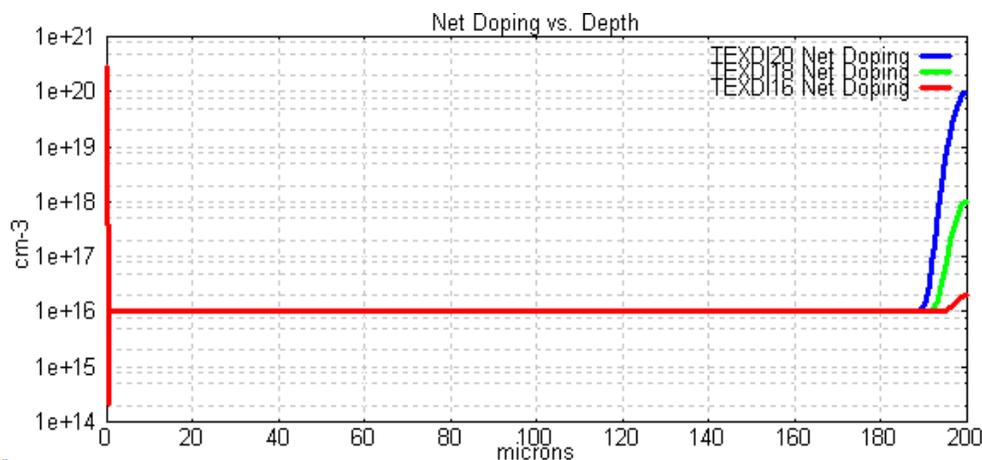
## 5.0 DIODE SIMULATION

### 5.1 P+ N N+ diodes

The diode option **ID=50** enables diodes to be simulated at a given bias condition. Below is shown a typical input file **TEXDI20.BIP** with a back diffused doping **NSUBO=1.E20**. Simulated also are **TEXDI18** and **TEXDI16** with doping levels **1.E18** and **1.E16**. The graph plots show the impurity profiles and the corresponding minority carrier concentrations vs depth for a forward bias **VCIN = -0.4V**.

```
&TITLE
TEXDI20: NP DIFFUSED DIODE (ID=50)
&PARAM
ID=50,VCIN=-0.4,
# impurity profile parameters
NE1=3.E20,NB1=1.0,NEPI=1.E16,
XJ1=0.3E-04,XEND=200.E-04,XSUBO=0.0,XSUB=3.E-04,NSUBO=1.E20,
# recombination lifetime parameters
TAUC=30.E-06,ITAUC=1,NTAUC=1.E16,SOX=1.E3,
#miscellaneous parameters
IEDGE=0,NJPLOT=1,
&END
```

**NPN** determines whether the diode is a P+ N N+ diode (**NPN = 0**) or an N+ P P+ diode (**NPN=1**). Here we focus attention on the wide base region. The difference in carrier distributions from the classical towards a uniform base doping is evident.



We include below an extract from the **BIPOLE3** listing files for the three cases, where the change in 'base' (EPI) current is evident.

TEX16.LST

VBIAS	JDIF	JSCL	JEPI	JTOTAL
-.400E+00	-.645E-05	-.173E-02	-.237E-04	-.176E-02

TEX18.LST

VBIAS	JDIF	JSCL	JEPI	JTOTAL
-.400E+00	-.645E-05	-.173E-02	-.164E-04	-.176E-02

TEX20.LST

VBIAS	JDIF	JSCL	JEPI	JTOTAL
-.400E+00	-.645E-05	-.173E-02	-.135E-04	-.175E-02

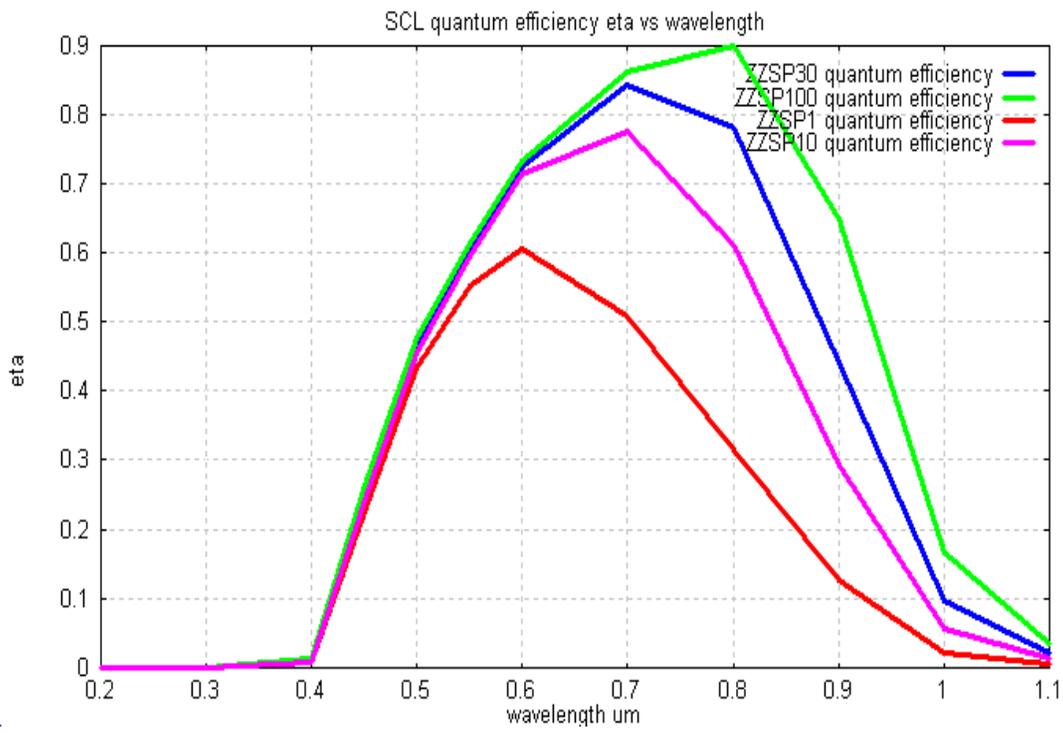
## 5.2 Photodiodes

For photodiodes the overall quantum detection efficiency is computed plus the quantum efficiencies of each region (neutral emitter, space charge region, neutral base) and the corresponding delay times. The parameter **NEX** can be set equal to 2 with the parameters **ALPHA** for absorption coefficient and **PHIS** for incident photon flux density used as described in the Reference Manual section 8.

A second useful combination is to use **NEX** =3 and add a table of wavelengths and absorption coefficients. The following file illustrates this case.

```
&TITLE
  texspec: NP DIFFUSED PHOTODIODE (ID=50,NEX=3)
&PARAM
  ID=50, NEX=3,
# impurity profile parameters
  NE1=3.E20,NB1=1.0,NEPI=1.E14,
  XJ1=1.0E-04,XEND=50.E-04,XSUBO=0.0,XSUB=3.E-04,NSUBO=1.E20,
#miscellaneous parameters
  vcin=10
&DATA
12
  0.200E-04 1.0e08
  0.300E-04 1.5e06
  0.400E-04 6.0e04
  0.450E-04 1.8e04
  0.500E-04 1.0e04
  0.550E-04 6.6e03
  0.600E-04 4.2e03
  0.700E-04 2.0e03
  0.800E-04 9.0e02
  0.900E-04 3.0e02
  1.000E-04 5.0e01
  1.100E-04 1.0e01
&END
```

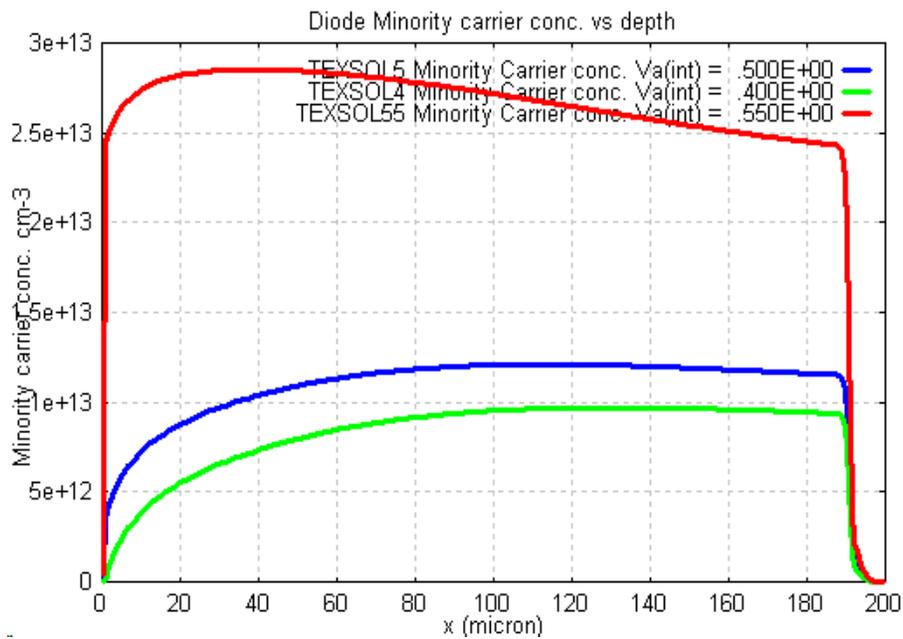
Executing this file results in a GRAPH menu *Photodiode Spectral Response*. Below is shown the plot of space charge layer quantum efficiency for bias voltages **VCIN** of 1, 10, 30, 100 (filenames ZZSP1, ZZSP10, ZZSP30, ZZSP100).



### 5.3 Solar cells

For solar cells the parameter **NEX** should be set to 0 or 1 corresponding respectively to AM0 and AM1 distributions. Small values of **RA** should be used. To illustrate simulation of solar cells we generate carrier concentration plots versus depth using the file TEXSOL4 shown below for a forward bias **VCIN** = -0.4. Also simulated is the same diode for **VCIN**=-0.5 (TEXSOL5) and **VCIN**=-0.55 (TEXSOL55).

```
&TITLE
  TEXSOL4: AM0 ILLUMINATION SOLAR CELL BSF EXAMPLE (ID=50)  vcin=-0.4
&PARAM
# diode parameters
  ID=50,NEX=0,
# impurity profile parameters
  NE1=3.E20,NB1=1.0,NEPI=1.E16,
  XJ1=0.5E-04,XEND=200.E-04,XSUBO=0.0,XSUB=3.E-04,NSUBO=1.E20,
# lifetime parameters,
  TAUC=30.E-06,ITAUC=1,NTAUC=1.E16,SOX=1.E3,
# miscellaneous parameters
  IEDGE=0,VCIN=-0.4,
  njplot=1,
  ra=1.1,
&END
```



The .lst file contains the following information(ETA is the overall efficiency)

AM0 SUN RESULTS: VCIN	JDIFF	JSCL	JEPI	JTOTAL	ETA
-.400E+00	.653E-02	.350E-02	.399E-01	.485E-01	.143E+00
-.500E+00	.624E-02	.293E-02	.398E-01	.397E-01	.147E+00
-.550E+00	.408E-02	.270E-02	.362E-01	.198E-01	.803E-01

## 6.USE OF BIPOLE3 EXTENSION MODULES

### 6.1 SPI Module for SPICE parameter extraction

We will use the above file TEX4 as an example. The SPICE parameter generation parameters are defined in Reference Manual Sect. 9.1.

**MODEL=4, MSPICE=1** is the most useful set; this forces Bipole3 to carry out simulations at two values of collector-base voltage one is **VCIN**, the second one is determined by the parameters **FVCIN, VCINF** as defined in Reference Manual Sect. 5.2. The default values are often adequate..

It is important before attempting to extract SPICE parameters to ensure that the collector current range is adequate to provide low current and high current and  $f_t$  fall-off regions. In this example we have decreased **VBEMIN** to 0.6 to ensure that the low-current fall-off region exists. The following parameters have been added to the tex4.bip file to create a file tex4m.bip.

```
model=4,mspice=1,mre=1,
```

```
vbemin=0.6,vcin=0.5,
```

The tex4m.lst file contains the SPICE file at the end. Alternatively the SPICE file is written to a file tex4m.wmo if **MODEL=40** is used instead of **MODEL=4**.

