EE 735: ASSIGNMENT 7

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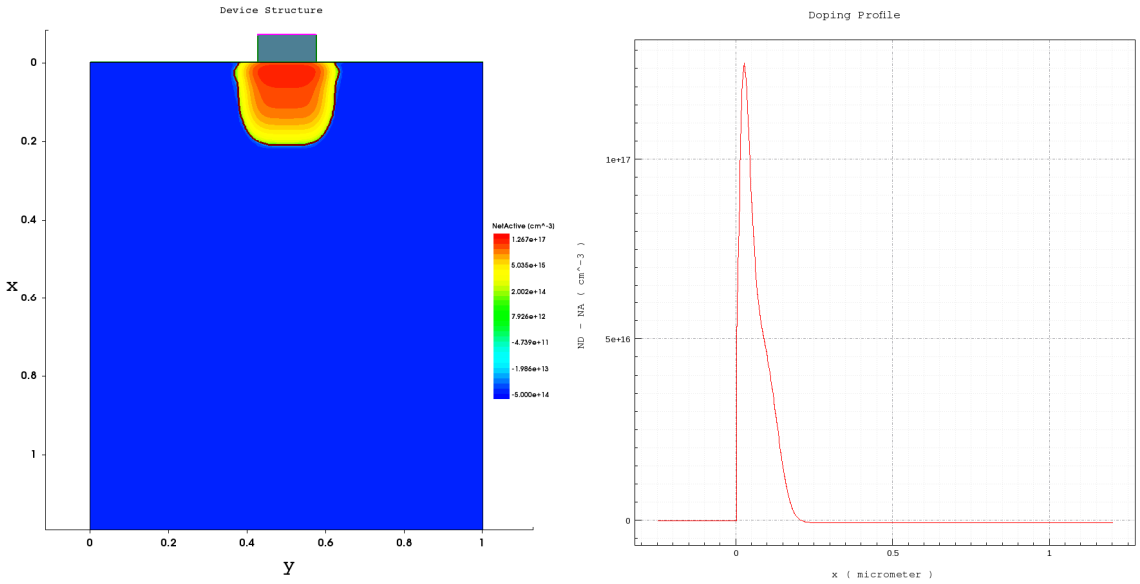
QUESTION 1

Create a p-n junction by implanting Phosphorus on a Boron doped (5e14 cm^{-3}) Si substrate. Check the impact of (a) implant energy (use 10, 20 and 40 keV) and (b) implant dose (use 1e12, 5e14 and 5e16 cm^{-2} for comparison) on the peak concentration and junction depth by plotting the net-active concentration (N_D-N_A) along the device depth. Explain your observations.

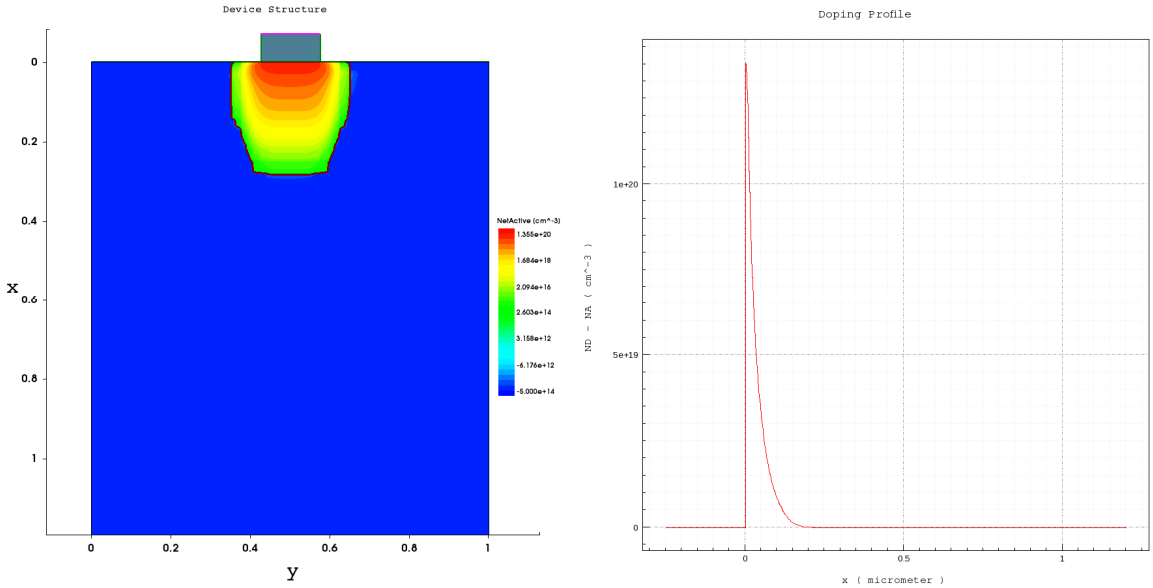
RESULT AND OBSERVATION

The device structure and doping profile for different implantation condition is given below,

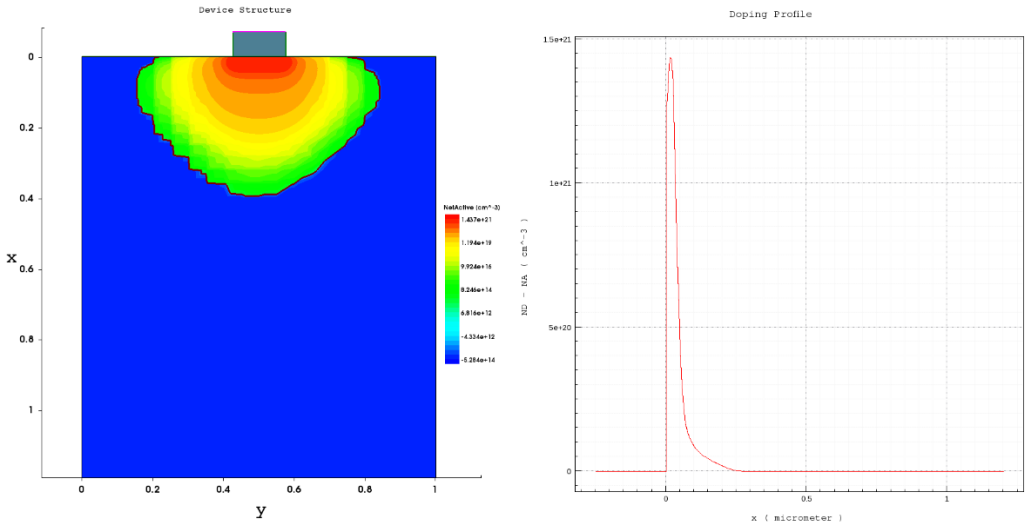
Implant energy:10 keV and implant dose: 1e12 cm^{-2}



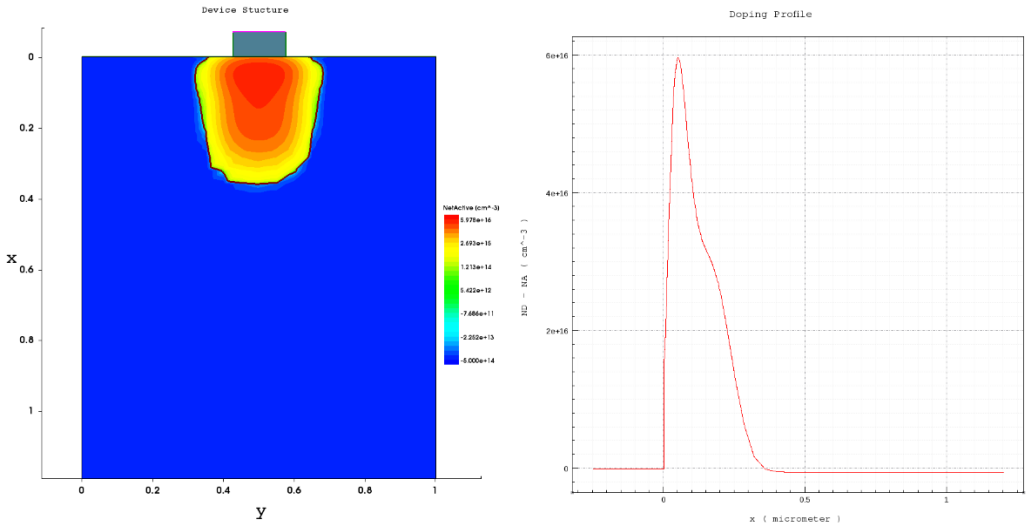
Implant energy:10 keV and implant dose: 5e14 cm^{-2}



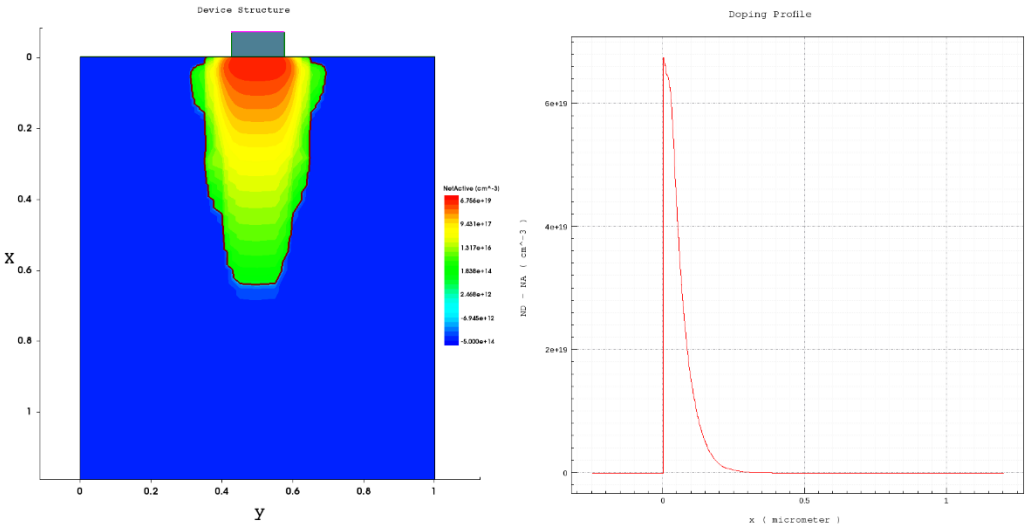
Implant energy:10 keV and implant dose: 5e16 cm^{-2}



