Indian Institute of Technology Tirupati

Department of Electrical Engineering

M.TECH : MVLSI

भारतीय प्रौद्योगिकी संस्थान तिरुपति

TIRUPATI

Device Simulation Laboratory (EE5195)

Instructor: Dr. Bhuktare Swapnil Sopanro

Assignment: 9

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Roll No: ee22m308

1) Consider a step pn junction of Si with uniform doping of ND & NA on the n and p sides of the junction. Solve for the electrostatics under equilibrium conditions using Newton-Raphson method. Plot the charge density, electric field & potential distribution inside the device. Also plot the energy band diagram. Compare your numerical results with the analytical solutions as discussed in the class. Do it for 3 cases mentioned below:

a) NA=ND=1016 cm-3 b) NA=1015 cm-3 & ND=1016 cm-3 c) NA=1016 cm-3 & ND=1015 cm-3

2) You can take the length of the device around 4 µm, take one half of the region as n type and anther half of the region as p type. 2) Simulate the above structure in sentaurus. You may take the width of the device to be 2 µm. Plot the charge density, electric field, potential distribution and the energy band diagrams.

Ans no 1:

On matlab

a) NA=ND=1016 cm-3

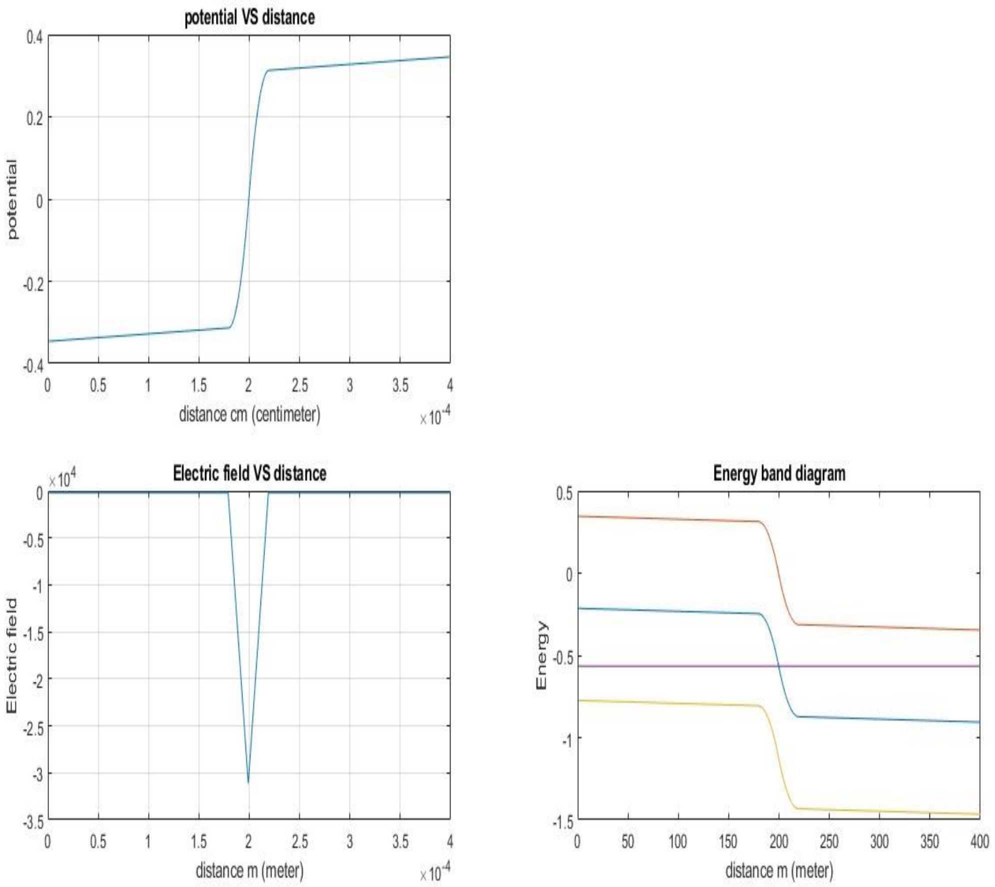
numerical:

with neglecting neglible concentration:

```
clear all;
clc;
q=1.6*(10)^(-19);
epsilon=103.368*(10)^(-14);
a=4*10^(-4);
ni=1.5*(10)^(10);
e = 0.0001;
h=a/400;
T=300;
Nc=4.82*(10^21)*(((1.182)*T)^1.5);
Vt=0.0258;
Na=10^16;
```

```
Nd=10^16;
Vo=(Vt*log((Na*Nd)/(ni^2)));
W=((((2*epsilon)/q)*((1/Nd)+(1/Na))*Vo)^0.5);
Wn=((W*Na)/(Na+Nd));
Wp=((W*Nd)/(Na+Nd));
k=(q*Na*(h)^2)/epsilon;
l=(q*Nd*(h)^2)/epsilon;
Vp=-(Vt*log(Na/ni));
Vn=(Vt*log(Nd/ni));
N=400;

V=linspace(Vp,Vn,400);
V1=V';
for i=1:400

F(1,1)=0;
F(400,1)=0;
for i=2:179
F(i,1)=V1(i+1)+V1(i-1)-2*V1(i);
end
for i=180:199
    F(i,1)=V1(i+1)+V1(i-1)-2*V1(i)-k;
end
for i=200:219
F(i,1)=V1(i+1)+V1(i-1)-2*V1(i)+l;
end
for i=220:399
F(i,1)=V1(i+1)+V1(i-1)-2*V1(i);
end
M(1,1)=1;
for i=2:400
M(i,i)=-2;
end
for i=2:399
M(i,i+1)=1;
end
for i=1:398
M(i+1,i)=1;
end
M(N,N)=1;
V2=V1-(inv(M)*F);
V1=V2;
end


subplot(2,2,1);
i=1:400;
x=i*h;
y=V2;
plot(x,y);
xlabel('distance cm (centimeter)');
ylabel('potential');
title('potential VS distance');
grid on;
 subplot(2,2,3);
 for i=1:399
    E(i)=-((V2(i+1)-V2(i))/h);
end
i=1:399;
```

```
x=i*h;
plot(x,E);
xlabel('distance m (meter)');
ylabel('Electric field');
title('Electric field VS distance');
grid on;
subplot(2,2,4)
Ec=-((V2));
Ev=(Ec-1.12);
Ei=(Ec+Ev)/2;
Efn=(-(Vt*log(Nc/Nd)));
Ef=(Efn*ones(1,length(V2)));
i=1:length(V2);
plot(i,Ei,i,Ec,i,Ev,i,Ef);
xlabel('distance m (meter)');
ylabel('Energy');
title('Energy band diagram');
```

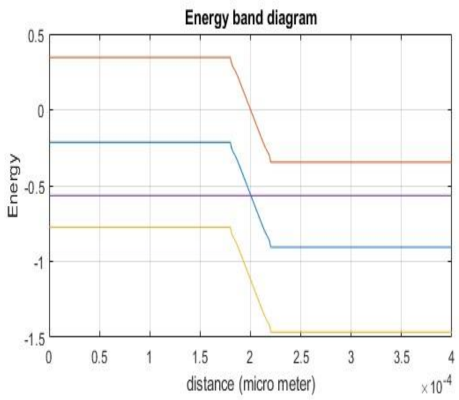


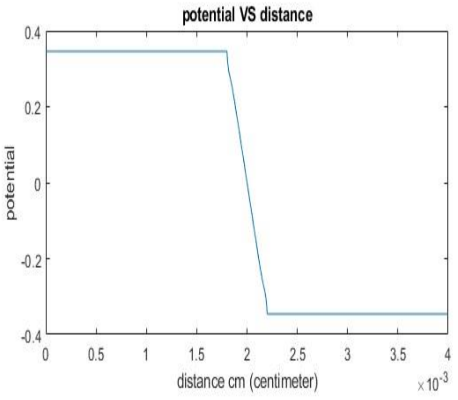
without neglecting concentration

```
clear all;
clc;
q=1.6*(10)^(-19);
epsilon=103.368*(10)^(-14);
```

```
a=4*10^(-4);
ni=1.5*(10)^(10);
h=a/400;
h1=a/4000;
Vt=0.0258;
Na=10^16;
Nd=10^16;
Vo=(Vt*log((Na*Nd)/(ni^2)));
W=((((2*epsilon)/q)*((1/Nd)+(1/Na))*Vo)^0.5);
Wn=((W*Na)/(Na+Nd));
Wp=((W*Nd)/(Na+Nd));
K=((q*ni*(h)^2)/(2*epsilon));
Vp=-(Vt*log(Na/ni));
Vn=(Vt*log(Nd/ni));
Siep=-(log(Na/ni));
Sien=(log(Nd/ni));
N=400;
T=300;
Nc=4.82*(10^21)*(((1.182)*T)^1.5);

Sie=linspace(Vp,Vn,400);
Sie1=Sie';

 F(1,1)=0;
 F(400,1)=0;
for i=1:400;
for i=2:399
  F(i,1)=(Sie1(i+1)+Sie1(i-1)-(2*Sie1(i))+(K*((exp(-(Sie1(i)/Vt)))-
(exp(Sie1(i)/Vt))+((Nd-Na)/ni))));
 end



for i=2:399
 M(i,i)=((-2)-((K/Vt)*((exp(-(Sie1(i)/Vt)))+(exp(Sie1(i)/Vt)))));
end

  M(1,1)=1;


M(N,N)=1;

Sie2=(Sie1-(inv(M)*F));
Sie1=Sie2;
end
Sie2=[Sie2(1)*ones(1,1800),Sie2',Sie2(end)*ones(1,1800)];
Ec=-((Sie2));
Ev=(Ec-1.12);
Ei=(Ec+Ev)/2;
subplot(2,2,2);
Efn=(-(Vt*log(Nc/Nd)));
Ef=(Efn*ones(1,length(Sie2)));
i=1:length(Sie2);
x=i*h1;
plot(x,Ei,x,Ec,x,Ev,x,Ef);
xlabel('distance (micro meter)');
ylabel('Energy');
title('Energy band diagram');
grid on;
```

```
hold on

subplot(2,2,3);
i=1:4000;
x=i*h;
y=Ec;
plot(x,y);
xlabel('distance cm (centimeter)');
ylabel('potential');
title('potential VS distance');
```