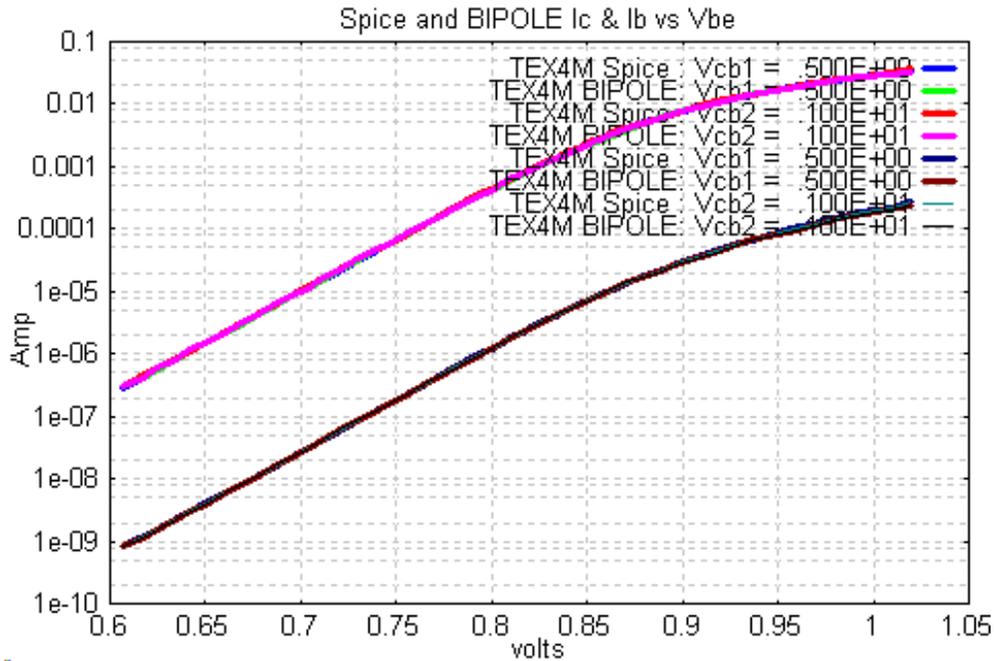
SPICE 2G6 Gummel-Poon model parameters:

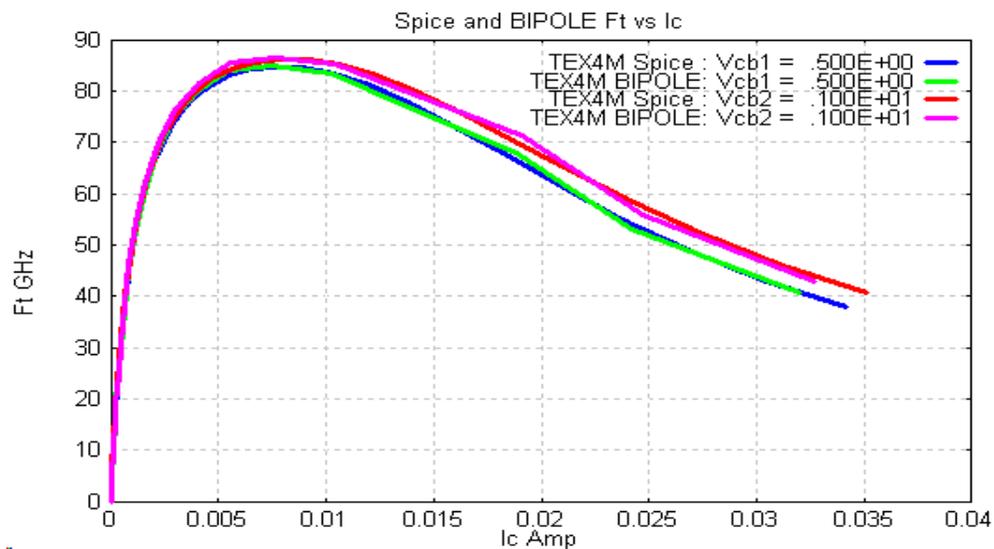
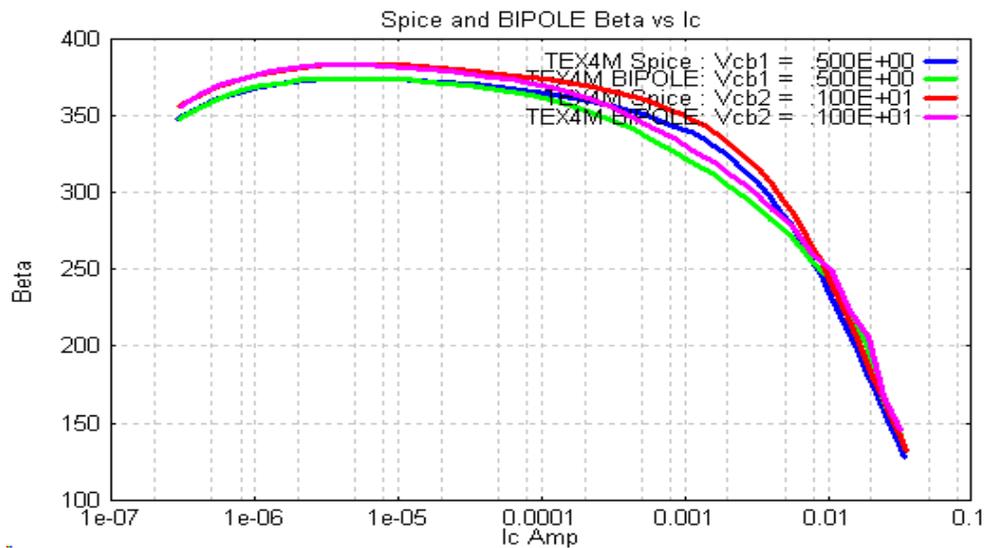
```
.MODEL M1.1 NPN
+ IS = 2.34E-17 ISE = 3.14E-14 ISC = 3.84E-14 IKF = 3.43E-02
+ IKR = 1.92E-01 ITF = 1.93E-01 BF = 5.06E+02 BR = 6.26E+00
+ NC = 2.00E+00 NE = 2.90E+00 VAF = 2.78E+01 VAR = 2.61E+00
+ RB = 2.66E+01 RBM = 6.06E-03 RE = 2.37E+00 RC = 1.05E+01
+ CJE = 2.24E-14 CJC = 1.06E-14 CJS = 1.63E-13 FC = 8.00E-01
+ VJE = 9.61E-01 VJC = 8.93E-01 VJS = 5.91E-01 XCJC = 2.83E-01
+ MJE = 4.55E-01 MJC = 3.66E-01 MJS = 2.90E-01 TR = 7.27E-10
+ TF = 1.39E-12 VTF = 2.94E+00 XTF = 3.72E+00 PTF = 5.28E+01
*+ RC=2.95E+01
```

An extra parameter **NTEMP** = 1 is necessary for extraction of the temperature parameters in the SPICE file. This generates an additional set of SPICE parameters as follows:

```
+ XTB = 5.15E-01 EG = 1.11E+00 XTI = 2.89E+00
```

Bipole3 provides two means of verifying the accuracy of the extracted SPICE model parameters. In the .lst file is a list of extraction accuracy. Using the GRAPH menus, the terminal characteristics generated by the Bipole3 simulation and directly from the SPICE equations may be compared. Below we show such graphs for Gummel plots (dc base and collector currents vs  $V_{BE}$ ), current gain vs  $I_C$ ,  $f_t$  vs  $I_C$ ; all plots are for the two values of  $V_{CB}$  (**VCIN**) used in the extraction. If the agreement is not satisfactory, the user can re-run with different conditions (e.g. adjust the bias range parameter values such as: **VCINF,FVCIN,VBEMIN,VBEMAX**).





## 6.2 BIP2NEUT Extension Module for 2D injection

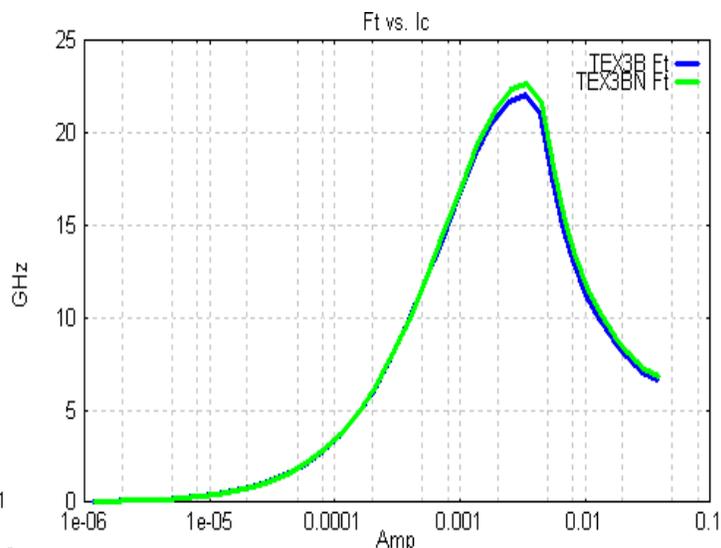
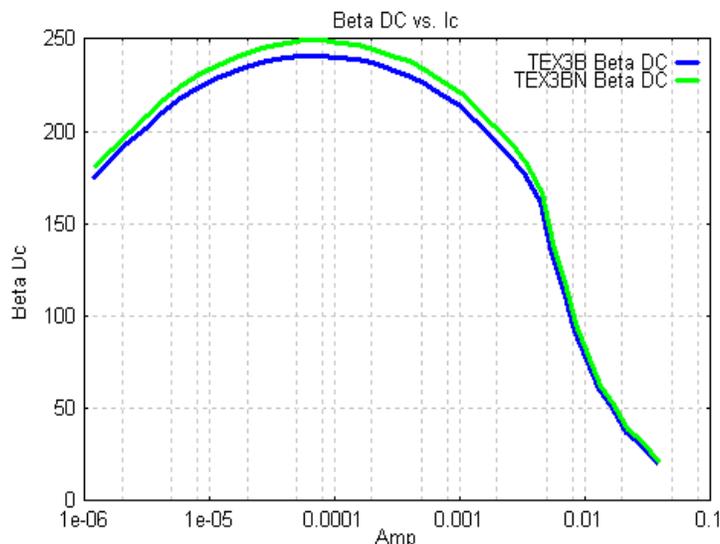
### 6.2.1 Vertical NPN transistors

This Extension Module is described in detail in the Bipole3 Reference Manual Sect. 9.4. Here we limit the examples to extraction of values for sidewall injection parameters FELAT, FQLAT

To invoke the Bip2neut Extension Module for determination of the **FELAT**, **FQLAT** parameters, specify **NEUT2D = 1** in the input file. This executes a full 2D simulation of the quasi neutral base region for a fixed low  $V_{BE}$  bias. The values of FELAT, FQLAT are extracted and printed in the .lst file. For the 25 GHz BJT TEX3B.BIP the following results are found from the .lst file (a value **VBE2D=0.5** has been added to the input file according to the warning).

```
FELAT      FQLAT
.424E+00   .476E+00
```

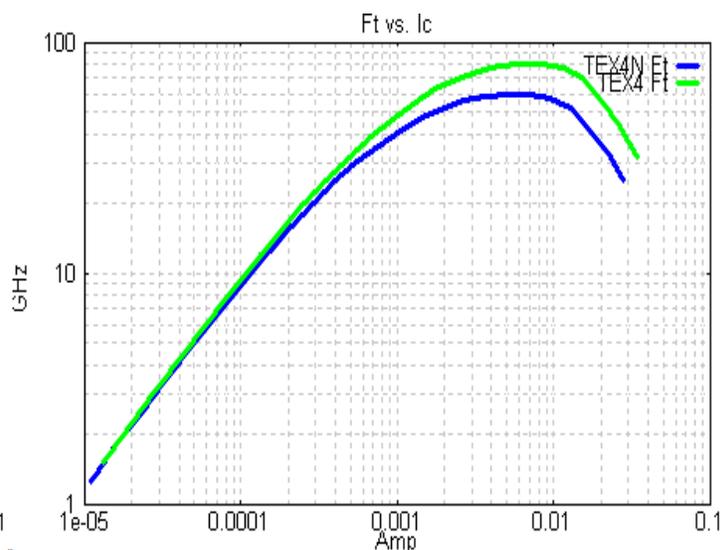
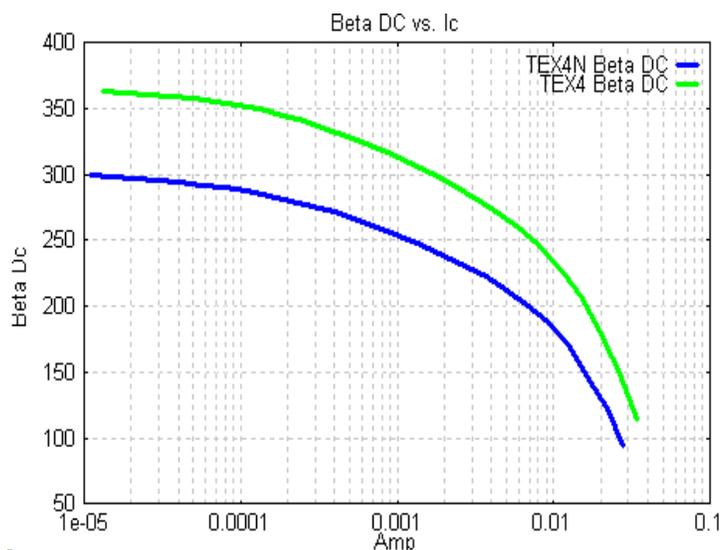
The following Bipgraph results illustrate the difference in terminal characteristics between the default values and the Bip2neut extracted values.