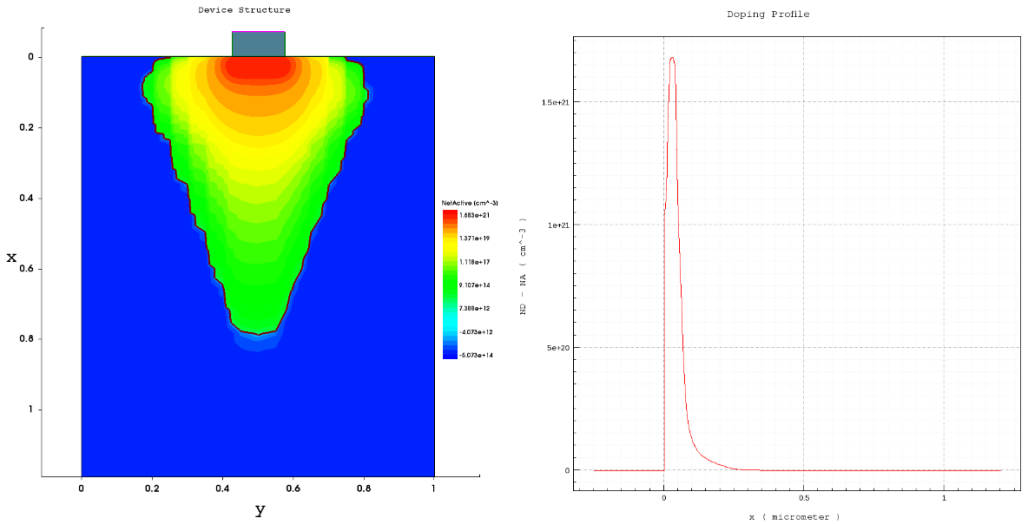
Implant energy:20 keV and implant dose: 1e12 cm^{-2}



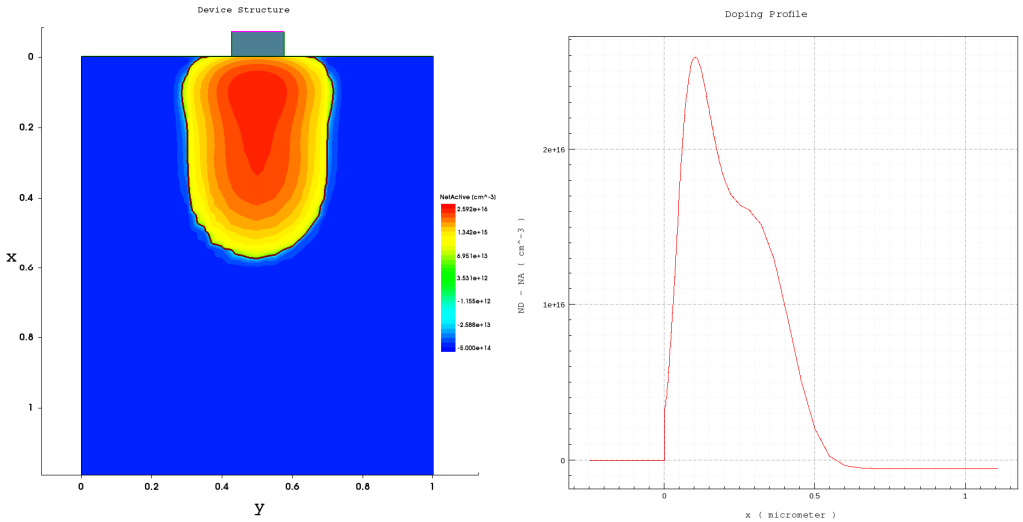
Implant energy:20 keV and implant dose: 5e14 cm^{-2}



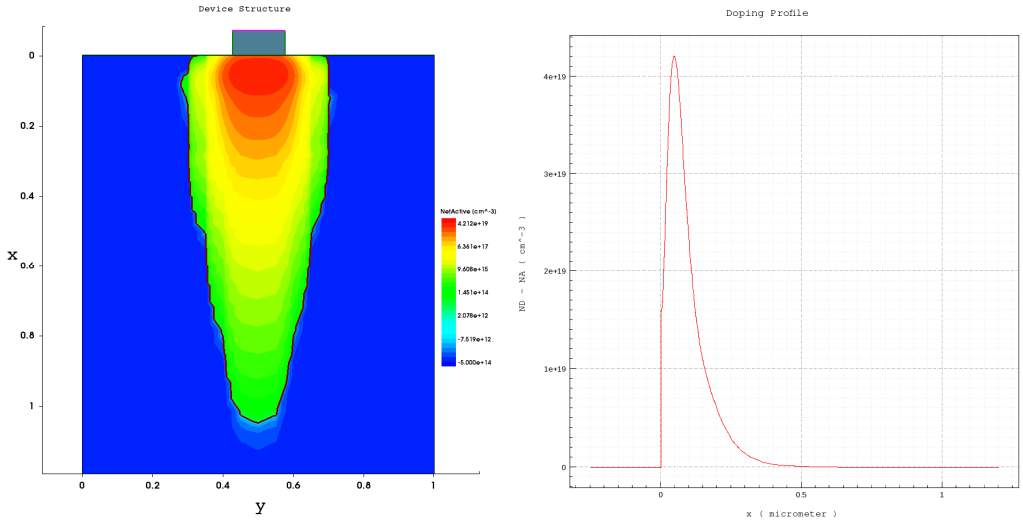
Implant energy:20 keV and implant dose: 5e16 cm^{-2}



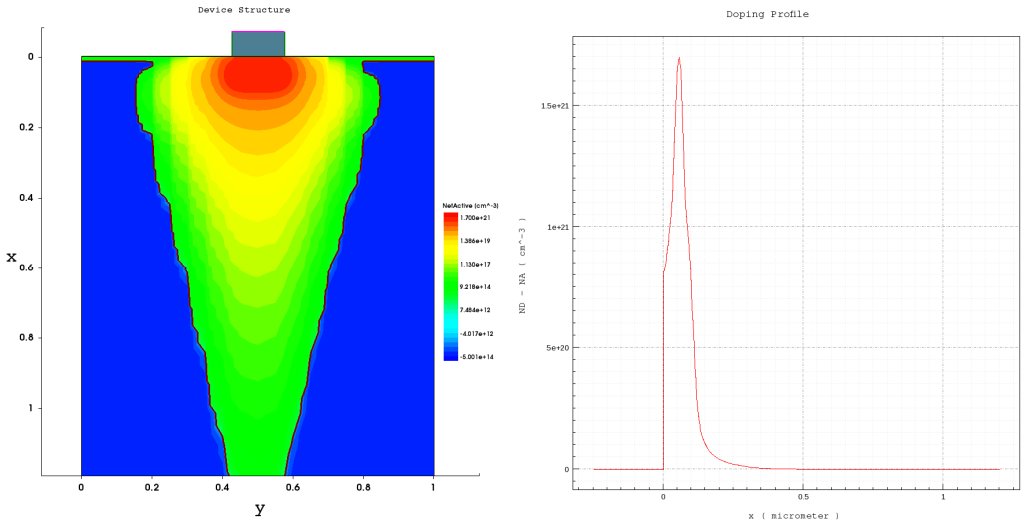
Implant energy:40 keV and implant dose: 1e12 cm^{-2}



Implant energy:40 keV and implant dose: 5e14 cm^{-2}



Implant energy:40 keV and implant dose: 5e16 cm^{-2}



Phosphorus Implantation			
Energy (keV)	Dose (cm^{-2})	Peak Donor Concentration (cm^{-3})	Junction Depth (µm)
10	1×10^{12}	1.267×10^{17}	0.21
10	5×10^{14}	1.355×10^{20}	0.28
10	5×10^{16}	1.437×10^{21}	0.39
20	1×10^{12}	5.978×10^{16}	0.36
20	5×10^{14}	6.756×10^{19}	0.65
20	5×10^{16}	1.683×10^{21}	0.78
40	1×10^{12}	2.592×10^{16}	0.57
40	5×10^{14}	4.212×10^{19}	1.07
40	5×10^{16}	1.700×10^{21}	NA

The junction depth is directly proportional to both implant energy and implant dose as with increase in the implant energy the junction depth increases and also with increase in implant dose the junction depth increases.

The peak concentration primarily depends on the implant dose, peak concentration increases with increase in implant dose. The peak concentration minutely depends on implant energy.