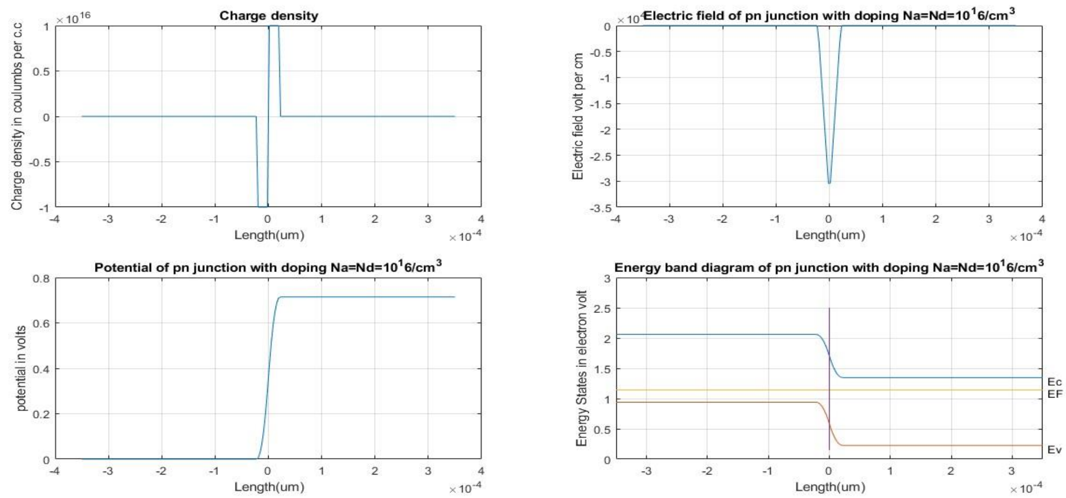




analytical:

```
close all;
clc;
syms b
T=300;
k=8.617e-5;
eO=8.85e-14;
q=1.602e-19;
K =11.8;
ni=1e10;
D =1.12;
xl=-3.5*10^-4;
xg =-xl;
```

```
NA =1e16; ND=1e16;
Vbi =  k*T*log((NA*ND)/ni^2);
xN=sqrt(2*K*eO/q*NA*Vbi/(ND*(NA+ND)));
xP=sqrt(2*K*eO/q*ND* Vbi/(NA *(NA+ND)));
a= linspace(xl, xg, 200);
b= linspace(xl, xg, 200);

z= linspace(xl, xg, 199);
Q= linspace(xl, xg, 198);
V1= (Vbi-(q*ND.*(xN-b).^2/(2*K*eO)).*(b<=xN)).*(b>=0);
V2=0.5*q*NA.*(xP+b).^2/(K*eO).*(b>=-xP & b <0);
Vx=V1+V2;
vp=Vx;
y =-1*diff(vp);
r=eO*K*diff(y);

VM = 3;
EF=Vx(1)+VM/2-k*T*log(NA/ni);
close
%plot (x,-Vx+EG/2+VMAX/2);
subplot(2,2,2);
ex1= (-q*NA*(xP+a)/(K*eO)).*(a>=-xP & a <0);
ex2=-q*ND*(xN-a)/(K*eO).*(a<=xN).*(a>=0);
ex=ex1+ex2;
plot (a,ex);     %Electric field
title("Electric field of pn junction with doping Na=Nd=10^16/cm^3")
xlabel("Length(um)");
ylabel("Electric field volt per cm")
grid on;
hold on
subplot(2,2,1);
r1= (-NA).*(a>=-xP & a <0);
r2=(ND).*(a<=xN).*(a>=0);
r=r1+r2;
plot (a,r); %Charge density
title("Charge density")
 xlabel("Length(um)");
ylabel("Charge density in coulumbs per c.c")
grid on;
 subplot(2,2,3);
 plot(a,vp);   %Potential
 title("Potential of pn junction with doping Na=Nd=10^16/cm^3")
 xlabel("Length(um)");
ylabel("potential in volts")
grid on;
subplot(2,2,4)
plot (a,-Vx+D/2+VM/2);
axis ([xl xg 0 VM]);
hold on
plot (a,-Vx-D/2+VM/2);
plot ([xl xg], [EF EF]);
plot ([0 0], [0.15 VM-0.5]);
text(xg* 1.02,(-Vx(200)-D/2+VM/2-.05), 'Ev');
text(xg*1.02,(-Vx(200)+D/2+VM/2-.05),'Ec');
text(xg* 1.02, EF-.05,"EF");
grid on;
title("Energy band diagram of pn junction with doping Na=Nd=10^16/cm^3")
xlabel("Length(um)");
ylabel("Energy States in electron volt")
```