The results are not significantly different. These values may now be inserted in the input file and the **NEUT2D** parameter deleted. The values will only change for large variations in the impurity profile so for "fine tuning" of device optimization it is usually not necessary to run Bip2neut more than once. Let us now perform the same comparison on the 70 GHz HBT TEX4.BIP, adding **NEUT2D=1** to create a file tex4n.bip. The values thus obtained are as follows:

```
FELAT      FQLAT
.214E+01   .108E+03
```

The corresponding changes in output characteristics are shown below.



These results show that for very shallow junction HBT devices it is advisable to use Bip2neut for determination of the FELAT, FQLAT parameters.

### 6.2.2 Lateral PNP transistors

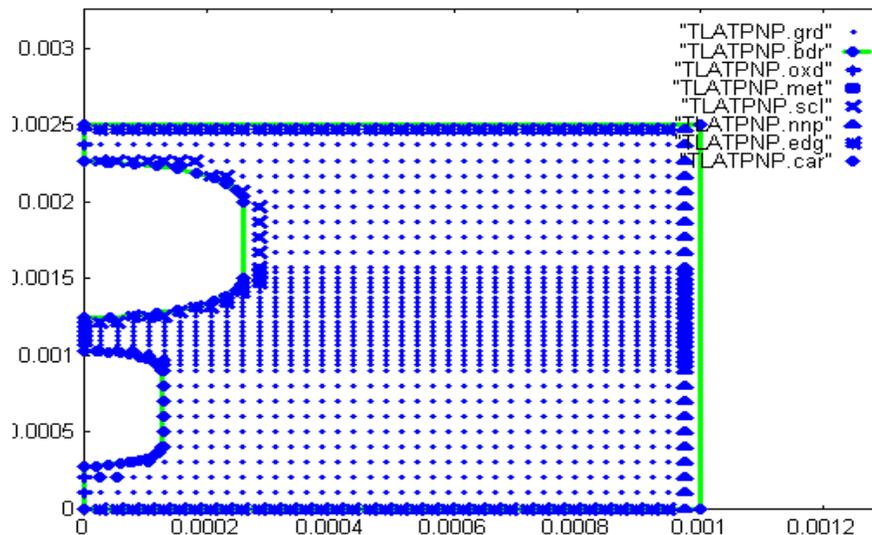
The following file illustrates the use of the BIP2NEUT Extension Module for lateral PNP analysis. Note the inclusion of **IGRAPH=6** to generate the following GRAPH plots.

```
&TITLE
  TLATPNP: Lateral PNP 2-D Neutral Base Region using BIP2NEUT:
  (No Buried Layer)
&PARAM
# BIPTWOD plotting parameter
  igrph=6
# Lifetime Parameters:
  itaue=1, itaub=1, ntaue=1.0e17, ntaub=1.0e17,
# cn=0.5e-31,
  taue=1.0e-05, taub=1.0e-05,
  itauc=1, tauc=1.0e-05, ntauc=1.0e17,
#1d Vertical NPN Parameters
  impur=0,
  xj1=0.6e-04,xj2=1.0e-04,xend=10.0e-04,
  nel=1.0e21,nbl=2.0e19,nepi=1.0e16,
#2d Lateral PNP Parameters
  ne3=0.0,
  nsubo=0.0 ,xsub=0.2e-04,nsub=2.0,xsubo=6.0e-04,
  esp=4.0e-04,wps=1.0e-04,wpc=3.0e-04,wpb=6.0e-04,
  elps=25.0e-04,snn=0.0,
#2DN parameters
  neut2d = 3,
  vsat = 1.0e07,soxb=1.0e01,soxe=1.0e01,sme=1.0e06,
  nx=40, ny=40, iedge=1,
  outsel=1, jscale=25.0,
  tdebug=1,
&END
```

The following plot shows the cross-section and grid. This is obtained by typing:

plotmesh filename

In the PC GUI version the plot is available in the GRAPH menus.

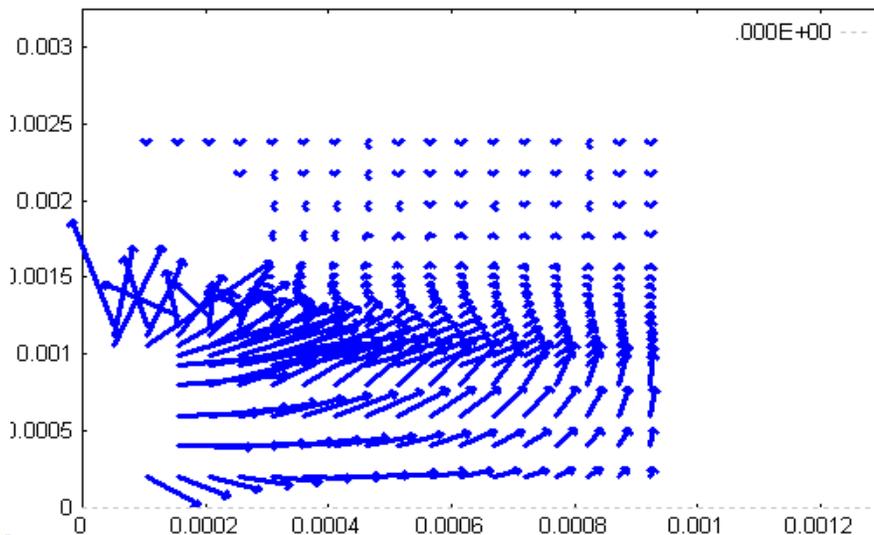


Next is shown the current vectors obtained by typing:

plotcur filename

or directly using the PC GUI GRAPH menus.

This plot is followed below by the .lst file giving the various currents, gain and delay time for this device.



BIP2NEUT 2-D simulation (per cm):

IBBM	IBBO	IBBR	IBB	IC
.000E+00	.695E-07	.106E-05	.113E-05	.154E-03
IBEM	IBEO	IBER	IBE	IB
.333E-04	.880E-08	.870E-06	.342E-04	.364E-04
Is(tot)	BETAP	Tdelay(LAT-PNP)		
.252E-16	.423E+01	.206E-07		

### 6.3 RCCALC Extension Module for 2D collector resistance

This Extension Module carries out 2D majority current flow simulation in both the x-y and y-z planes. It is useful when the collector buried layer and/or sinker does not have a sufficiently high doping concentration to reduce the collector resistance to a very low value. We illustrate use of RCCALC using the TEX2B file as a starting point. To use RCCALC, all mask dimensions must be specified, so we use an editor to edit TEX2B.BIP and copy the mask data from TEX2B.LST into a new file TEXRC.BIP. To get a reasonable device to illustrate the use of RCCALC the epitaxial layer doping **NEPI** is increased to 1.E16 with **VCIN** = 2.0 and we specify a maximum simulation depth **XEND**= 4.E-04. The complete file is shown below:

```
&TITLE
TEXRC: RCCALC Extension Module example
&PARAM
# Epitaxial layer data
  NEPI=1.E16,tepi=3.e-04,xend=4.e-04,
# mask parameters copied from tex2b.lst file
ELEM = 2.00E-04
B      = 1.40E-03  ESB  = 2.00E-04  ECB  = 2.00E-04
BPB   = 1.80E-03  ELPB = 1.00E-03  WPS  = 5.00E-05
ELPS  = 2.20E-03  ELNS  = 1.80E-03  BPS  = 2.60E-03  BNS  = 2.20E-03
ELCN  = 2.00E-04  ELEN  = 8.00E-04  ELC  = 2.00E-04  BPC  = 2.00E-03
IC=1,mask=1,
```

```
# parameter to reduce Ic current increase step
crlat=1.2,
# RCCALC parameters
irc=-2
nbur = 1,irc=3,icirc=1,
nbur=3,
#
vcin=2.
&END
```

As per Bipole3 Reference Manual Sect. 9.3, the values of **NBUR**, **IRC**, **ICIRC** must be specified to invoke and use **RCCALC**.

To show the usefulness of this Extension Module we examine this BJT and then compare the results with a device which is the same except that the position of the base contact is moved to the far side of the collector sinker, thus providing a shorter collector current path. The second device **TEXRCL1** has **LOCAT=1**, with the value of collector sinker to emitter edge **ELEN** changed from 8.E-04 to **ELEN=2.5 E-04**.

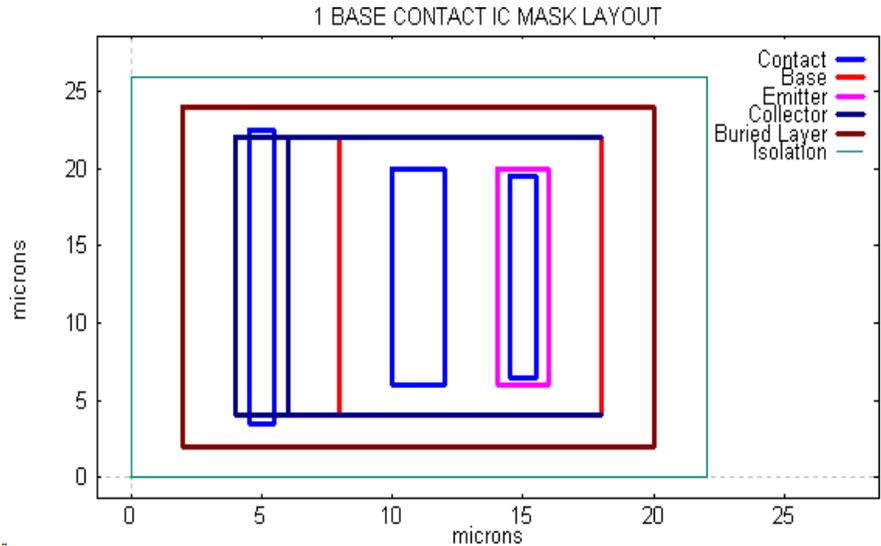
Execution of this file generates a .lst file with values of collector resistance in each plane extracted. Files are also produced which enable graphs of current flow to be visualised as shown below by typing:

plotrcyz filename for Y-Z plane plots

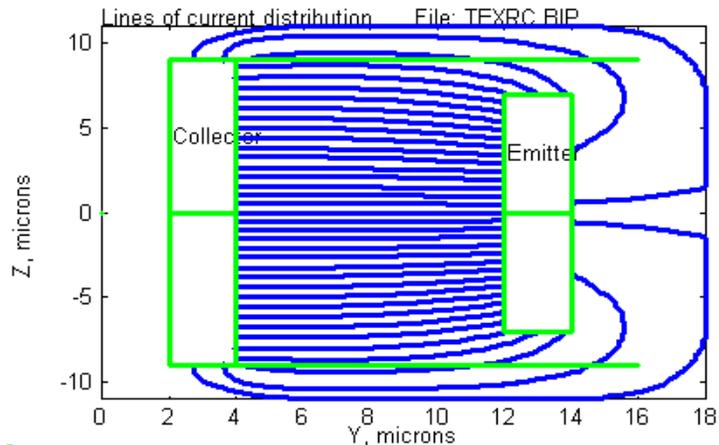
plotrcxy filename for X-Y plane plots

In the PC GUI version both these plots are available in the *2D Plots* GRAPH menu.