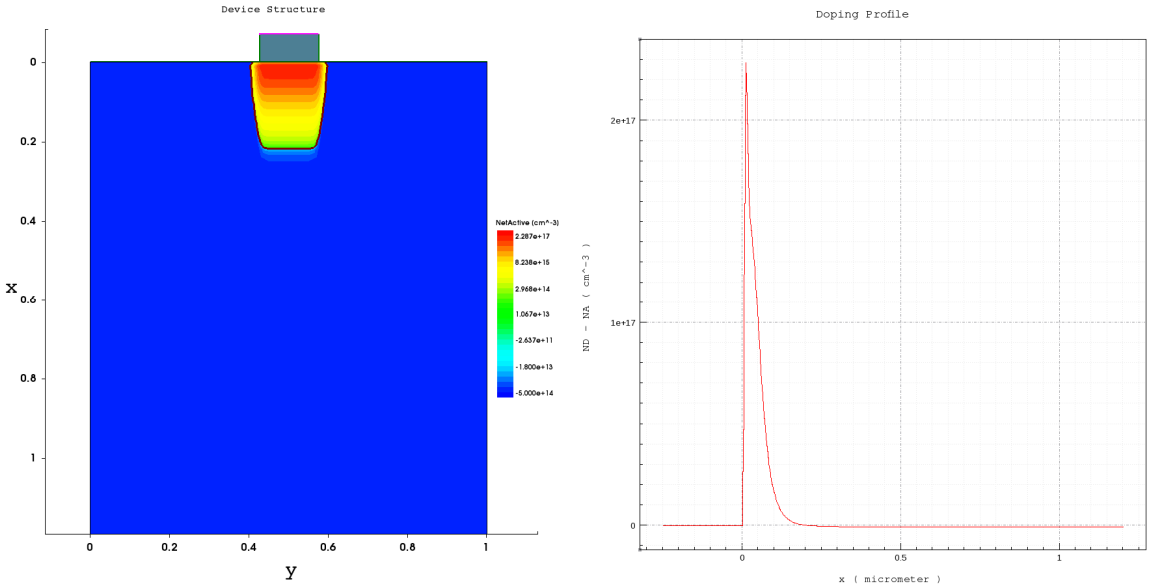
QUESTION 2

In **question 1** use **Arsenic** instead of Phosphorus and compare the results. Explain the observations.

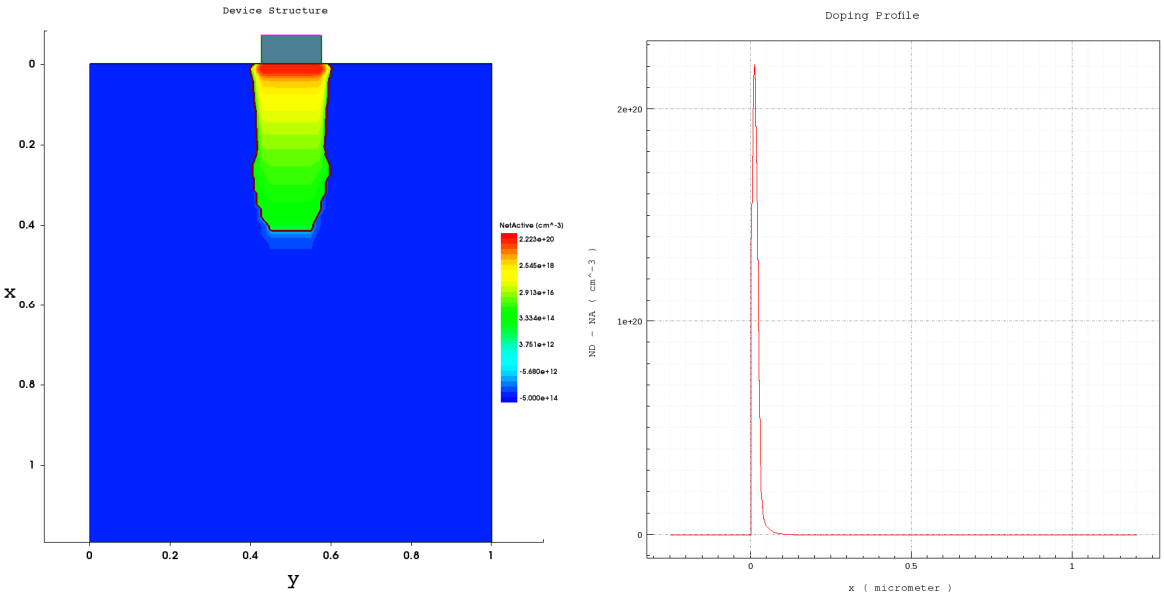
RESULT AND OBSERVATION

The device structure and doping profile for different implantation condition is given below,

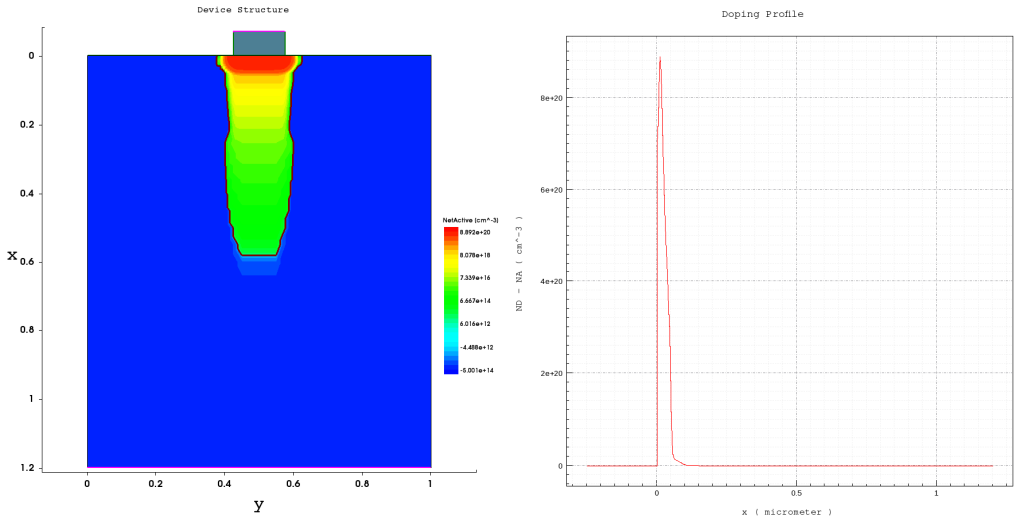
Implant energy:10 keV and implant dose: 1e12 cm^{-2}



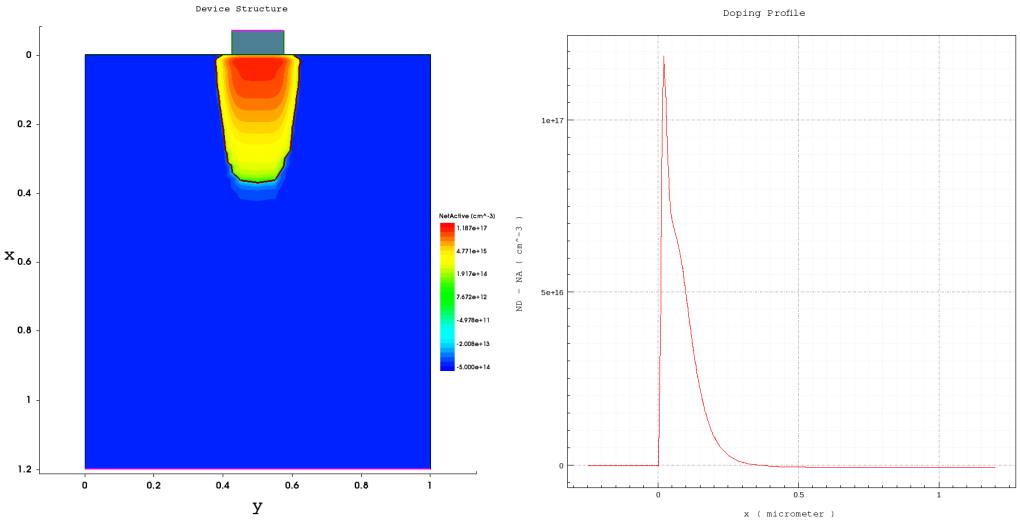
Implant energy:10 keV and implant dose: 5e14 cm^{-2}



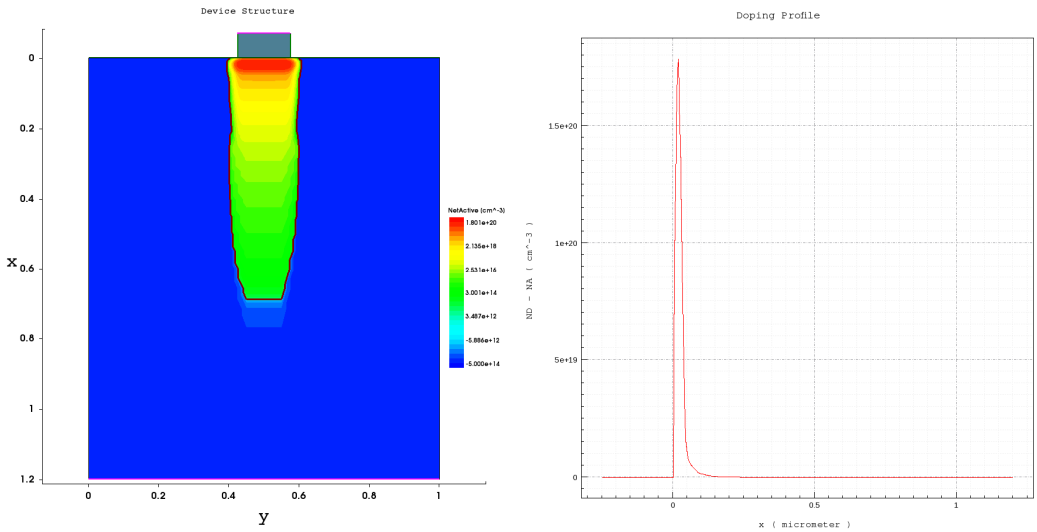
Implant energy:10 keV and implant dose: 5e16 cm^{-2}