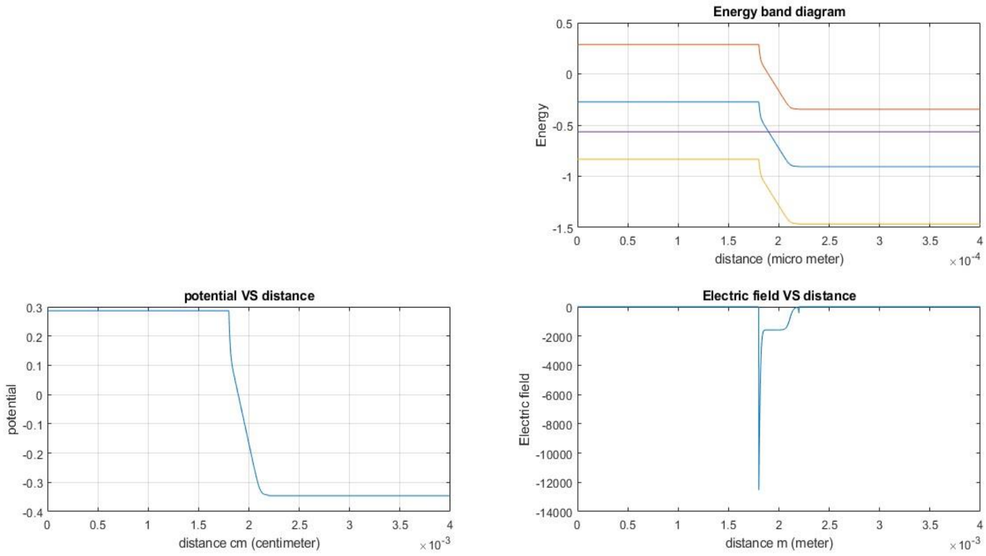


b) NA=10^15 cm-3 & ND=10^16 cm-3

Numerical:

```
clear all;
clc;
q=1.6*(10)^(-19);
epsilon=103.368*(10)^(-14);
a=4*10^(-4);
ni=1.5*(10)^(10);
h=a/400;
h1=a/4000;
Vt=0.0258;
Na=10^15;
Nd=10^16;
Vo=(Vt*log((Na*Nd)/(ni^2)));
W=((((2*epsilon)/q)*((1/Nd)+(1/Na))*Vo)^0.5);
Wn=((W*Na)/(Na+Nd));
Wp=((W*Nd)/(Na+Nd));
K=((q*ni*(h)^2)/(2*epsilon));
Vp=-(Vt*log(Na/ni));
Vn=(Vt*log(Nd/ni));
Siep=-(log(Na/ni));
Sien=(log(Nd/ni));
N=400;
T=300;
Nc=4.82*(10^21)*(((1.182)*T)^1.5);

Sie=linspace(Vp,Vn,400);
Sie1=Sie';

 F(1,1)=0;
 F(400,1)=0;
for i=1:400;
for i=2:399
```

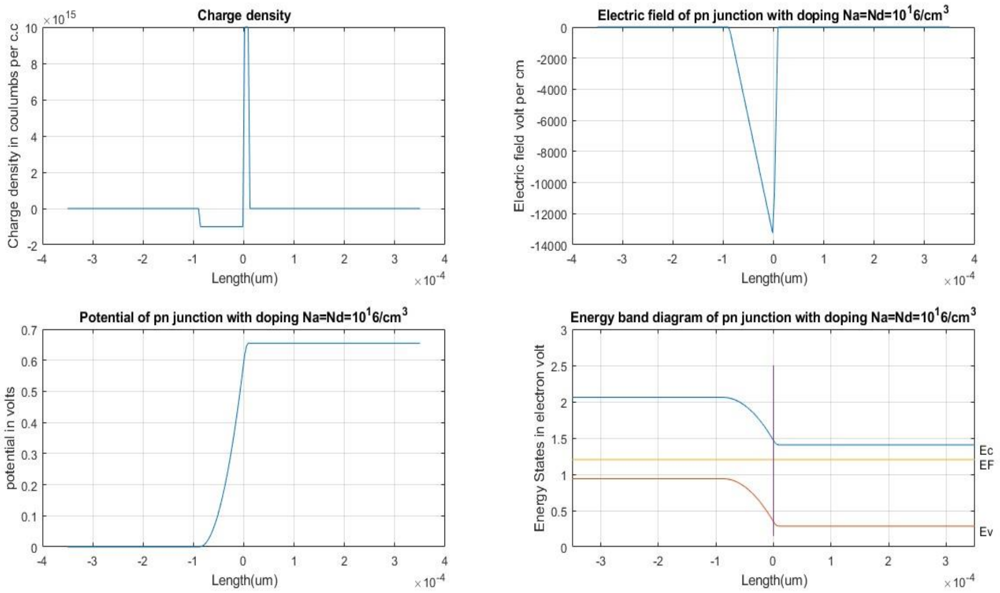
```
  F(i,1)=(Sie1(i+1)+Sie1(i-1)-(2*Sie1(i))+(K*((exp(-(Sie1(i)/Vt)))-
(exp(Sie1(i)/Vt))+((Nd-Na)/ni))));
 end



for i=2:399
 M(i,i)=((-2)-((K/Vt)*((exp(-(Sie1(i)/Vt)))+(exp(Sie1(i)/Vt)))));
end

  M(1,1)=1;


M(N,N)=1;

Sie2=(Sie1-(inv(M)*F));
Sie1=Sie2;
end
Sie2=[Sie2(1)*ones(1,1800),Sie2',Sie2(end)*ones(1,1800)];
Ec=-((Sie2));
Ev=(Ec-1.12);
Ei=(Ec+Ev)/2;
subplot(2,2,2);
Efn=(-(Vt*log(Nc/Nd)));
Ef=(Efn*ones(1,length(Sie2)));
i=1:length(Sie2);
x=i*h1;
plot(x,Ei,x,Ec,x,Ev,x,Ef);
xlabel('distance (micro meter)');
ylabel('Energy');
title('Energy band diagram');
grid on;
hold on

subplot(2,2,3);
i=1:4000;
x=i*h;
y=Ec;
plot(x,y);
xlabel('distance cm (centimeter)');
ylabel('potential');
title('potential VS distance');
grid on;
 subplot(2,2,4);
 for i=1:3999
    E(i)=((Ec(i+1)-Ec(i))/h);
end
i=1:3999;
x=i*h;
plot(x,E);
xlabel('distance m (meter)');
ylabel('Electric field');
title('Electric field VS distance');
```