**TEXRC file: LOCAT=0, ELEN=8 um**

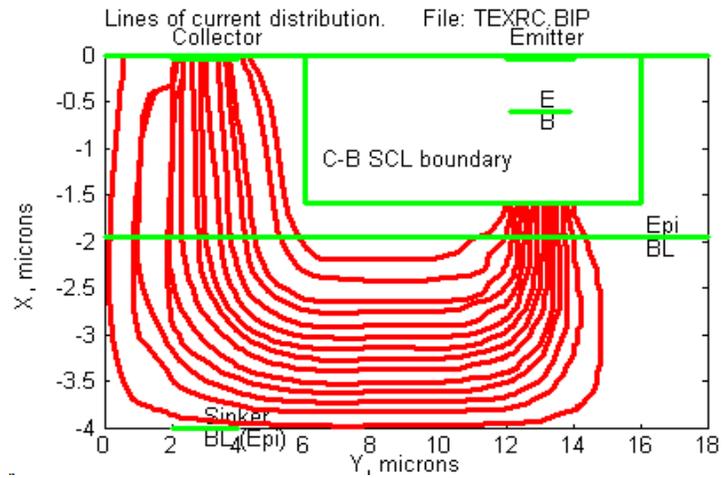


**Current flow in Y-Z plane**

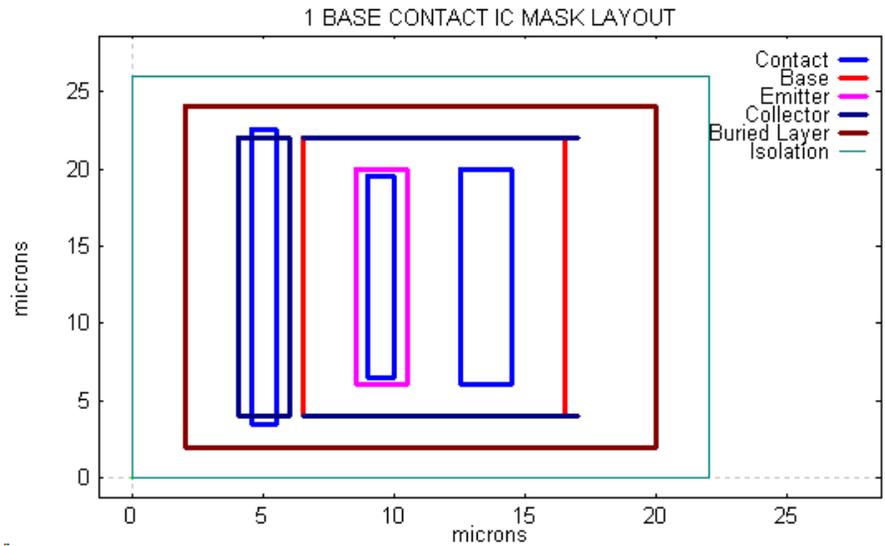


**Current flow in X-Y plane**

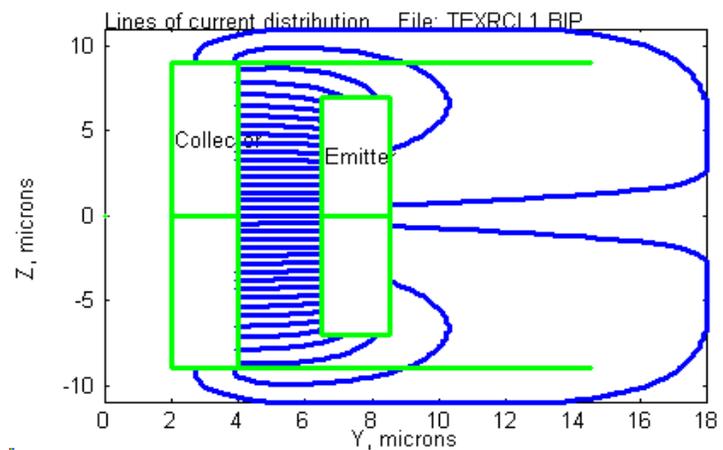
From .lst file,  $R_{ctot} = 67 + 175 = 242 \text{ ohm}$



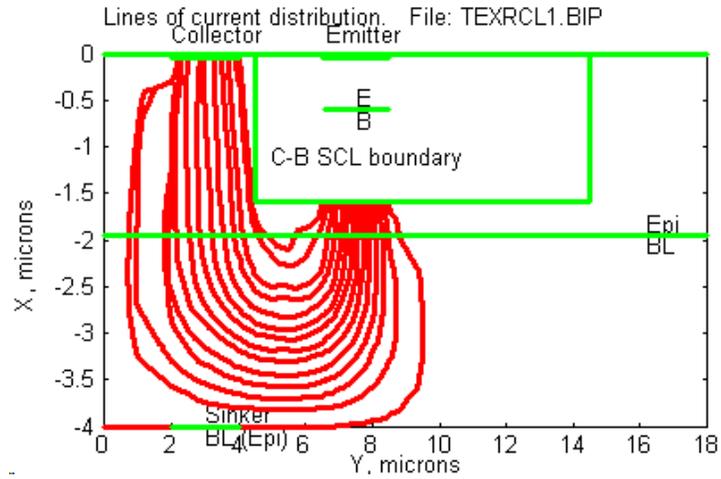
**TEXRCL1 file: locat=1, elen=2.5 um**



**current flow in Y - Z plane**

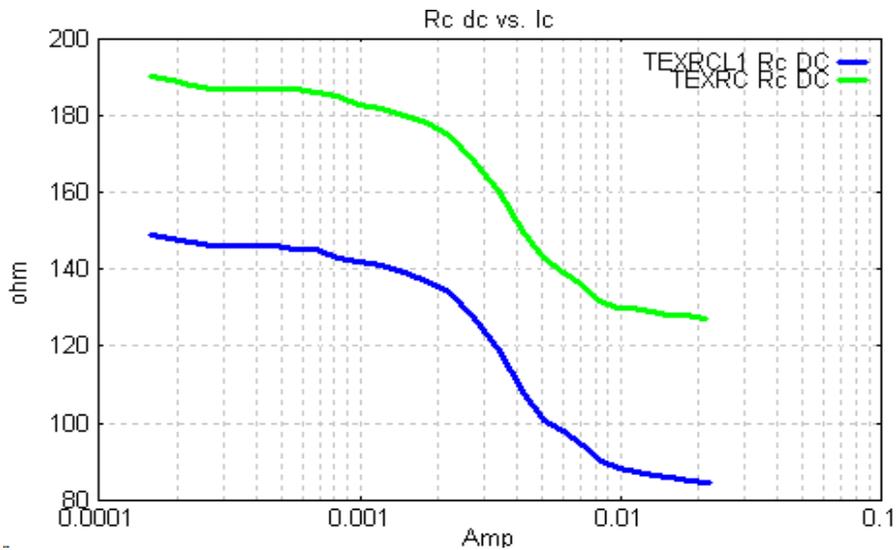


current flow in X-Y plane

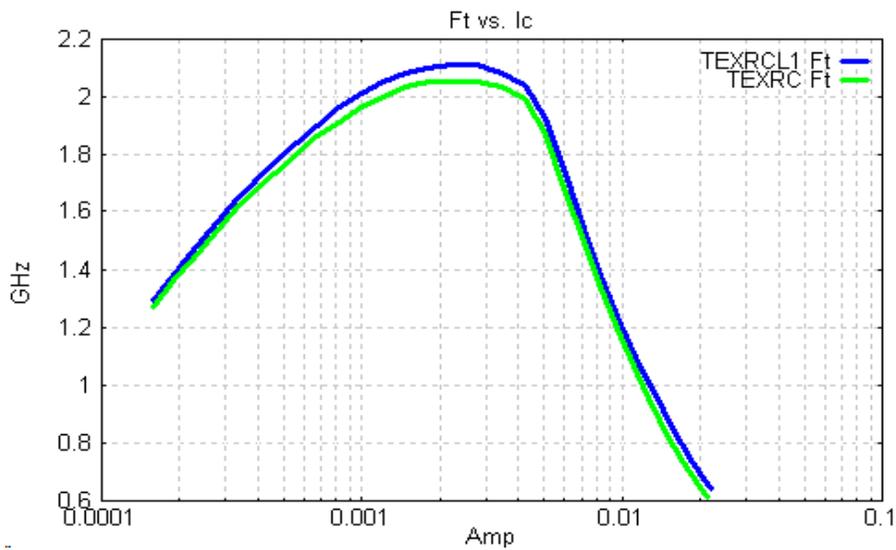


From .lst file  $R_{ctot} = 27 + 129 = 159 \text{ ohm}$

The collector resistance of the two devices may be readily compared using Bipgraph "Internal Characteristics vs IC" as shown below.



The terminal characteristics in this transistor are only slightly influenced by the layout - see the  $f_t$  vs  $I_C$  plot below.



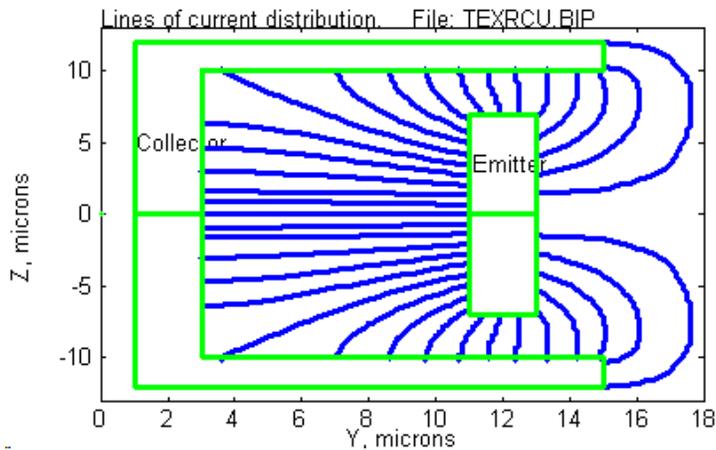
The main use of RCCALC is for certain BiCMOS BJT structures in which the buried layer may not be doped sufficiently to maintain a low collector resistance. In this case, the advantage of using more complex layouts such as a U or a rectangular sinker configuration may be studied using **ICIRC** = 1 or 2. We now examine the effect of adding a U shaped collector sinker using **ICIRC**=1. The buried layer and isolation mask dimensions must now be increased to accommodate the extra sinker diffusion. The modified file has the following extra lines to create a file TEXRCU.BIP for the first case (base contact between collector and emitter)

```
# parameters for U collector sinker
icirc=1,elc1=2e-04,
elcn=1e-04,bpc=20e-04,bns=26e-04,bps=30e-04,
```

Execution of RCCALC provides the following current line plot by typing:

plotrcyz filename

or directly with the PC GUI version in the *2D Plots* GRAPH menu.

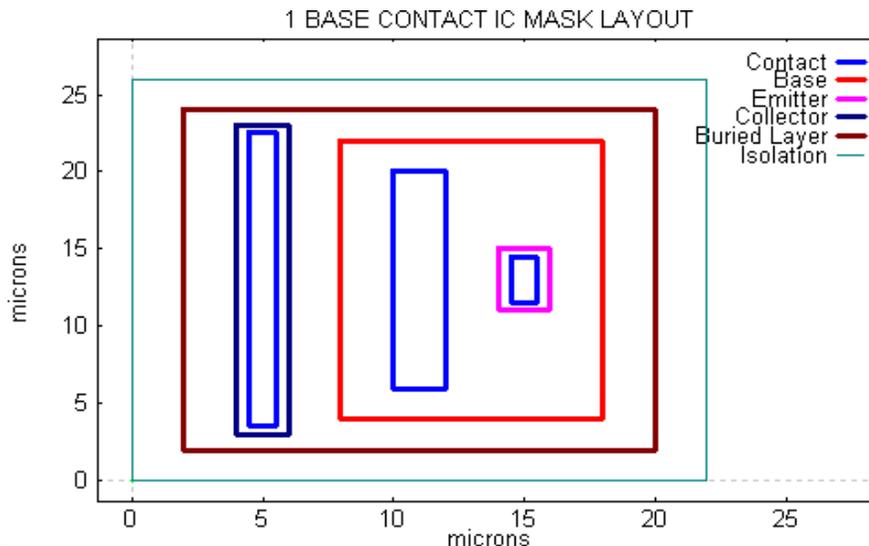


The collector resistance Rctot from the .lst file is reduced from 242 ohm to 176 ohm

## 6.4 RBCALC Module for 2D base resistance

The RBCALC Extension Module performs 2D majority carrier current flow simulations in the active and extrinsic base regions in a plane parallel to the surface. It is intended for use in integrated BJT structures in which the base contact layout is such that the one dimensional treatment in the basic Bipole3 simulation is not sufficiently accurate. This occurs particularly in single base contact structures with a significant amount of current flow around the emitter diffusion outside the active region. It is invoked using the **IRB** input parameter. We use the file TEXRC but modify the emitter dimensions by setting **B=2.E-04** (2 um emitter) to illustrate more clearly the use of the RBCALC module. The resulting input file TEXRB.BIP and mask is shown below:

```
&TITLE
TEXRBa: RBCALC Extension Module example
      using IRB=3
&PARAM
# Epitaxial layer data
  NEPI=1.E16,tepi=3.e-04,xend=4.e-04,
# mask parameters copied from tex2b.lst file
  ELEM = 2.00E-04
  B     = 1.40E-03  ESB  = 2.00E-04  ECB  = 2.00E-04
  BPB  = 1.80E-03  ELPB = 1.00E-03  WPS  = 5.00E-05
  ELPS = 2.20E-03  ELNS = 1.80E-03  BPS  = 2.60E-03  BNS  = 2.20E-03
  ELCN = 2.00E-04  ELEN = 8.00E-04  ELC  = 2.00E-04  BPC  = 2.00E-03
  IC=1,mask=1,
  b = 4e-04, bbased=14e-04,
# parameter to reduce Ic current increase step
  crlat=1.2,
  nbur=3,
#
  vcin=2.
  facn = 3,
# rbcalc parameters
  irb=3,del03d = 0.025,
  crej = 1.4, ntot = 15,
  iglat=2,igraph=10,
&END
```



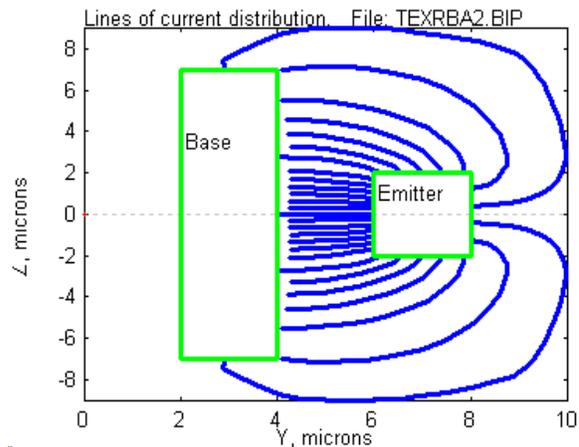
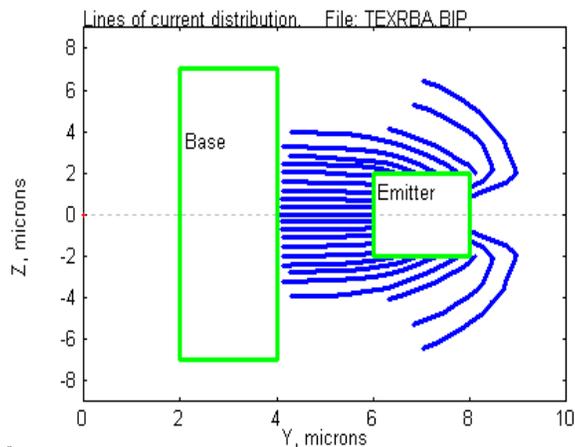
Setting **IGLAT** to the nth value of Lateral Simulation current in the .lst file, with **IGRAPH**=10 provides graph plots of current lines. For **IGLAT**=2 ( $V_{be} = 0.785$ ) and **IGLAT**=12 ( $V_{be} = 1.02$ ) the following plots are obtained by typing:

plotrb filename

In the PC GUI version this plot is available directly in the *2D Plots* GRAPH menu.