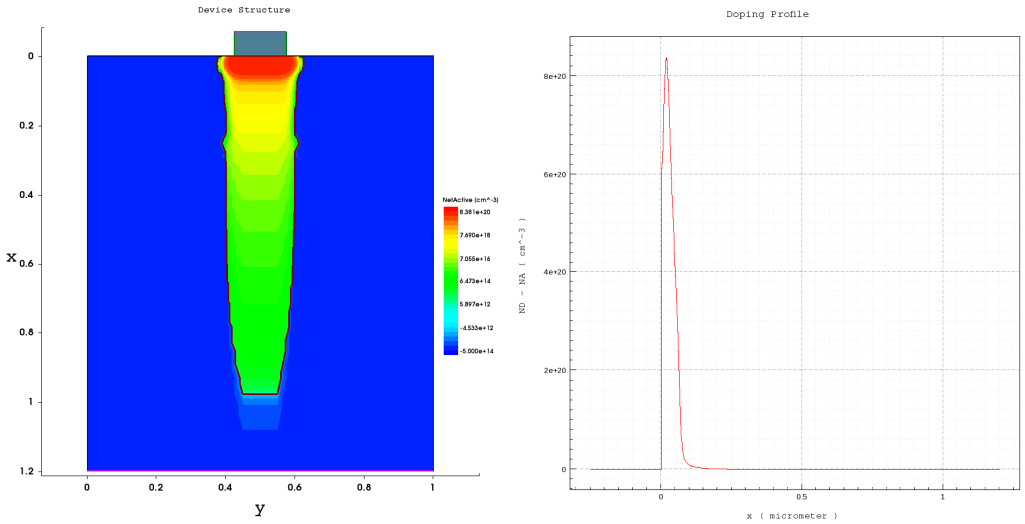
Implant energy:20 keV and implant dose: 1e12 cm^{-2}



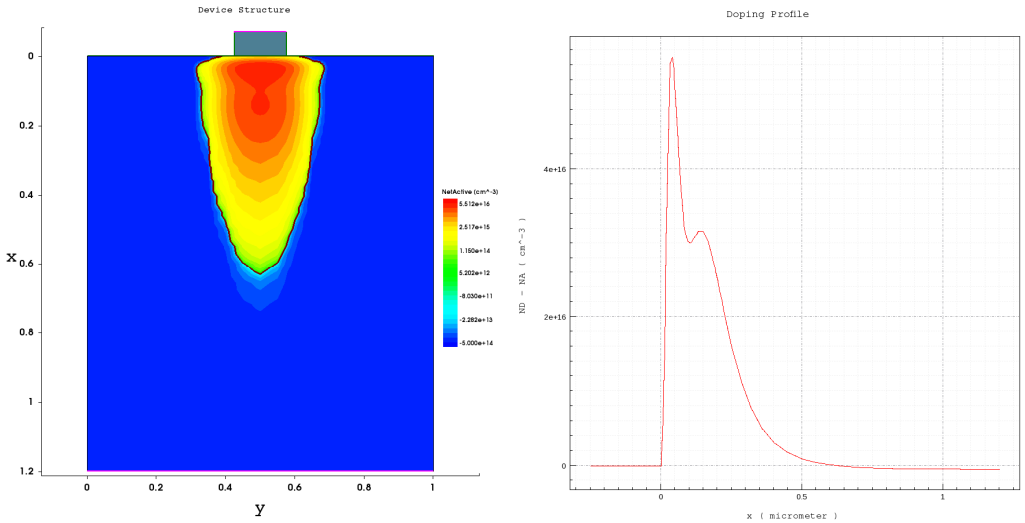
Implant energy:20 keV and implant dose: 5e14 cm^{-2}



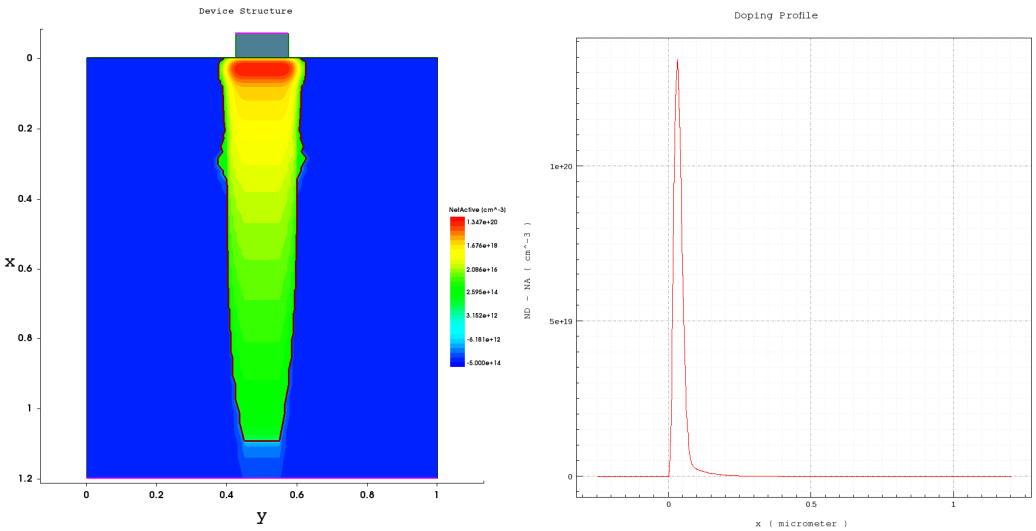
Implant energy:20 keV and implant dose: 5e16 cm^{-2}



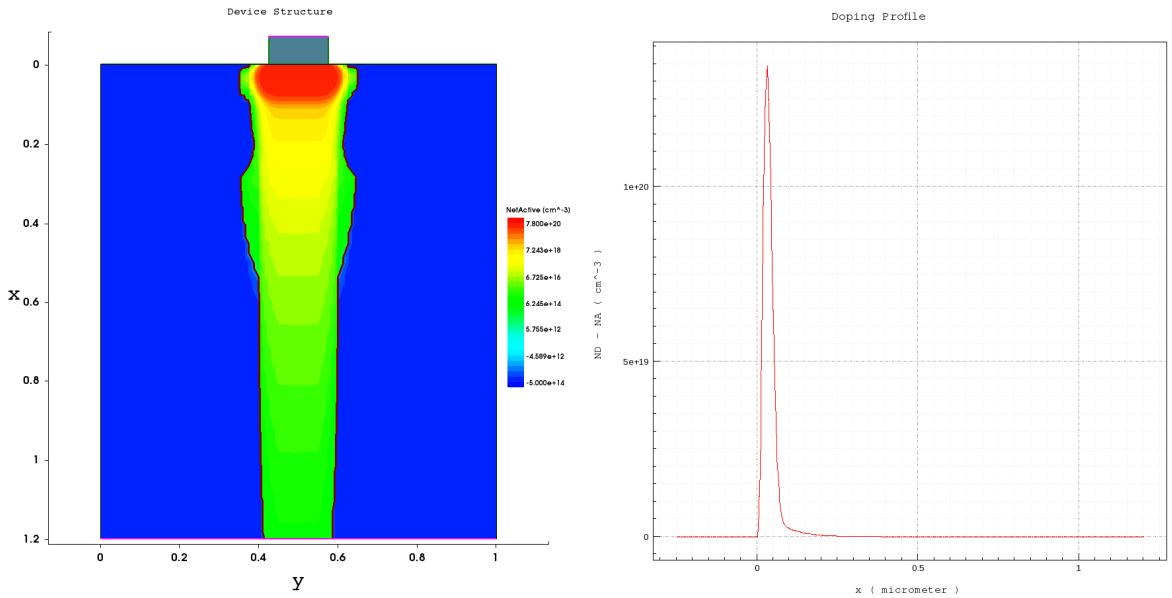
Implant energy:40 keV and implant dose: 1e12 cm^{-2}



Implant energy:40 keV and implant dose: 5e14 cm^{-2}



Implant energy:40 keV and implant dose: 5e16 cm^{-2}



Arsenic Implantation			
Energy (keV)	Dose (cm^{-2})	Peak Donor Concentration (cm^{-3})	Junction Depth (µm)
10	1×10^{12}	2.287×10^{17}	0.22
10	5×10^{14}	2.223×10^{20}	0.42
10	5×10^{16}	8.892×10^{20}	0.58
20	1×10^{12}	1.187×10^{17}	0.37
20	5×10^{14}	1.801×10^{20}	0.69
20	5×10^{16}	8.381×10^{20}	0.98
40	1×10^{12}	5.512×10^{16}	0.63
40	5×10^{14}	1.347×10^{20}	1.09
40	5×10^{16}	7.800×10^{20}	NA

The junction depth is directly proportional to both implant energy and implant dose as with increase in the implant energy the junction depth increases and also with increase in implant dose the junction depth increases.

The peak concentration primarily depends on the implant dose, peak concentration increases with increase in implant dose. The peak concentration minutely depends on implant energy.

Phosphorus vs. Arsenic

The junction depth for Arsenic implantation is higher than Phosphorus implantation for same implant energy and implant dose. The lateral diffusion in y-direction is less for Arsenic than Phosphorus.