Analytical:

```
close all;
clc;
syms b
T=300;
k=8.617e-5;
eO=8.85e-14;
q=1.602e-19;
K =11.8;
ni=1e10;
D =1.12;
xl=-3.5*10^-4;
xg =-xl;
NA =1e15; ND=1e16;
Vbi =  k*T*log((NA*ND)/ni^2);
xN=sqrt(2*K*eO/q*NA*Vbi/(ND*(NA+ND)));
xP=sqrt(2*K*eO/q*ND* Vbi/(NA *(NA+ND)));
a= linspace(xl, xg, 200);
b= linspace(xl, xg, 200);

z= linspace(xl, xg, 199);
Q= linspace(xl, xg, 198);
V1= (Vbi-(q*ND.*(xN-b).^2/(2*K*eO)).*(b<=xN)).*(b>=0);
V2=0.5*q*NA.*(xP+b).^2/(K*eO).*(b>=-xP & b <0);
Vx=V1+V2;
vp=Vx;
y =-1*diff(vp);
r=eO*K*diff(y);

VM = 3;
EF=Vx(1)+VM/2-k*T*log(NA/ni);
close
%plot (x,-Vx+EG/2+VMAX/2);
subplot(2,2,2);
ex1= (-q*NA*(xP+a)/(K*eO)).*(a>=-xP & a <0);
ex2=-q*ND*(xN-a)/(K*eO).*(a<=xN).*(a>=0);
ex=ex1+ex2;
```

```
plot (a,ex);     %Electric field
title("Electric field of pn junction with doping Na=Nd=10^16/cm^3")
xlabel("Length(um)");
ylabel("Electric field volt per cm")
grid on;
hold on
subplot(2,2,1);
r1= (-NA).*(a>=-xP & a <0);
r2=(ND).*(a<=xN).*(a>=0);
r=r1+r2;
plot (a,r); %Charge density
title("Charge density")
 xlabel("Length(um)");
ylabel("Charge density in coulumbs per c.c")
grid on;
 subplot(2,2,3);
 plot(a,vp);   %Potential
 title("Potential of pn junction with doping Na=Nd=10^16/cm^3")
 xlabel("Length(um)");
ylabel("potential in volts")
grid on;
subplot(2,2,4)
plot (a,-Vx+D/2+VM/2);
axis ([xl xg 0 VM]);
hold on
plot (a,-Vx-D/2+VM/2);
plot ([xl xg], [EF EF]);
plot ([0 0], [0.15 VM-0.5]);
text(xg* 1.02,(-Vx(200)-D/2+VM/2-.05), 'Ev');
text(xg*1.02,(-Vx(200)+D/2+VM/2-.05),'Ec');
text(xg* 1.02, EF-.05,"EF");
grid on;
title("Energy band diagram of pn junction with doping Na=Nd=10^16/cm^3")
xlabel("Length(um)");
ylabel("Energy States in electron volt")
```