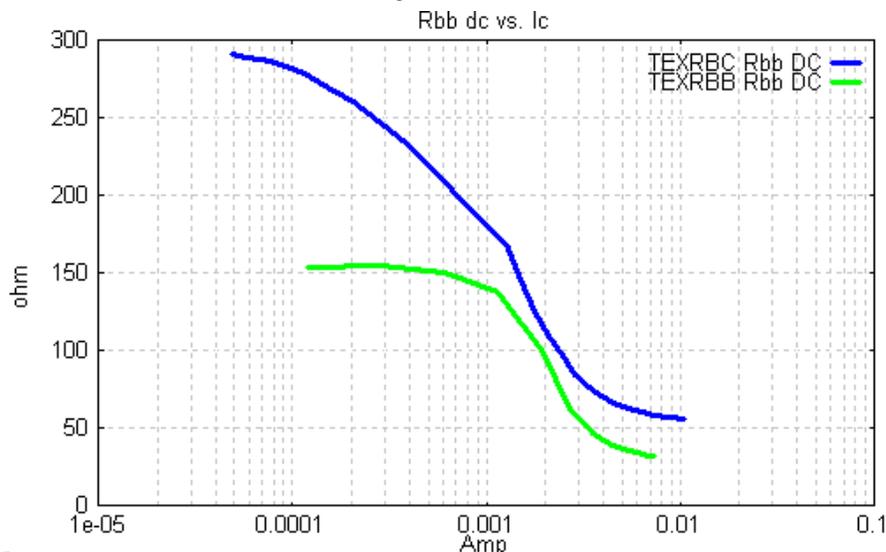
$V_{be} = 0.785$

$V_{be} = 1.02$

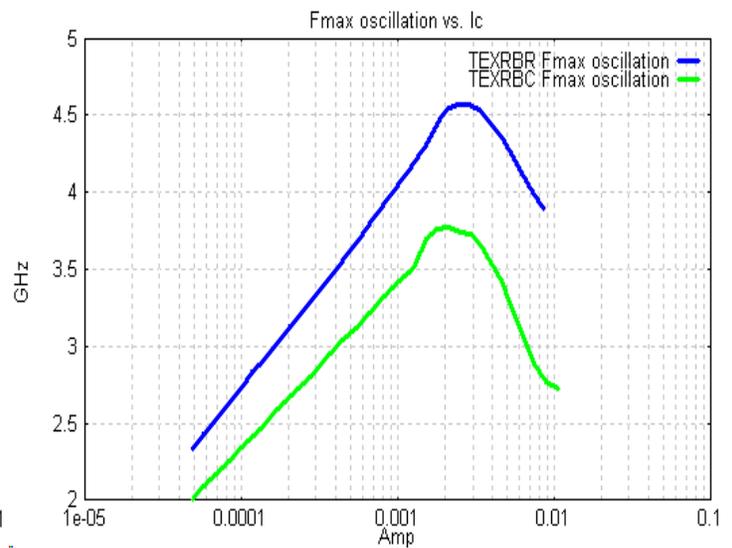
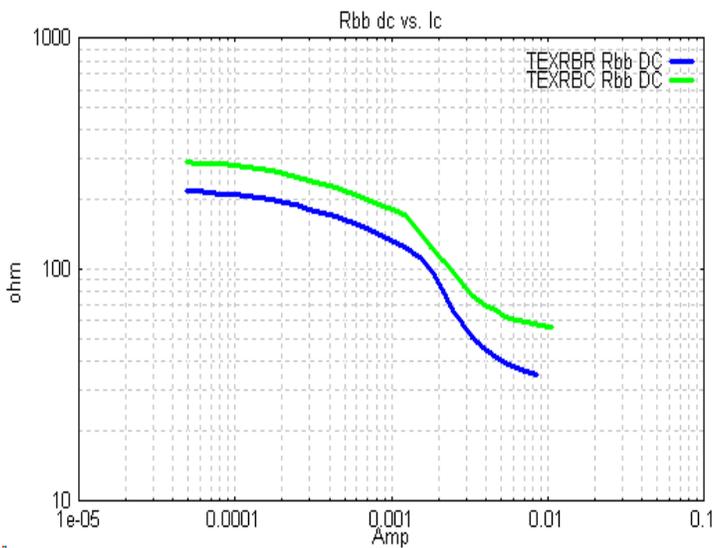


The corresponding values of base resistance (from the .lst file) are: 155 and 32.7 ohm

By executing the same file with the line **igraph=10,iglat=2**, deleted one can obtain the normal Bipgraph plots. Below we show the plot of  $R_{bdc}$  vs  $I_c$  from the Internal Characteristics vs  $I_c$  menu using RBCALC (TEXRBB) and without RBCALC (TEXRBC)



The base resistance value using RBCALC is significantly lower because two dimensional current flow around the emitter is simulated. For computational reasons, high frequency behaviour is best simulated using the 'Reduced' form of RBCALC. using **I3D=1,MRB=1**. This also give substantially faster execution time by performing the complete 2D simulation at only very low and very high  $V_{BE}$  bias. The file TEXRBR illustrates this type of simulation. It is instructive to compare results obtained with only Bipole3 directly TEXRBC, and results obtained with the Reduced RBCALC simulation TEXRBR. Below we show dc base resistance from the "Internal Characteristics vs  $I_c$ " menu,  $f_{maxosc}$  vs  $I_c$  from "Terminal Characteristics" menu. Note that  $f_t$  vs  $I_c$  and  $\beta$  vs  $I_c$  are practically unchanged because these characteristics are nearly independent of base resistance variations.



In summary, the full form of RBCALC is useful for detailed studies of the effects of mask layout on base resistance. The Reduced form using **I3D=1,MRB=1** is recommended for the study of terminal characteristics, particularly  $f_t$  and  $f_{maxosc}$ .

Finally, it may be noted that RCCALC and reduced RBCALC may be combined as in the distribution example RCRBSIM.BIP

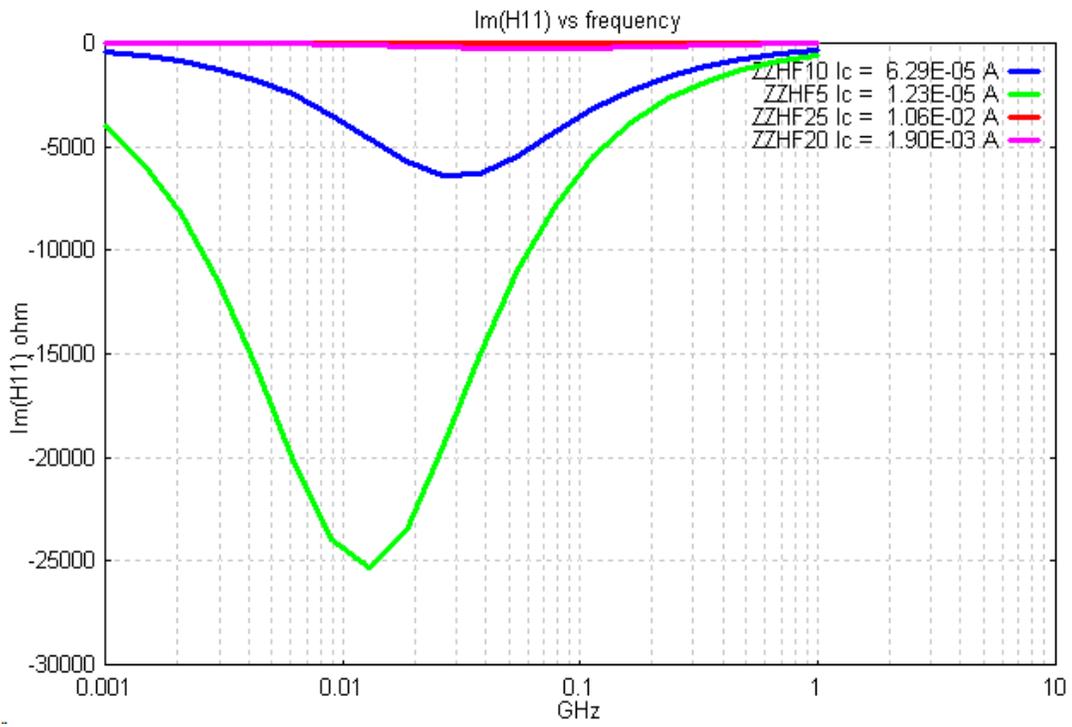
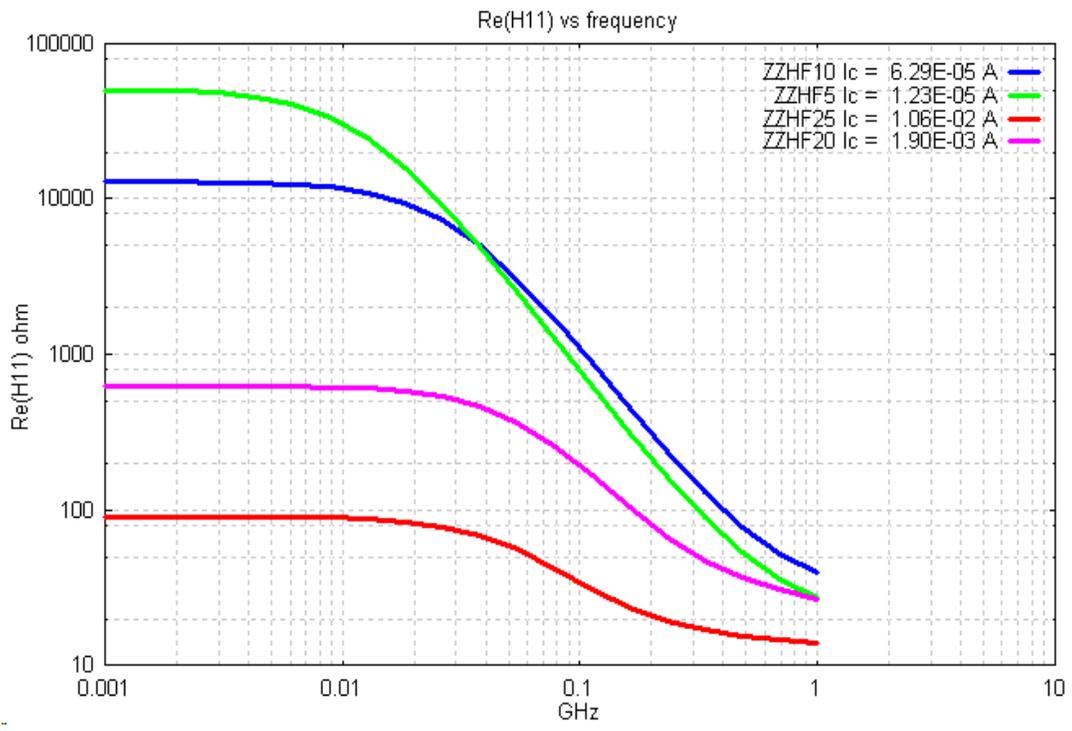
### 6.5 HFCALC Extension Module for small signal high frequency h, y, z, s parameters