QUESTION 3

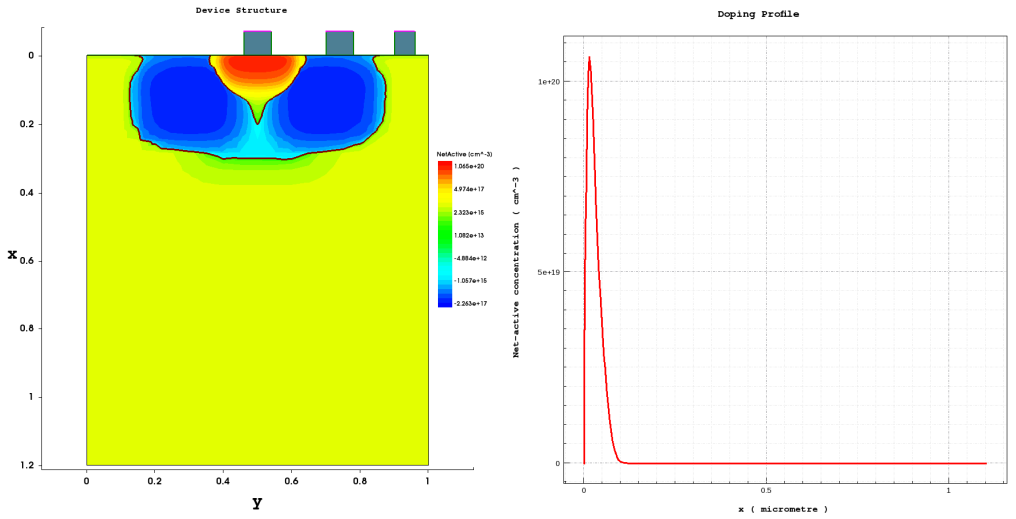
Create BJT $\mathbf{n^+p^-n}$ with collector-base junction depth ~ 300 nm and base-emitter junction depth ~ 200 nm. Make n+ and p region doping as uniform as possible with Phosphorus concentration, N_D = 1e20 cm^{-3} and Boron concentration, N_A =1e14 cm^{-3}, by changing the parameters such as implant dose, implant energy, diffusion or annealing time and temperature etc. Assume background doping to be N_D = 1e16 cm^{-3} for n^- region. Plot the net-active concentration both on linear and log scale.

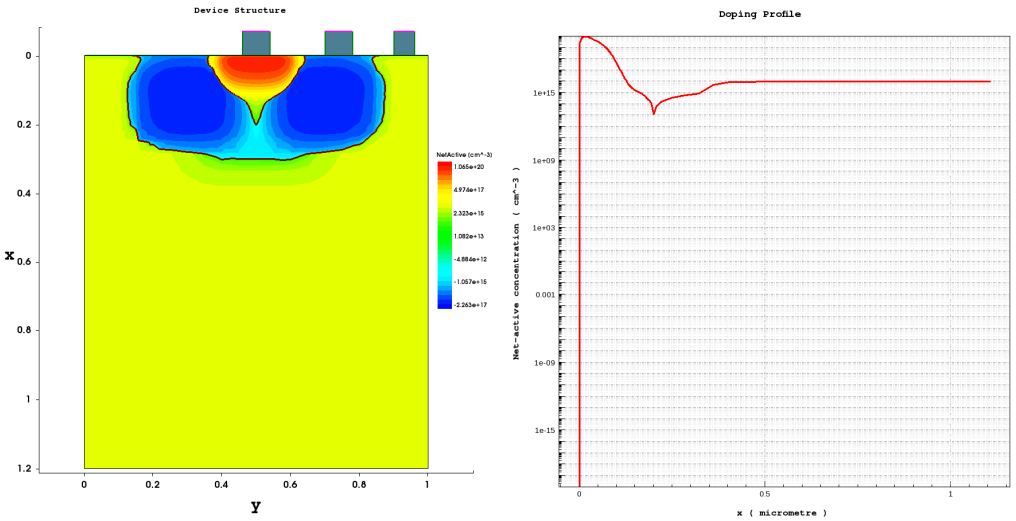
In the given $\mathbf{n^+p^-n}$ junction structure, plot the energy band diagram (E_C, E_V, E_F) along the junctions under the application of (a) in common emitter configuration (b) common base configuration and (c) common collector configuration. Also, plot the quasi-Fermi level in these cases.

Plot the IV curves of the BJT in common emitter as well as common base configuration.

RESULT AND OBSERVATION

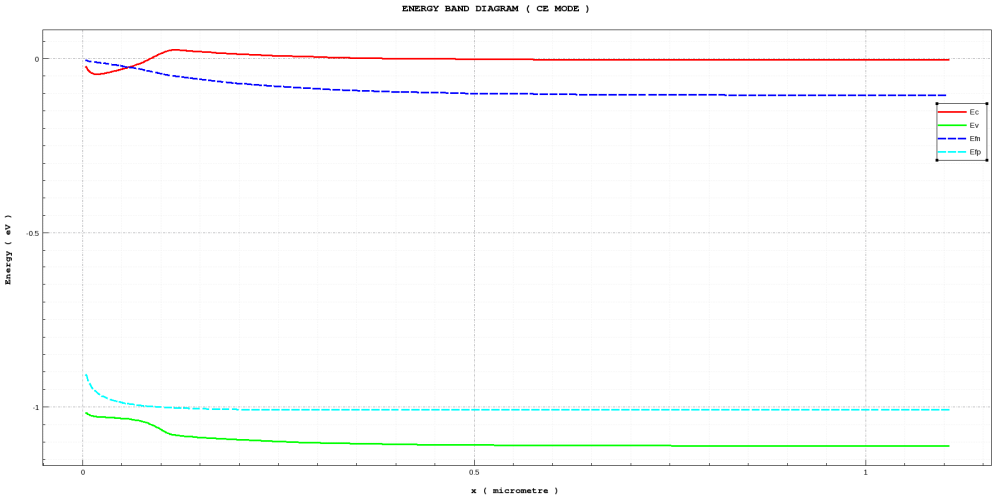
The net-active concentration both on linear and log scale is given below,