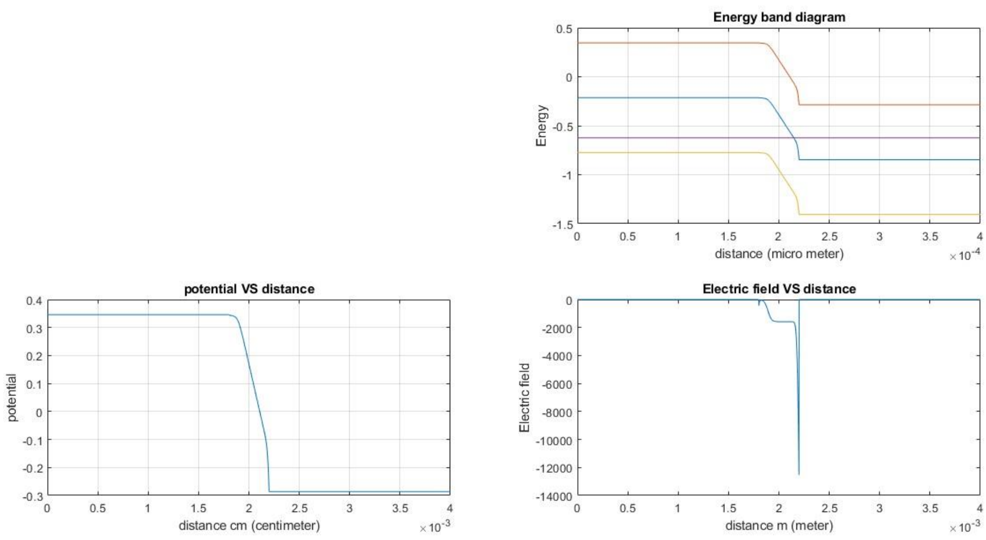


c) NA=10^16 cm-3 & ND=10^15 cm-3

Numerical:

```
clear all;
clc;
q=1.6*(10)^(-19);
epsilon=103.368*(10)^(-14);
a=4*10^(-4);
ni=1.5*(10)^(10);
h=a/400;
h1=a/4000;
Vt=0.0258;
Na=10^16;
Nd=10^15;
Vo=(Vt*log((Na*Nd)/(ni^2)));
W=((((2*epsilon)/q)*((1/Nd)+(1/Na))*Vo)^0.5);
Wn=((W*Na)/(Na+Nd));
Wp=((W*Nd)/(Na+Nd));
K=((q*ni*(h)^2)/(2*epsilon));
Vp=-(Vt*log(Na/ni));
Vn=(Vt*log(Nd/ni));
Siep=-(log(Na/ni));
Sien=(log(Nd/ni));
N=400;
T=300;
Nc=4.82*(10^21)*(((1.182)*T)^1.5);

Sie=linspace(Vp,Vn,400);
Sie1=Sie';

 F(1,1)=0;
 F(400,1)=0;
for i=1:400;
for i=2:399
  F(i,1)=(Sie1(i+1)+Sie1(i-1)-(2*Sie1(i))+(K*((exp(-(Sie1(i)/Vt)))-
(exp(Sie1(i)/Vt))+((Nd-Na)/ni))));
 end



for i=2:399
 M(i,i)=((-2)-((K/Vt)*((exp(-(Sie1(i)/Vt))+(exp(Sie1(i)/Vt)))));
end

  M(1,1)=1;


M(N,N)=1;

Sie2=(Sie1-(inv(M)*F));
Sie1=Sie2;
end
Sie2=[Sie2(1)*ones(1,1800),Sie2',Sie2(end)*ones(1,1800)];
Ec=-((Sie2));
Ev=(Ec-1.12);
Ei=(Ec+Ev)/2;
subplot(2,2,2);
Efn=(-(Vt*log(Nc/Nd)));
Ef=(Efn*ones(1,length(Sie2)));
i=1:length(Sie2);
x=i*h1;
plot(x,Ei,x,Ec,x,Ev,x,Ef);
```

```
xlabel('distance (micro meter)');
ylabel('Energy');
title('Energy band diagram');
grid on;
hold on

subplot(2,2,3);
i=1:4000;
x=i*h;
y=Ec;
plot(x,y);
xlabel('distance cm (centimeter)');
ylabel('potential');
title('potential VS distance');
grid on;
 subplot(2,2,4);
 for i=1:3999
     E(i)=((Ec(i+1)-Ec(i))/h);
end
i=1:3999;
x=i*h;
plot(x,E);
xlabel('distance m (meter)');
ylabel('Electric field');
title('Electric field VS distance');
```