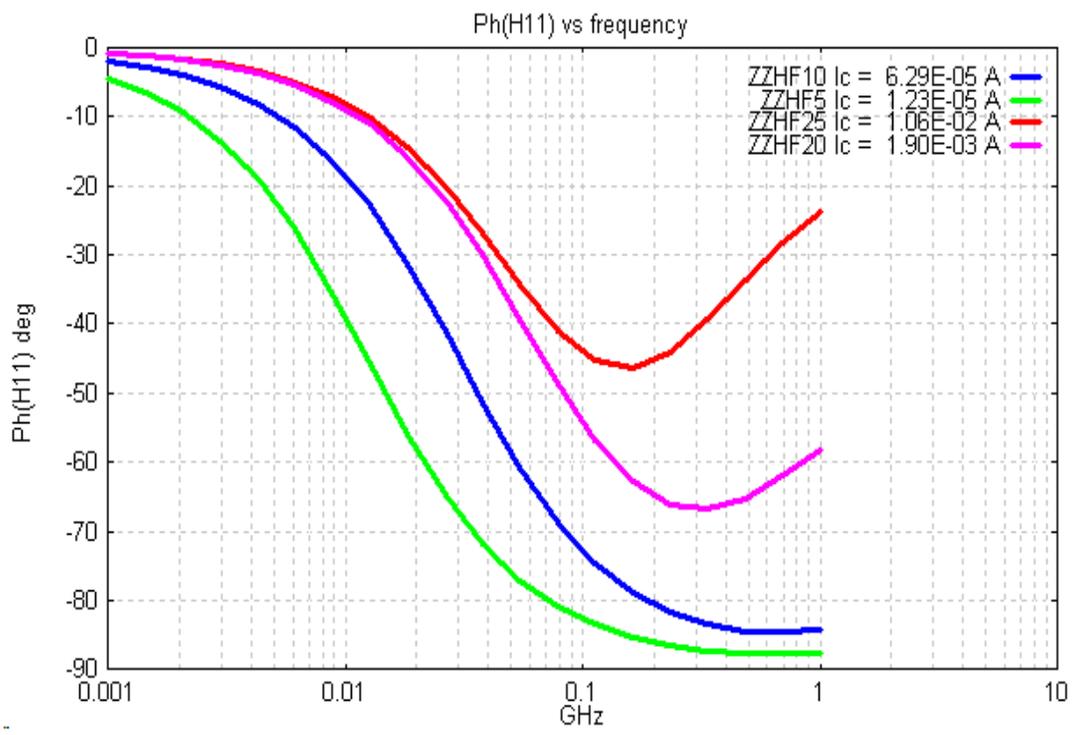
This module uses a combination of small signal time dependent solutions of the transport equations in the vertical plane with a distributed equivalent circuit representation in the lateral (horizontal) direction to simulate the transistor at high frequencies for a specified dc bias. It is invoked by specifying **IHFC =1** in the input file.

The file TEXHFC will be used to illustrate the use of the HFCALC module with **ISECT = 5** (default) corresponding to a 5 section lateral representation giving a reasonably accurate simulation of the 2D high frequency effects.

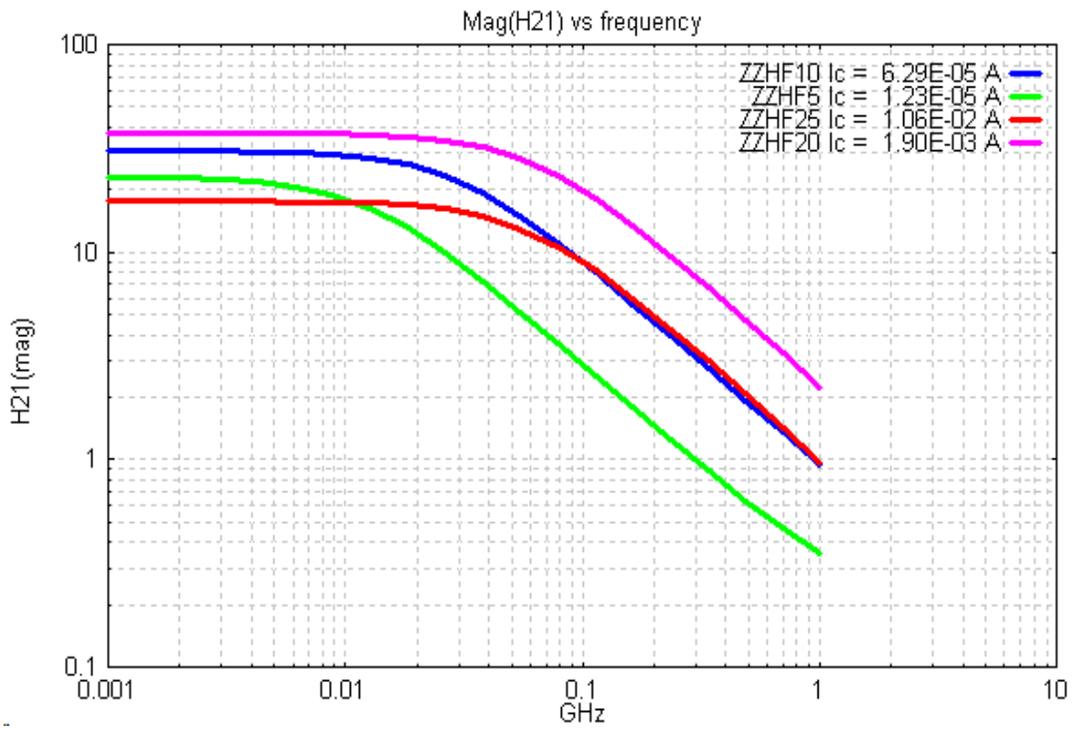
We have used **IGLAT=5, 10, 20, 25** corresponding (from the 1st file Lateral Simulation table) to collector currents of 0.012 mA, .063 mA, 1.9 mA and 10.6 mA respectively ( $f_t$  peaks for this transistor with a value of 2.2 GHz for  $I_c = 2mA$ ).

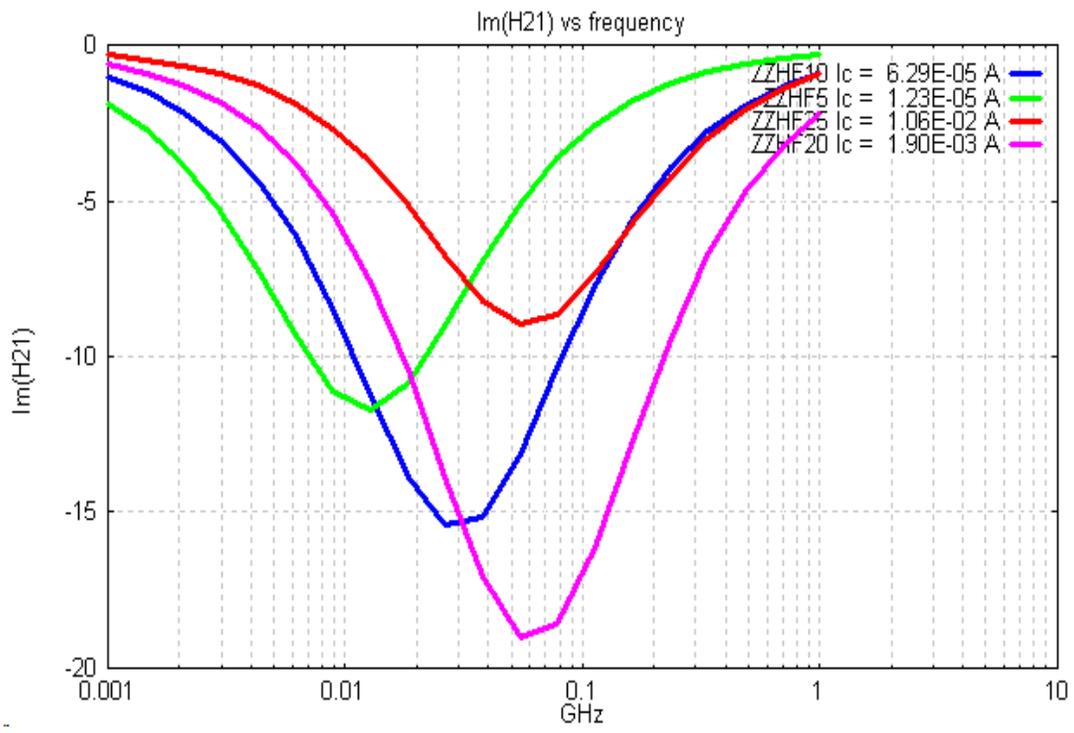
The results of the small signal high frequency simulation are available in the GRAPH menu as H, Y, Z and S parameters. The first graphs below show h11 Real, Imaginary, Phase versus frequency; each of the four bias points used correspond to one curve.





The next two graphs show h21 magnitude and phase versus frequency.





## 7. MOSFET Extension Module for MOSFET simulation

Although Bipole3 was developed for bipolar transistors, the MOSCALC module was added to allow prototype simulation of MOSFET devices.

The purpose of the **MOSCALC** extension module is to provide MOSFET simulation compatible with the fast execution time and ease of use of BIPOLE3. The simulation is for a self aligned gate MOSFET structure and is based on vertical numerical integration of Poisson's equation including free carrier charge. (single Gaussian vertical impurity profiles are used to define threshold adjustment implants) coupled to horizontal numerical integration of the majority carrier drift equation in the conducting channel. Poisson's equation in polar coordinate solution is used for the drain-substrate space charge region. Mobility dependence on doping level and on both vertical and horizontal electric fields is included.

The output consists of tables for a given  $V_{ds}$  including  $I_{ds}$ ,  $g_m$ , source-drain transit time  $t_{ds}$  and figure of merit  $C_{ox}/g_m$ .

BIPOLE3 graphs are provided for the following quantities:

- band, electric field and inversion layer charge versus depth diagrams for given surface potential
- inversion layer charge, surface potential, gate capacitance (high and low frequency) versus gate potential
- graphs of horizontal electric field and velocity versus 'y' for given  $V_{gs}$  and  $I_{ds}$
- graphs of  $I_{ds}$  vs  $V_{ds}$  for different  $V_{gs}$  values, and of  $I_{ds}$  vs  $V_{gs}$  at a specified  $V_{ds}$ .

The following examples illustrate some possibilities using this software. Note that the distribution files contain more examples, such as use of `mostyp=3` and `mostyp=-3` for  $I_{ds}$  plots and also for velocity and electric field plots versus horizontal distance.

## Examples

As for bipolar transistors, all input parameters have default values given in the Reference Manual. The following is a summary of the most basic values:

LFET	WFET	LS	LD	Nepi	Tox	XJD
.500E-03	.500E-03	.500E-03	.500E-03	.150E+16	.100E+04	.100E-04

LFET is the mask channel length (source to drain direction) in microns

WFET is the mask channel width (perpendicular to LFET) in microns

LS is the mask source length in microns

LD is the mask source length in microns

Nepi is the background channel doping  $\text{cm}^{-3}$

Tox is the oxide thickness in Angstroms

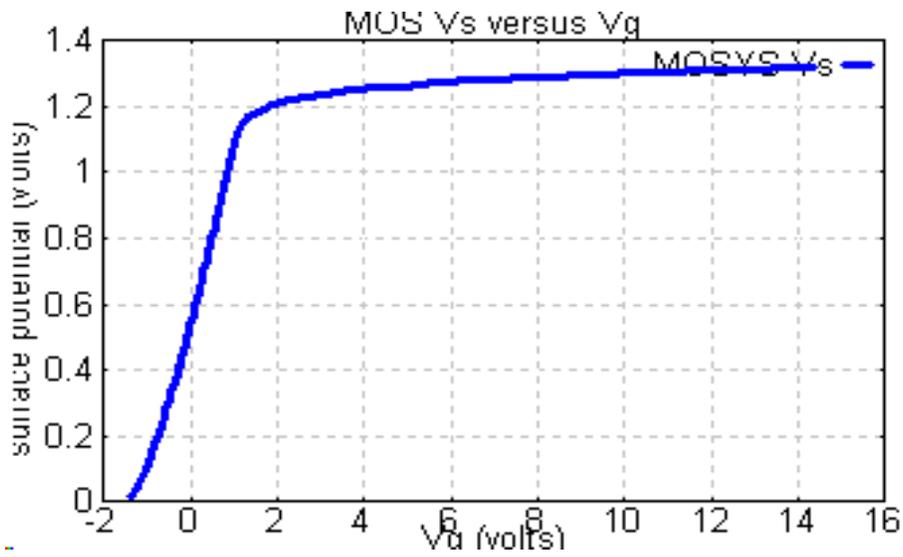
XJD is the source and drain junction depth in microns

### 7.1 Basic MOS properties

The input file `mosys.bip` serves to examine basic MOS properties.