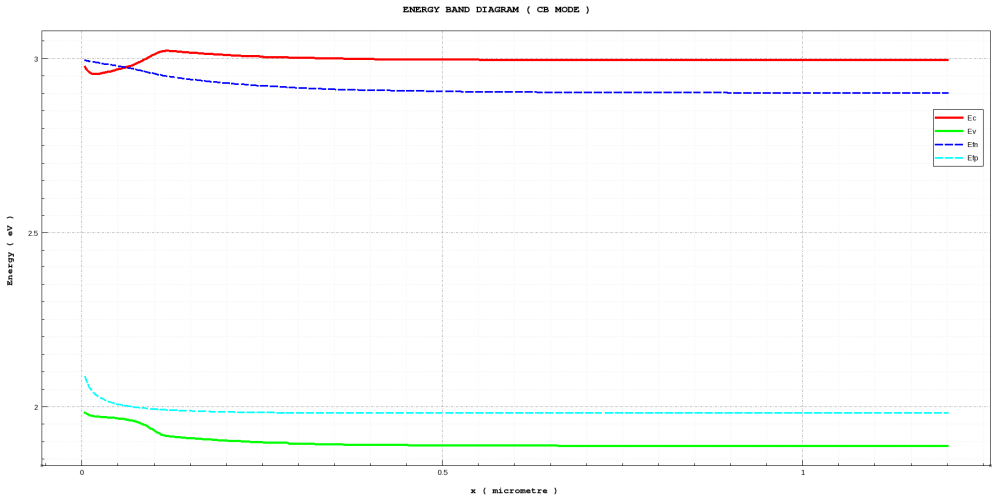


The energy band diagram for various configurations is given below,

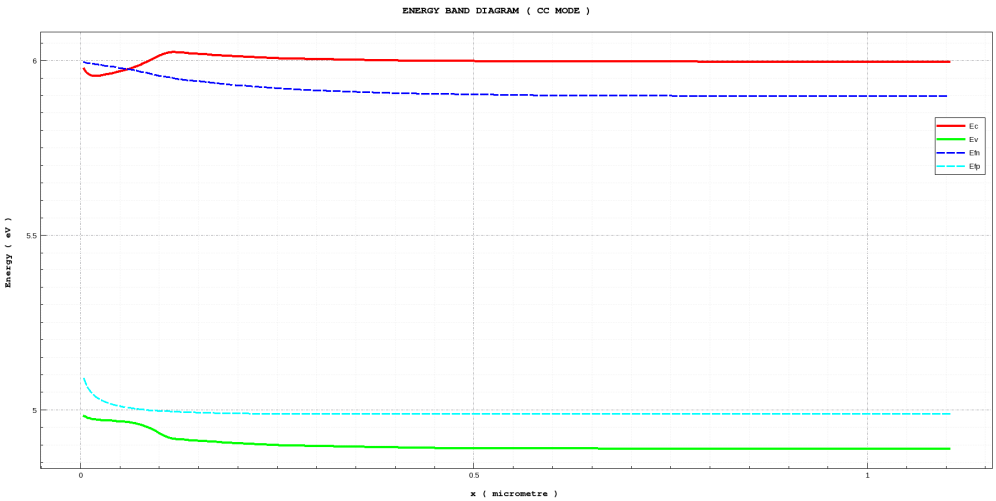
Common Emitter Configuration



Common Base Configuration

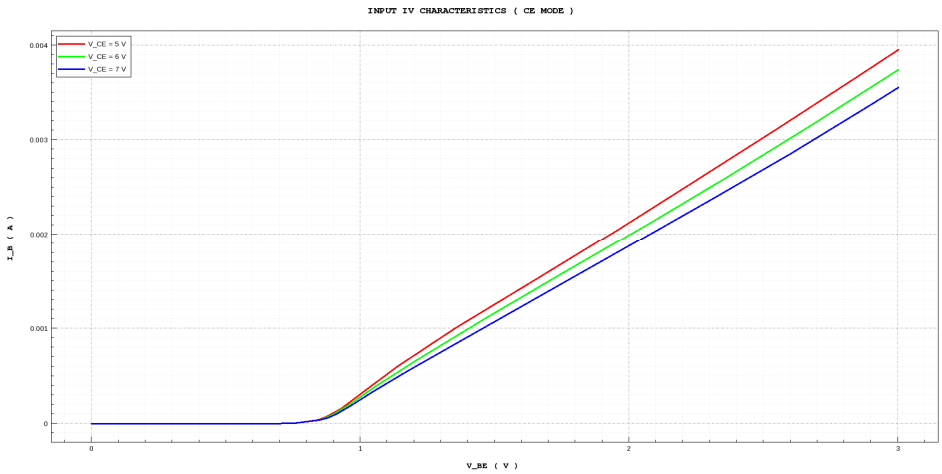


Common Collector Configuration

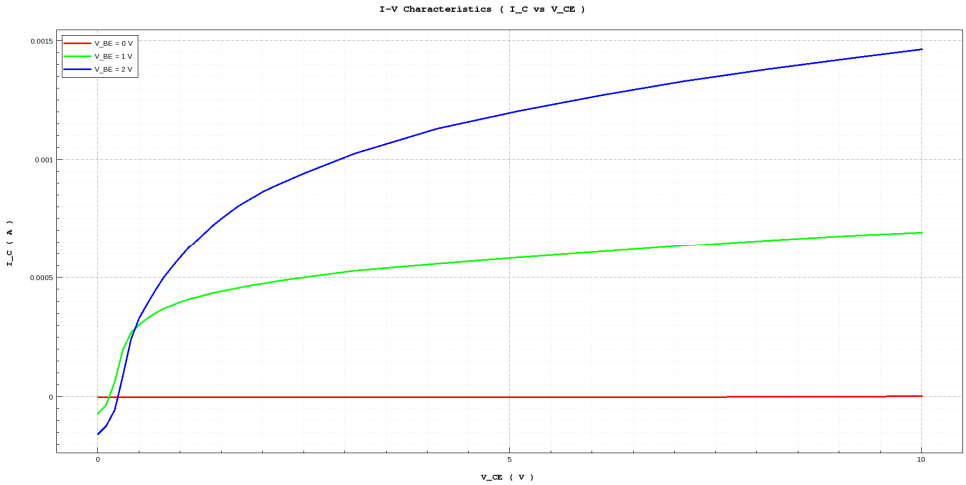


The IV characteristics of the BJT in common-emitter configuration is given below,

Input Characteristics

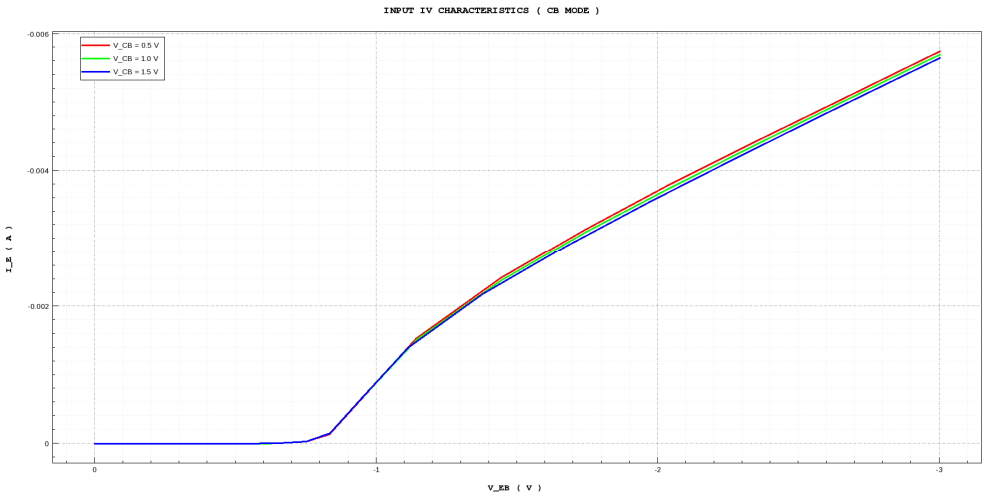


Output Characteristics

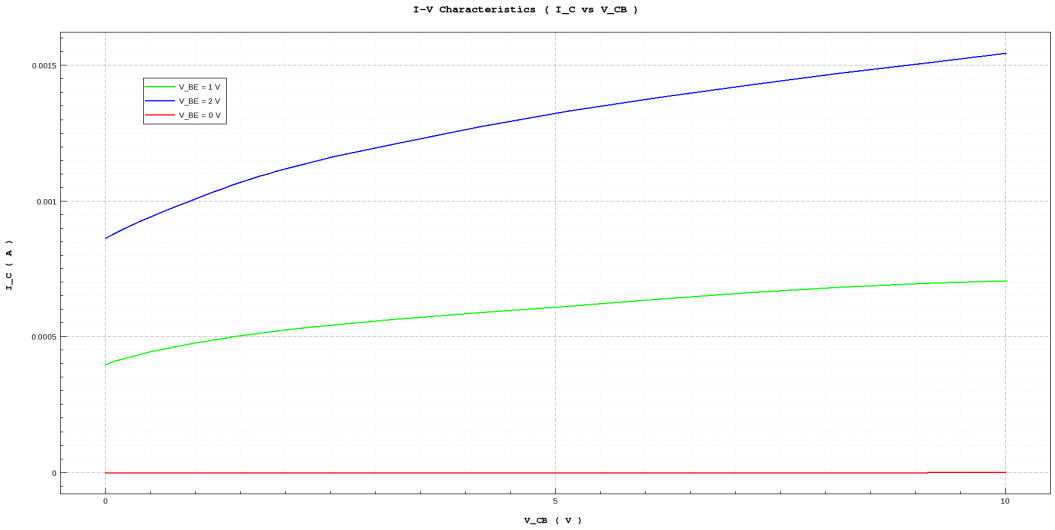


The IV characteristics of the BJT in common-base configuration is given below,

Input Characteristics



Output Characteristics



CODE

QUESTION 1

SPROCESS CODE:

```
# 1D Grid definition in x direction
line x location= 0.0 spacing=1.0<nm> tag=SiTop
line x location=50<nm> spacing=10<nm>
line x location=100<nm> spacing=20<nm>
line x location=500<nm> spacing=50<nm>
line x location=1200<nm> spacing=100<nm> tag=SiBottom

# 1D Grid definition in y direction
line y location=0.0 spacing=50<nm> tag=Left
line y location=1000<nm> spacing=50<nm> tag=Right

# Initial simulation domain
region Silicon xlo=SiTop xhi=SiBottom ylo=Left yhi=Right
# Initial doping concentration in the region defined
init concentration=5e+14<cm-3> field=Boron wafer.orient=100
# Global Mesh settings for automatic meshing in newly generated layers.
#This strategy is used when there is change in initial geometry due to
#deposit, oxidation and etching
mgoals min.normal.size =2<nm> normal.growth.ratio =1.4 accuracy=1e-5


deposit material= {Oxide} type=isotropic time=1 rate= {0.15}
grid remesh
mask name=implant_mask segments= {0<um> 0.425<um> 0.575<um> 1.0<um> }

etch material= {oxide} type=anisotropic time=1 rate= {0.17}
mask=implant_mask
grid remesh

#Save the structure file after etching
struct tdr =1_pn_oxide_etch_before_implant;

refinebox Silicon min= {0.0 0.4} max= {0.2 0.6}\
xrefine= {0.01 0.01 0.01} yrefine = {0.01 0.01 0.01}
grid remesh

#Change energy and dose as required
implant Phosphorus energy=10<keV> dose=1e12<cm-2> tilt = 0

diffuse temperature=1060<C> time=1.2<s>
#save the structure after implantation and diffusion
struct tdr =2_pn_after_implant_diffusion

etch material= {Oxide} type=isotropic time= 1 rate= {0.17}
grid remesh
#save structure file after oxide etch
struct tdr =3_pn_after_imp_diff_oxide_etch;

deposit material= {Aluminum} type=isotropic time=1 rate= {0.07}
grid remesh
#save structure after contact deposition
struct tdr =4_pn_after_metal_depos ;
```

```
mask name=contacts_mask1 left=0.425<um> right=0.575<um>
etch material= {Aluminum} type=anisotropic time=1 rate= {0.08}
mask=contacts_mask1
grid remesh

contact name = "n" box Aluminum adjacent.material = Ambient\
xlo= -0.071 xhi= -0.069 ylo = 0.425 yhi = 0.575
contact name = "p" box silicon adjacent.material = Ambient\
xlo= 1.19 xhi = 1.21 ylo = 0.0 yhi = 1
# save final structure
struct tdr = 5_pn_final_structure
```