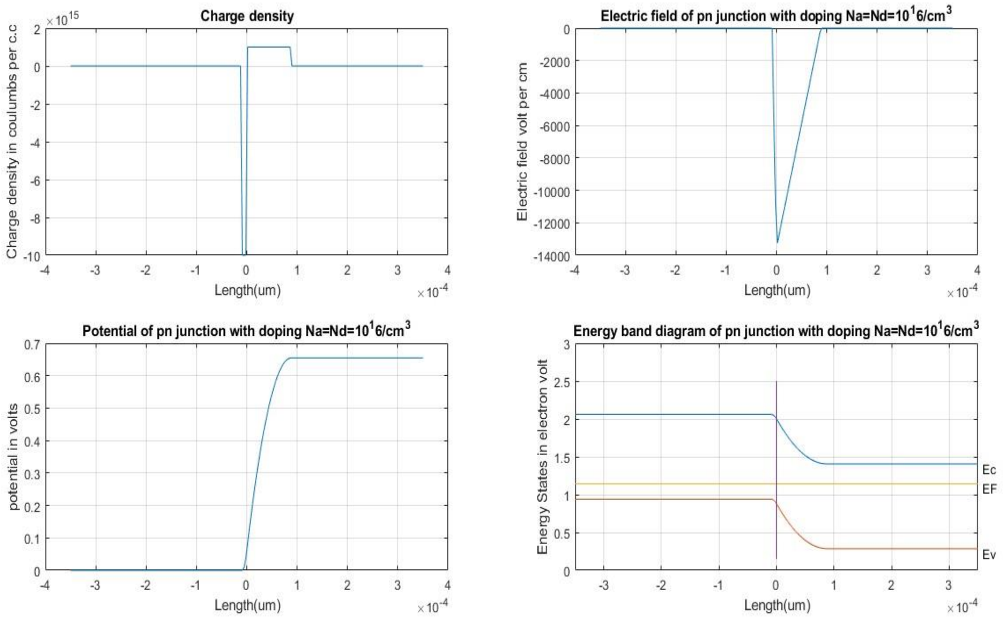


Analytical:

```
close all;
clc;
syms b
T=300;
k=8.617e-5;
eO=8.85e-14;
q=1.602e-19;
K =11.8;
ni=1e10;
D =1.12;
xl=-3.5*10^-4;
```

```
xg =-xl;
NA =1e16; ND=1e15;
Vbi =  k*T*log((NA*ND)/ni^2);
xN=sqrt(2*K*eO/q*NA*Vbi/(ND*(NA+ND)));
xP=sqrt(2*K*eO/q*ND* Vbi/(NA *(NA+ND)));
a= linspace(xl, xg, 200);
b= linspace(xl, xg, 200);

z= linspace(xl, xg, 199);
Q= linspace(xl, xg, 198);
V1= (Vbi-(q*ND.*(xN-b).^2/(2*K*eO)).*(b<=xN)).*(b>=0);
V2=0.5*q*NA.*(xP+b).^2/(K*eO).*(b>=-xP & b <0);
Vx=V1+V2;
vp=Vx;
y =-1*diff(vp);
r=eO*K*diff(y);

VM = 3;
EF=Vx(1)+VM/2-k*T*log(NA/ni);
close
%plot (x,-Vx+EG/2+VMAX/2);
subplot(2,2,2);
ex1= (-q*NA*(xP+a)/(K*eO)).*(a>=-xP & a <0);
ex2=-q*ND*(xN-a)/(K*eO).*(a<=xN).*(a>=0);
ex=ex1+ex2;
plot (a,ex);     %Electric field
title("Electric field of pn junction with doping Na=Nd=10^16/cm^3")
xlabel("Length(um)");
ylabel("Electric field volt per cm")
grid on;
hold on
subplot(2,2,1);
r1= (-NA).*(a>=-xP & a <0);
r2=(ND).*(a<=xN).*(a>=0);
r=r1+r2;
plot (a,r); %Charge density
title("Charge density")
 xlabel("Length(um)");
ylabel("Charge density in coulumbs per c.c")
grid on;
 subplot(2,2,3);
 plot(a,vp);   %Potential
 title("Potential of pn junction with doping Na=Nd=10^16/cm^3")
 xlabel("Length(um)");
ylabel("potential in volts")
grid on;
subplot(2,2,4)
plot (a,-Vx+D/2+VM/2);
axis ([xl xg 0 VM]);
hold on
plot (a,-Vx-D/2+VM/2);
plot ([xl xg], [EF EF]);
plot ([0 0], [0.15 VM-0.5]);
text(xg* 1.02,(-Vx(200)-D/2+VM/2-.05), 'Ev');
text(xg*1.02,(-Vx(200)+D/2+VM/2-.05),'Ec');
text(xg* 1.02, EF-.05,"EF");
grid on;
title("Energy band diagram of pn junction with doping Na=Nd=10^16/cm^3")
xlabel("Length(um)");
```

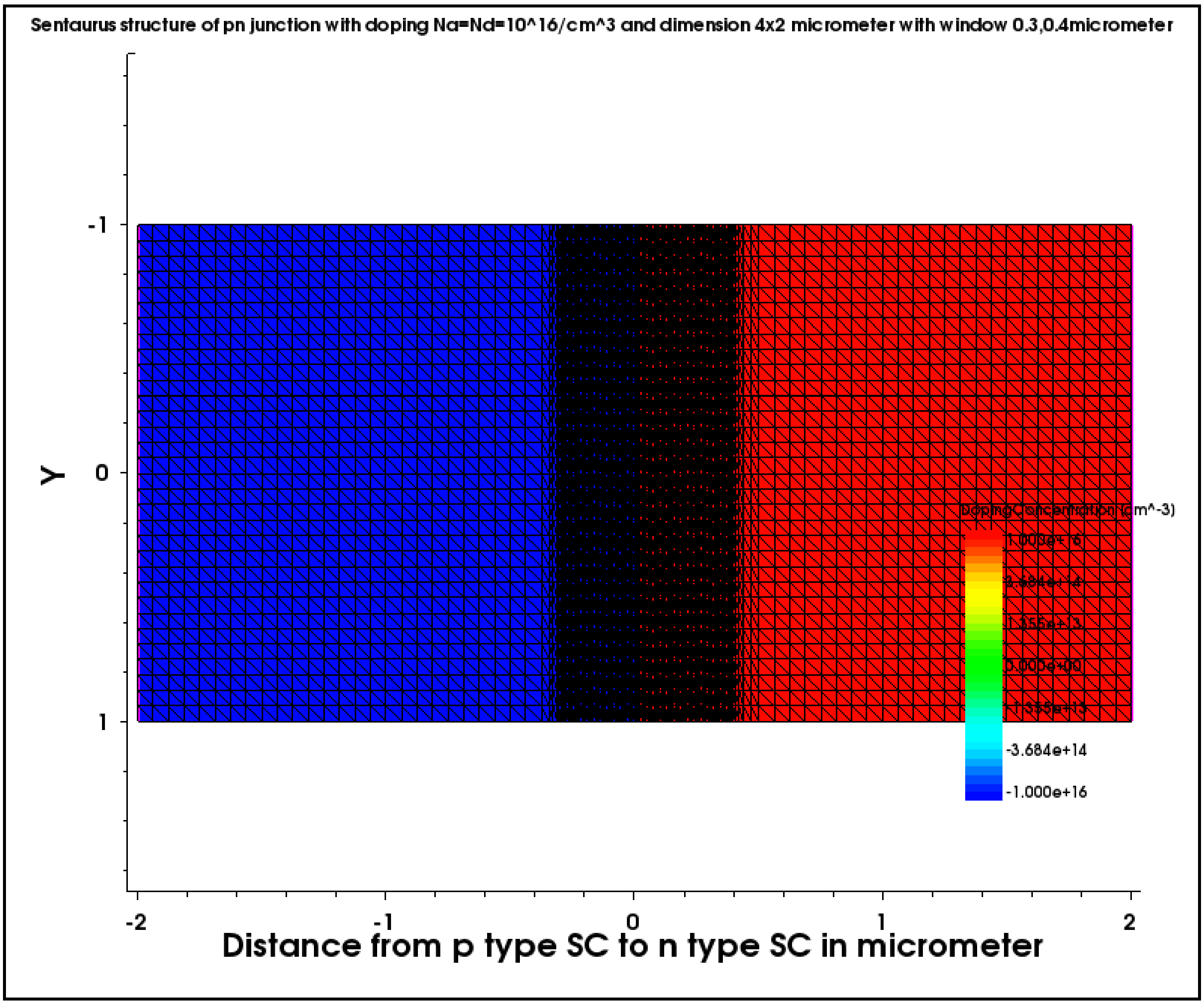
```
ylabel("Energy States in electron volt")
```