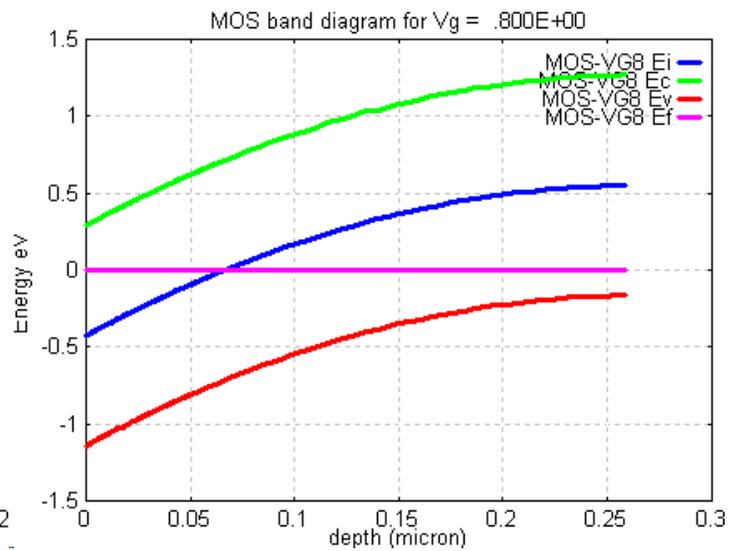
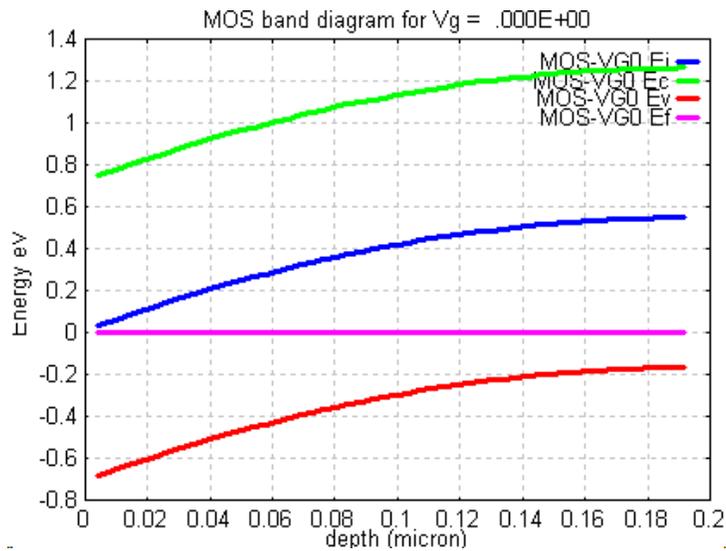
```
&TITLE
MOSYS: Vs vs Vg & gate capacitance simulation
&PARAM
mostyp=2,
# channel properties
nepi=2.e16,tox=500,
# bias values
vdsmax=3,
&END
```

First we show the plot of surface potential  $V_s$  versus gate voltage  $V_g$ .



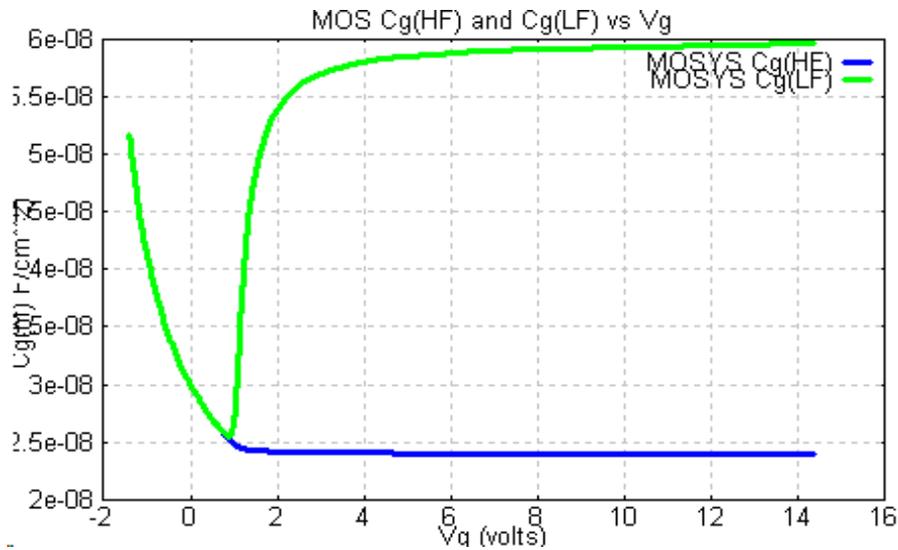
## 7.2 Band diagrams

The band diagrams are available from the BIPGRAPH plots. Below we show band diagrams for the reference MOSFET mosys.bip for two values of gate bias, 0 volts and 0.8 volts



### 7.3 LF and HF capacitance

Next we show plots of low frequency and high frequency gate capacitance versus gate voltage  $V_g$ .



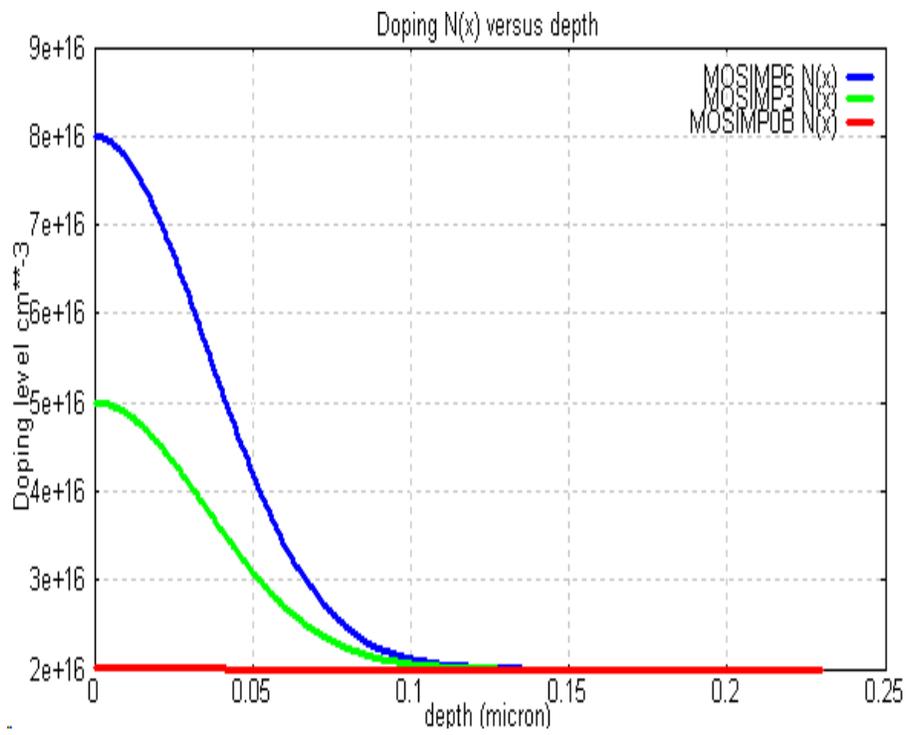
### 7.4 Threshold voltage channel implants

To illustrate the effect of channel implants we use the  $ne_3, xe_3$  gaussian function to represent the implant. The files mosimp0, mosimp3, mosimp6 use  $ne_3=1e14$  (no implant=t),  $3e16$  and  $6e16$  respectively with the gaussian characteristic length in the vertical direction,  $xe_3$  held constant at .05 micron.

The following is the mosimp3 file. MOSIMP3: reference MOSFET for plots vs  $V_s$

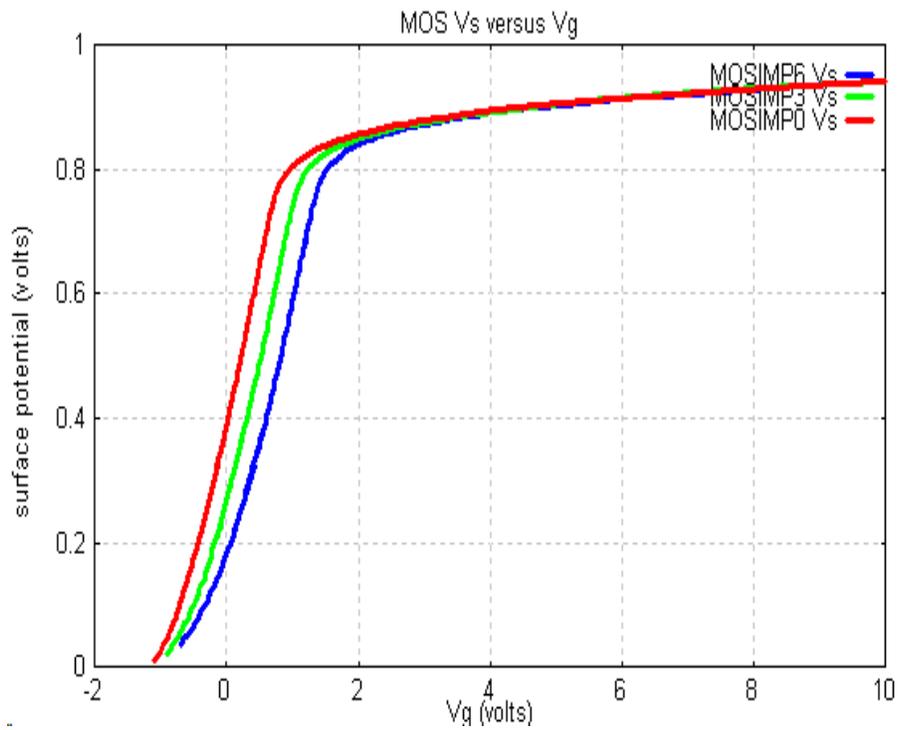
```
&PARAM
mostyp=2,
#doping, oxide thickness,
nepi=2.e16,tox=500,
#channel implant details
ne3=3.e16,xe3=.05e-04,
&END
```

The channel implant impurity profiles are obtained using mostyp=1 to give the following plots.

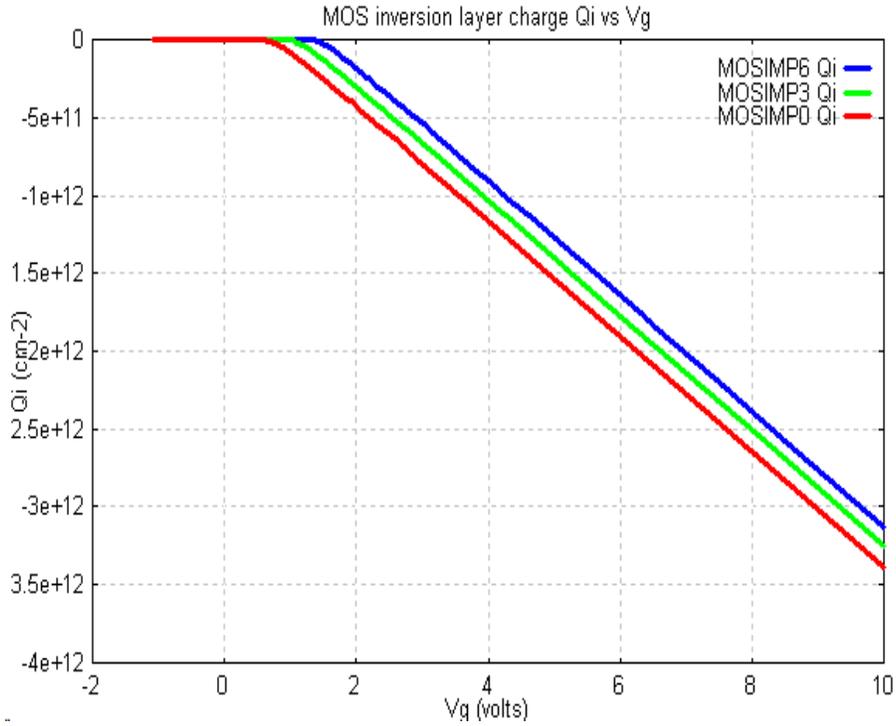


Next we show plots of surface potential vs  $V_g$  and charge  $Q_i$  vs  $V_g$

**$V_s$  versus  $V_g$  plot for different channel implants: MOSIMP0, MOSIMP3, MOSIMP6:**



**Qi versus Vg plot for different channel implants: MOSIMP0, MOSIMP3, MOSIMP6:**



The corresponding values of threshold voltage from the 1st files are as follows:

MOSIMP0: Extracted Vth = .904E+00 volt

MOSIMP3: Extracted Vth = .127E+01 volt

MOSIMP6: Extracted Vth = .162E+01 volt

**7.5 Terminal characteristics**

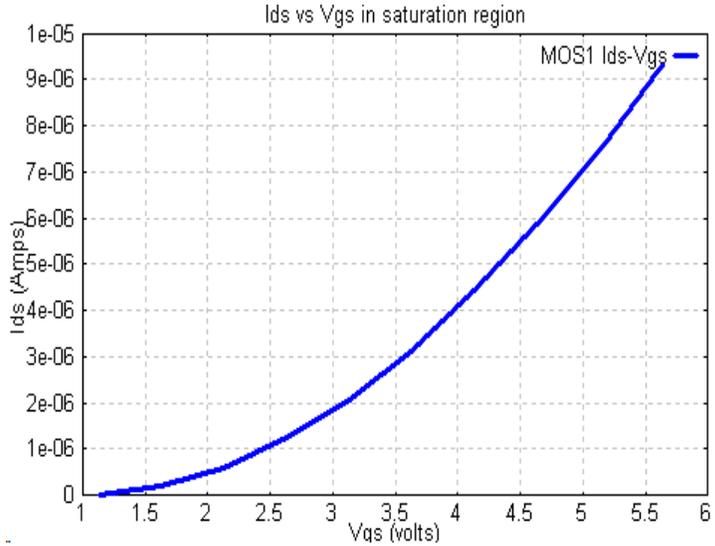
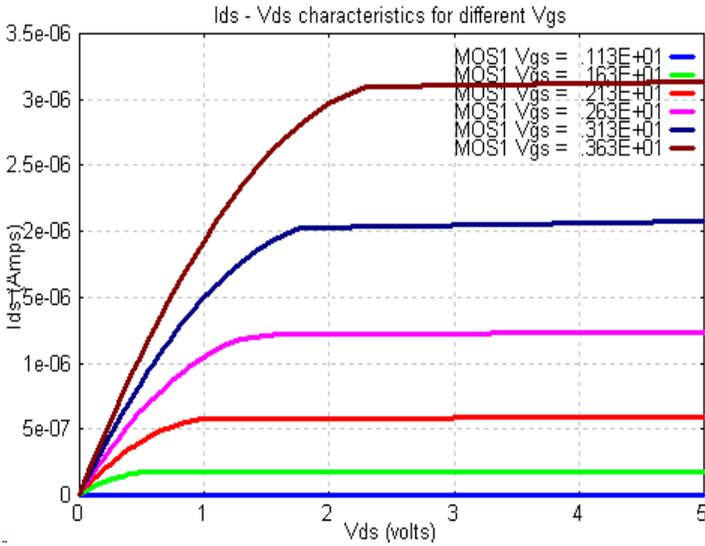
Terminal electrical characteristics are probably the most important results of MOSFET simulation. Below we show BIPGRAPH plots of Ids vs Vds for various Vgs and also Ids vs Vgs in saturation for the reference MOSFET with a mask channel length LFET = 20 um. The maximum Vds bias is 5 V. The initial gate bias is 0 V and the gate bias increment is 0.5 V.