QUESTION 2

SPROCESS CODE:

```
# 1D Grid definition in x direction
line x location= 0.0 spacing=1.0<nm> tag=SiTop
line x location=50<nm> spacing=10<nm>
line x location=100<nm> spacing=20<nm>
line x location=500<nm> spacing=50<nm>
line x location=1200<nm> spacing=100<nm> tag=SiBottom

# 1D Grid definition in y direction
line y location=0.0 spacing=50<nm> tag=Left
line y location=1000<nm> spacing=50<nm> tag=Right

# Initial simulation domain
region Silicon xlo=SiTop xhi=SiBottom ylo=Left yhi=Right
# Initial doping concentration in the region defined
init concentration=5e+14<cm-3> field=Boron wafer.orient=100
# Global Mesh settings for automatic meshing in newly generated layers.
#This strategy is used when there is change in initial geometry due to
#deposit, oxidation and etching
mgoals min.normal.size =2<nm> normal.growth.ratio =1.4 accuracy=1e-5


deposit material= {Oxide} type=isotropic time=1 rate= {0.15}
grid remesh
mask name=implant_mask segments= {0<um> 0.425<um> 0.575<um> 1.0<um> }

etch material= {oxide} type=anisotropic time=1 rate= {0.17}
mask=implant_mask
grid remesh

#Save the structure file after etching
struct tdr =1_pn_oxide_etch_before_implant;

refinebox Silicon min= {0.0 0.4} max= {0.2 0.6}\
xrefine= {0.01 0.01 0.01} yrefine = {0.01 0.01 0.01}
grid remesh

#Change energy and dose as required
implant Arsenic energy=10<keV> dose=1e12<cm-2> tilt = 0

diffuse temperature=1060<C> time=1.2<s>
#save the structure after implantation and diffusion
struct tdr =2_pn_after_implant_diffusion

etch material= {Oxide} type=isotropic time= 1 rate= {0.17}
grid remesh
#save structure file after oxide etch
struct tdr =3_pn_after_imp_diff_oxide_etch;

deposit material= {Aluminum} type=isotropic time=1 rate= {0.07}
grid remesh
#save structure after contact deposition
struct tdr =4_pn_after_metal_depos ;


mask name=contacts_mask1 left=0.425<um> right=0.575<um>
etch material= {Aluminum} type=anisotropic time=1 rate= {0.08}
mask=contacts_mask1
```

```
grid remesh

contact name = "n" box Aluminum adjacent.material = Ambient\
xlo= -0.071 xhi= -0.069 ylo = 0.425 yhi = 0.575
contact name = "p" box silicon adjacent.material = Ambient\
xlo= 1.19 xhi = 1.21 ylo = 0.0 yhi = 1
# save final structure
struct tdr = 5_pn_final_structure
```

QUESTION 3

SPROCESS CODE:

```
# 1D Grid definition in x direction
line x location= 0.0 spacing=1.0<nm> tag=SiTop
line x location=50<nm> spacing=10<nm>
line x location=100<nm> spacing=20<nm>
line x location=500<nm> spacing=50<nm>
line x location=1200<nm> spacing=100<nm> tag=SiBottom

# 1D Grid definition in y direction
line y location=0.0 spacing=50<nm> tag=Left
line y location=1000<nm> spacing=50<nm> tag=Right

# Initial simulation domain
region Silicon xlo=SiTop xhi=SiBottom ylo=Left yhi=Right
# Initial doping concentration in the region defined
init concentration=1e+16<cm-3> field=Phosphorus wafer.orient=100
# Global Mesh settings for automatic meshing in newly generated layers.
#This strategy is used when there is change in initial geometry due to

#deposit, oxidation and etching
mgoals min.normal.size =2<nm> normal.growth.ratio =1.4 accuracy=1e-5

deposit material= {Oxide} type=isotropic time=50 rate= {0.15}
grid remesh
mask name=implant_mask segments= {0<um> 0.3<um> 0.7<um> 1.0<um> }

etch material= {oxide} type=anisotropic time=50 rate= {0.17}
mask=implant_mask
grid remesh

#Save the structure file after first etching
struct tdr =1_npn_oxide_etch_before_implant_one;

refinebox Silicon min= {0.0 0.4} max= {0.2 0.6}\
xrefine= {0.01 0.01 0.01} yrefine = {0.01 0.01 0.01}
grid remesh

implant Boron energy=28<keV> dose=2.5e11<cm-2> tilt = 0

diffuse temperature=1060<C> time=3<s>
#save the structure after first implantation and diffusion
struct tdr =2_npn_after_implant_diffusion_one

etch material= {Oxide} type=isotropic time= 50 rate= {0.17}
grid remesh
#save structure file after first oxide etch
struct tdr =3_npn_after_imp_diff_oxide_etch_one;

deposit material= {Oxide} type=isotropic time=10 rate= {0.15}
grid remesh
mask name=implant_mask segments= {0<um> 0.425<um> 0.575<um> 1.0<um> }

etch material= {oxide} type=anisotropic time=10 rate= {0.17}
mask=implant_mask
grid remesh

#Save the structure file after second etching
struct tdr =4_npn_oxide_etch_before_implant_two;
```

```
refinebox Silicon min= {0.0 0.4} max= {0.2 0.6}\
xrefine= {0.01 0.01 0.01} yrefine = {0.01 0.01 0.01}
grid remesh

implant Phosphorus energy=4<keV> dose=5.2e14<cm-2> tilt = 0

diffuse temperature=1060<C> time=3<s>
#save the structure after second implantation and diffusion
struct tdr =5_npn_after_implant_diffusion_two

etch material= {Oxide} type=isotropic time= 10 rate= {0.17}
grid remesh
#save structure file after second oxide etch
struct tdr =6_npn_after_imp_diff_oxide_etch_two;

deposit material= {Oxide} type=isotropic time=20 rate= {0.15}
grid remesh
mask name=implant_mask2 segments= {0<um> 0.2<um> 0.4<um> 0.6<um> 0.8<um>
1.0<um> }

etch material= {oxide} type=anisotropic time=20 rate= {0.17}
mask=implant_mask2
grid remesh

#Save the structure file after third etching
struct tdr =7_npn_oxide_etch_before_implant_three;

refinebox Silicon min= {0.0 0.4} max= {0.2 0.6}\
xrefine= {0.01 0.01 0.01} yrefine = {0.01 0.01 0.01}
grid remesh

implant Boron energy=12.6<keV> dose=4e12<cm-2> tilt = 0

diffuse temperature=1060<C> time=3<s>
#save the structure after third implantation and diffusion
struct tdr =8_npn_after_implant_diffusion_three

etch material= {Oxide} type=isotropic time= 20 rate= {0.17}
grid remesh
#save structure file after third oxide etch
struct tdr =9_npn_after_imp_diff_oxide_etch_three;

deposit material= {Aluminum} type=isotropic time=1 rate= {0.07}
grid remesh

#save structure after contact deposition
struct tdr =10_npn_after_metal_depos ;

mask name=contact_mask segments= {0.46<um> 0.54<um> 0.7<um> 0.78<um>
0.9<um> 0.96<um> }
etch material= {Aluminum} type=anisotropic time=1 rate= {0.08}
mask=contact_mask
grid remesh

#save structure after contact creation
struct tdr =11_npn_after_contact ;

grid remesh
contact name = "e" box Aluminum adjacent.material = Ambient\
xlo= -0.071 xhi= -0.069 ylo = 0.46 yhi = 0.54
```

```
contact name = "b" box Aluminum adjacent.material = Ambient\
xlo= -0.071 xhi= -0.069 ylo = 0.7 yhi = 0.78
contact name = "c" box Aluminum adjacent.material = Ambient\
xlo= -0.071 xhi= -0.069 ylo = 0.9 yhi = 0.96

#save final structure
struct tdr = 12_npn_final_structure
```

SDEVICE CODE:

Input Characteristics for CE mode

```
File {
Grid= "12_npn_final_structure_fps.tdr"
Current= "input_char.plt"
Plot= "CE_mode_ip.tdr"
Output= "CE_mode_ip.log"
}
Electrode {

{ Name= "e" Voltage= 0.0 }
{ Name= "b" Voltage= 0.0 }
{ Name= "c" Voltage= 0.0 }

}
Physics {

Mobility (DopingDep)
EffectiveIntrinsicDensity(BandGapNarrowing(oldSlotboom))
Recombination (Avalanche(CarrierTempDrive)
Band2Band (E2)
SRH)
# turn them on or off to see the effect of each recombination mechanism
}

Plot {
eDensity hDensity eCurrent hCurrent
ConductionBandEnergy ValenceBandEnergy
eQuasiFermiEnergy hQuasiFermiEnergy
eTemperature
ElectricField eEparallel hEparallel
Potential SpaceCharge
SRHRecombination Auger AvalancheGeneration
eMobility hMobility eVelocity hVelocity
Doping DonorConcentration AcceptorConcentration
}

CurrentPlot {
Potential ((0.1 0.05) (0.582 0.009) (0.5 0.5))
}

Math {
Extrapolate
RelErrControl
Iterations=20
}

Solve {
# initial collector-emitter voltage Vce=0.0V
```

```
Poisson
Coupled { Poisson Electron }
Coupled { Poisson Electron Hole }
Save (FilePrefix="vc0")
# ramp base and save solutions:

# second collector-emitter voltage Vce=5.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="c" voltage=5.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vc1")

# third collector-emitter voltage Vce=6.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="c" voltage=6.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vc2")

# fourth collector-emitter voltage Vce=7.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="c" voltage=7.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vc3")

# first curve
Load(FilePrefix="vc0")
NewCurrentPrefix="vc0_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# second curve
Load(FilePrefix="vc1")
NewCurrentPrefix="vc1_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=3.0 }
)
{Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# third curve
Load(FilePrefix="vc2")
NewCurrentPrefix="vc2_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
```

```
range = (0.2 1.0)))}

# fourth curve
Load(FilePrefix="vc3")
NewCurrentPrefix="vc3_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

}
```

Output Characteristics for CE mode

```
File {
Grid= "12_npn_final_structure_fps.tdr"
Current= "output_char.plt"
Plot= "CE_mode_op.tdr"
Output= "CE_mode_op.log"
}
Electrode {

{ Name= "e" Voltage= 0.0 }
{ Name= "b" Voltage= 0.0 }
{ Name= "c" Voltage= 0.0 }

}
Physics {

Mobility (DopingDep)
EffectiveIntrinsicDensity(BandGapNarrowing(oldSlotboom))
Recombination (Avalanche(CarrierTempDrive)
Band2Band (E2)
SRH)
# turn them on or off to see the effect of each recombination mechanism
}

Plot {
eDensity hDensity eCurrent hCurrent
ConductionBandEnergy ValenceBandEnergy
eQuasiFermiEnergy hQuasiFermiEnergy
eTemperature
ElectricField eEparallel hEparallel
Potential SpaceCharge
SRHRecombination Auger AvalancheGeneration
eMobility hMobility eVelocity hVelocity
Doping DonorConcentration AcceptorConcentration
}

CurrentPlot {
Potential ((0.1 0.05) (0.582 0.009) (0.5 0.5))
}

Math {
Extrapolate
RelErrControl
Iterations=20
```

```
}

Solve {
# initial base-emitter voltage Vbe=0.0V
Poisson
Coupled { Poisson Electron }
Coupled { Poisson Electron Hole }
Save (FilePrefix="vb0")
# ramp base and save solutions:

# second base-emitter voltage Vbe=1.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="b" voltage=1.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vb1")

# third base-emitter voltage Vbe=2.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="b" voltage=2.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vb2")

# first curve
Load(FilePrefix="vb0")
NewCurrentPrefix="vb0_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="c" voltage=10.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# second curve
Load(FilePrefix="vb1")
NewCurrentPrefix="vb1_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="c" voltage=10.0 }
)
{Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# third curve
Load(FilePrefix="vb2")
NewCurrentPrefix="vb2_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="c" voltage=10.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

}
```

Input Characteristics for CB mode

```
File {
Grid= "12_npn_final_structure_fps.tdr"
Current= "input_char.plt"
Plot= "CB_mode_ip.tdr"
Output= "CB_mode_ip.log"
}
Electrode {

{ Name= "e" Voltage= 0.0 }
{ Name= "b" Voltage= 0.0 }
{ Name= "c" Voltage= 0.0 }

}
Physics {

Mobility (DopingDep)
EffectiveIntrinsicDensity(BandGapNarrowing(oldSlotboom))
Recombination (Avalanche(CarrierTempDrive)
Band2Band (E2)
SRH)
# turn them on or off to see the effect of each recombination mechanism
}


Plot {
eDensity hDensity eCurrent hCurrent
ConductionBandEnergy ValenceBandEnergy
eQuasiFermiEnergy hQuasiFermiEnergy
eTemperature
ElectricField eEparallel hEparallel
Potential SpaceCharge
SRHRecombination Auger AvalancheGeneration
eMobility hMobility eVelocity hVelocity
Doping DonorConcentration AcceptorConcentration
}

CurrentPlot {
Potential ((0.1 0.05) (0.582 0.009) (0.5 0.5))
}

Math {
Extrapolate
RelErrControl
Iterations=20
}


Solve {
# initial collector-base voltage Vcb=0.0V
Poisson
Coupled { Poisson Electron }
Coupled { Poisson Electron Hole }
Save (FilePrefix="vc0")
# ramp base and save solutions:

# second collector-base voltage Vcb=0.5V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="c" voltage=0.5 } )
```

```
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vc1")

# third collector-base voltage Vcb=1V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="c" voltage=1.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vc2")

# fourth collector-base voltage Vcb=1.5V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="c" voltage=1.5 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="vc3")

# first curve
Load(FilePrefix="vc0")
NewCurrentPrefix="vc0_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="e" voltage=-3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# second curve
Load(FilePrefix="vc1")
NewCurrentPrefix="vc1_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="e" voltage=-3.0 }
)
{Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# third curve
Load(FilePrefix="vc2")
NewCurrentPrefix="vc2_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="e" voltage=-3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# fourth curve
Load(FilePrefix="vc3")
NewCurrentPrefix="vc3_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="e" voltage=-3.0 }
)
{ Coupled {Poisson Electron Hole }
```

```
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

}
```

Output Characteristics for CB mode

```
File {
Grid= "12_npn_final_structure_fps.tdr"
Current= "output_char.plt"
Plot= "CB_mode_op.tdr"
Output= "CB_mode_op.log"
}
Electrode {

{ Name= "e" Voltage= 0.0 }
{ Name= "b" Voltage= 0.0 }
{ Name= "c" Voltage= 0.0 }

}
Physics {

Mobility (DopingDep)
EffectiveIntrinsicDensity(BandGapNarrowing(oldSlotboom))
Recombination (Avalanche(CarrierTempDrive)
Band2Band (E2)
SRH)
# turn them on or off to see the effect of each recombination mechanism
}


Plot {
eDensity hDensity eCurrent hCurrent
ConductionBandEnergy ValenceBandEnergy
eQuasiFermiEnergy hQuasiFermiEnergy
eTemperature
ElectricField eEparallel hEparallel
Potential SpaceCharge
SRHRecombination Auger AvalancheGeneration
eMobility hMobility eVelocity hVelocity
Doping DonorConcentration AcceptorConcentration
}

CurrentPlot {
Potential ((0.1 0.05) (0.582 0.009) (0.5 0.5))
}

Math {
Extrapolate
RelErrControl
Iterations=20
}


Solve {
# initial base-emitter voltage Vbe=0.0V
Poisson
Coupled { Poisson Electron }
Coupled { Poisson Electron Hole }
Save (FilePrefix="ve0")
```

```
# ramp base and save solutions:

# second base-emitter voltage Vbe=1.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="e" voltage=-1.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="ve1")

# third base-emitter voltage Vbe=2.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="e" voltage=-2.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="ve2")

# first curve
Load(FilePrefix="ve0")
NewCurrentPrefix="ve0_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="c" voltage=10.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# second curve
Load(FilePrefix="ve1")
NewCurrentPrefix="ve1_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="c" voltage=10.0 }
)
{Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# third curve
Load(FilePrefix="ve2")
NewCurrentPrefix="ve2_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="c" voltage=10.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

}
```

Input Characteristics for CC mode

```
File {
Grid= "12_npn_final_structure_fps.tdr"
Current= "input_char.plt"
Plot= "CC_mode_ip.tdr"
Output= "CC_mode_ip.log"
```

```
}
Electrode {

{ Name= "e" Voltage= 0.0 }
{ Name= "b" Voltage= 0.0 }
{ Name= "c" Voltage= 0.0 }

}
Physics {

Mobility (DopingDep)
EffectiveIntrinsicDensity(BandGapNarrowing(oldSlotboom))
Recombination (Avalanche(CarrierTempDrive)
Band2Band (E2)
SRH)
# turn them on or off to see the effect of each recombination mechanism
}


Plot {
eDensity hDensity eCurrent hCurrent
ConductionBandEnergy ValenceBandEnergy
eQuasiFermiEnergy hQuasiFermiEnergy
eTemperature
ElectricField eEparallel hEparallel
Potential SpaceCharge
SRHRecombination Auger AvalancheGeneration
eMobility hMobility eVelocity hVelocity
Doping DonorConcentration AcceptorConcentration
}

CurrentPlot {
Potential ((0.1 0.05) (0.582 0.009) (0.5 0.5))
}

Math {
Extrapolate
RelErrControl
Iterations=20
}

Solve {
# initial collector-emitter voltage Vce=0.0V
Poisson
Coupled { Poisson Electron }
Coupled { Poisson Electron Hole }
Save (FilePrefix="ve0")
# ramp base and save solutions:

# second collector-emitter voltage Vce=4.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="e" voltage=-4.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="ve1")

# third collector-emitter voltage Vce=5.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="e" voltage=-5.0 } )
{ Coupled { Poisson Electron Hole } }
```

```
Save(FilePrefix="ve2")

# fourth collector-emitter voltage Vce=6.0V
Quasistationary
(InitialStep=0.1 Maxstep=0.1 MinStep=0.0001
Goal { name="e" voltage=-6.0 } )
{ Coupled { Poisson Electron Hole } }
Save(FilePrefix="ve3")

# first curve
Load(FilePrefix="ve0")
NewCurrentPrefix="ve0_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=-3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# second curve
Load(FilePrefix="ve1")
NewCurrentPrefix="ve1_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=-3.0 }
)
{Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# third curve
Load(FilePrefix="ve2")
NewCurrentPrefix="ve2_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=-3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

# fourth curve
Load(FilePrefix="ve3")
NewCurrentPrefix="ve3_"
Quasistationary
(InitialStep=0.01 Maxstep=0.1 MinStep=0.0001
Goal{ name="b" voltage=-3.0 }
)
{ Coupled {Poisson Electron Hole }
CurrentPlot (time=
(range = (0 0.2) intervals=20;
range = (0.2 1.0)))}

}
```