The following is the MOS.BIP file used for a conventional long channel device.

```

&TITLE
MOS1: MOSFET standard reference device
&PARAM
  mostyp=-3,
# mask & other dimensions
  lfet=20e-04,wfet=1.e-04,nepi=2.e16,tox=500,xjd=1.0e-04,
# bias values
  vdsmax=5,vgs=0,dvgs=.5,
&END

```



The following is an extract from the lst file containing capacitances (F) at specified bias, tsd (source drain transit time, sec) gm (transconductance, A/V), ft (unity current gain frequency, Hz)

Vfb = -.124E+01; phif = .370E+00; nominal Vth = .682E+00

Low field channel mobility = .616E+03 cm\*\*2/Vs

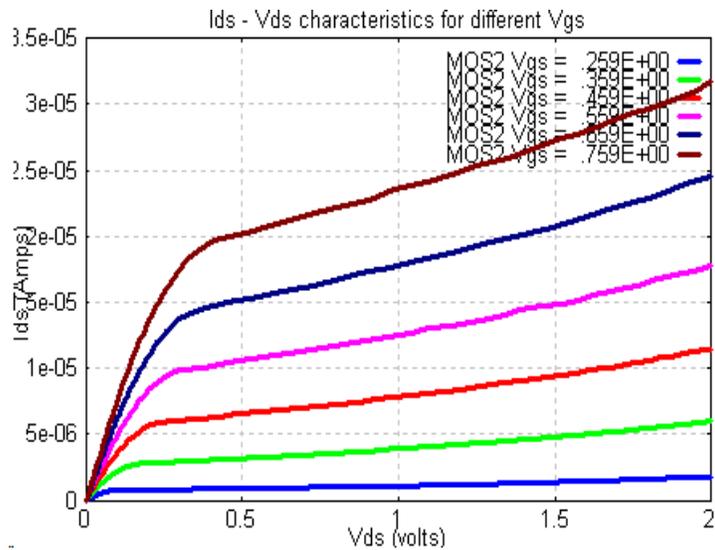
COX	CJS(0)	CJD(Vds)	Cgd
.120E-13	.801E-14	.296E-14	.480E-15

Vgs	Vds	Ids	tsd	gm	COX/tsd	ft
.782E+00	.500E+01	.510E-08	.136E-06	.510E-07	.885E-07	.117E+07
.128E+01	.500E+01	.179E-06	.239E-07	.349E-06	.503E-06	.668E+07
.178E+01	.500E+01	.592E-06	.128E-07	.825E-06	.940E-06	.125E+08
.228E+01	.500E+01	.123E-05	.933E-08	.128E-05	.129E-05	.171E+08
.278E+01	.500E+01	.207E-05	.700E-08	.168E-05	.171E-05	.227E+08
.328E+01	.500E+01	.316E-05	.558E-08	.217E-05	.215E-05	.285E+08
.378E+01	.500E+01	.437E-05	.500E-08	.241E-05	.240E-05	.318E+08
.428E+01	.500E+01	.582E-05	.426E-08	.290E-05	.282E-05	.374E+08
.478E+01	.500E+01	.752E-05	.370E-08	.340E-05	.325E-05	.431E+08
.528E+01	.500E+01	.917E-05	.354E-08	.330E-05	.339E-05	.450E+08

### 7.6 Short channel MOSFET $I_{ds}$ - $V_{ds}$ characteristics

Next we illustrate a short channel device with  $L_{FET} = 1 \mu\text{m}$ ; the other parameters are shown below in the input file MOS2.bip.

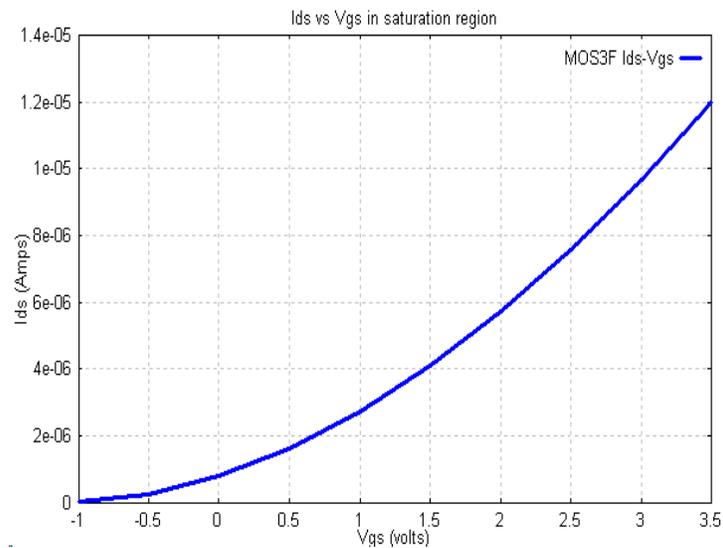
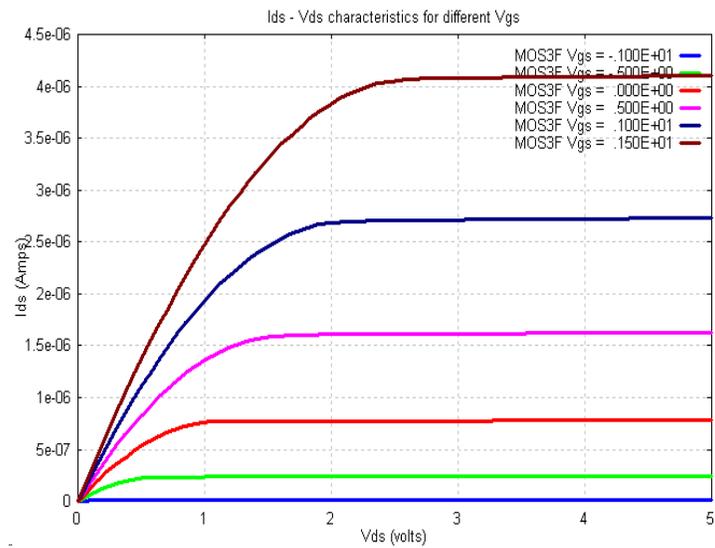
```
&TITLE
MOS2: MOSFET short channel, analytic Poisson solution
&PARAM
# mos simulation parameter
mostyp=-3,
# channel length (mask dimension)
lfet=1.0e-04,
# other dimensions, etc.
wfet=1.e-04,nepi=1.e16,tox=250,xjd=0.27e-04,
# bias values
vdsmax=2,vgs=0,dvgs=.1,
&END
```



### 7.7 Depletion mode MOSFET $I_{ds}$ - $V_{ds}$ characteristics

Here we illustrate a depletion mode MOSFET with the following input file:

```
&TITLE
MOS3F: depletion mode MOSFET
mostyp=3,
# mask & other dimensions
lfet=20e-04,wfet=1.e-04,nepi=3.e15,tox=500,xjd=1.0e-04,
qox=5e11,
# bias values
vdsmax=5,nvgs=10,vgs=-1,dvgs=.5,ramu=0.3
&END
```

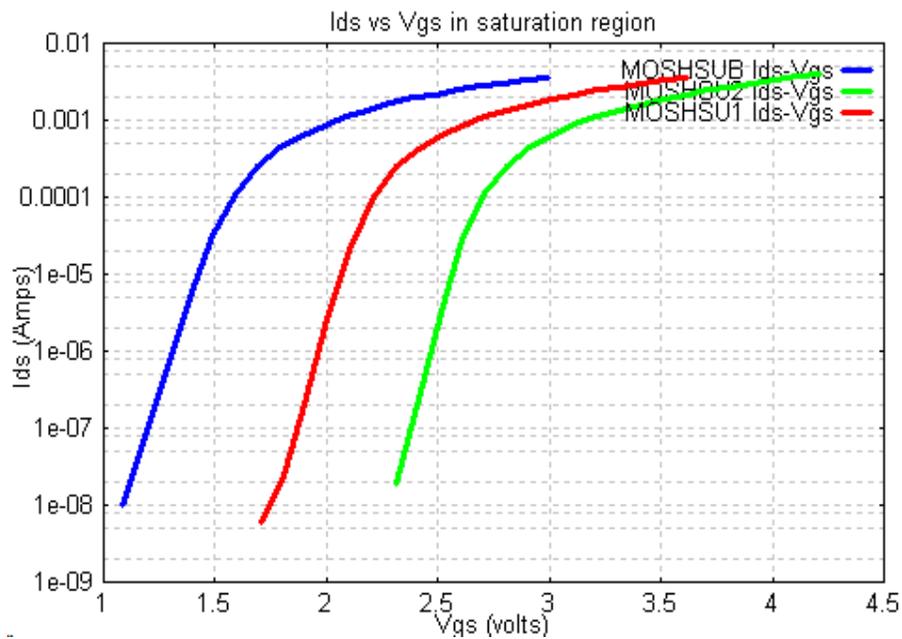


### 7.8 Sub-threshold operation $\log(I_{ds})$ versus $V_{gs}$

The following file is used to demonstrate sub-threshold simulation of MOSFET devices:

```
&TITLE
MOSHSUB MOSFET short channel device, full simulation
&PARAM
  mostyp=3,
# mask & other dimensions
  lfet=.25e-04,wfet=30.e-04,nepi=1.E17,tox=250,xjd=.05e-04,
# bias values
  vdsmax=2.0,nvgs=20,vgs=0.2,dvgs=.1,
# bias step parameters
  ramu=0.3,felat=0.1,
&END
```

Note the use of a log vertical  $I_{ds}$  scale. The values of  $V_{SUB}$  are respectively 0, 1.0, 2.0 for the files moshsub, moshsu1, moshsu2



## 8.0 ADDITIONAL BIP FILES INCLUDED IN THE BIPOLE3 DISTRIBUTION

A number of additional files are included for reference purposes with Bipole3. Each of these illustrates a particular aspect of Bipole3 simulation. They are described briefly below:

### **exion15.bip**

includes ION=15 to demonstrate the effect of including the classical ionization integral for all Vbe bias.

### **extba0.bip**

illustrates an extrinsic base using IPLUS=2, IEXTBAS = 0

### **extba1.bip**

illustrates an extrinsic base using IPLUS=2, IEXTBAS = 1

### **bicmos1.bip**

BJT in a deep N well with no epitaxial layer

### **bicmos1n.bip**

BJT in a deep N well CMOS process with no epitaxial layer and no buried layer

### **tss.bip**

This is a complete double polysilicon silicided base contact BJT

### **ex7.bip**

this illustrates use of IVSAT=1, NVCB=2 to generate  $I_c - V_{cesat}$  tables

### **exlatpnp.bip**

A lateral PNP BJT with SPICE file generation

### **ex2plat.bip**

A file to generate SPICE parameters for the lateral parasitic PNP BJT

### **zz-16.bip**

same as zz16.bip but using IGRAPH=1, IGLAT=-16 for BIPTWOD contour plots

### **exqsat.bip**

SPICE file generation using SPI with Quasi-saturation effects included

**2dnemit.bip**

BIP2NEUT Extension Module example for generating contour plots in quasi neutral emitter using BIPTWOD

**2dlatpnp.bip**

BIP2NEUT lateral PNP simulation with SPICE file generation

**rcrbsim.bip**

Combined use of RBCALC (reduced) and RCCALC

**trans-1h.bip**

HDM empirical model results for 100 GHz transistor using IHDM=1