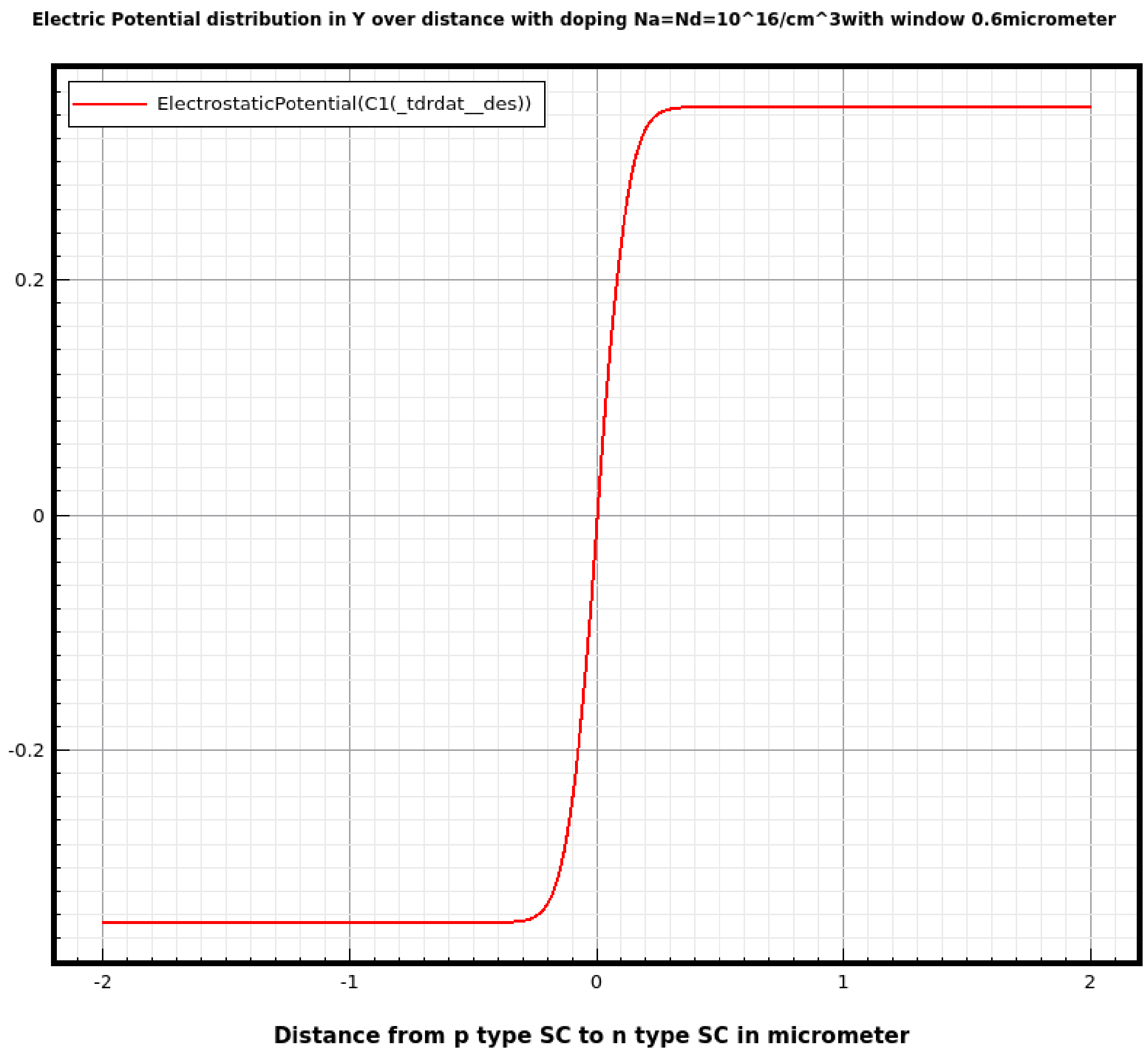


2) Simulate the above structure in sentaurus. You may take the width of the device to be 2 µm. Plot the charge density, electric field, potential distribution and the energy band diagrams.

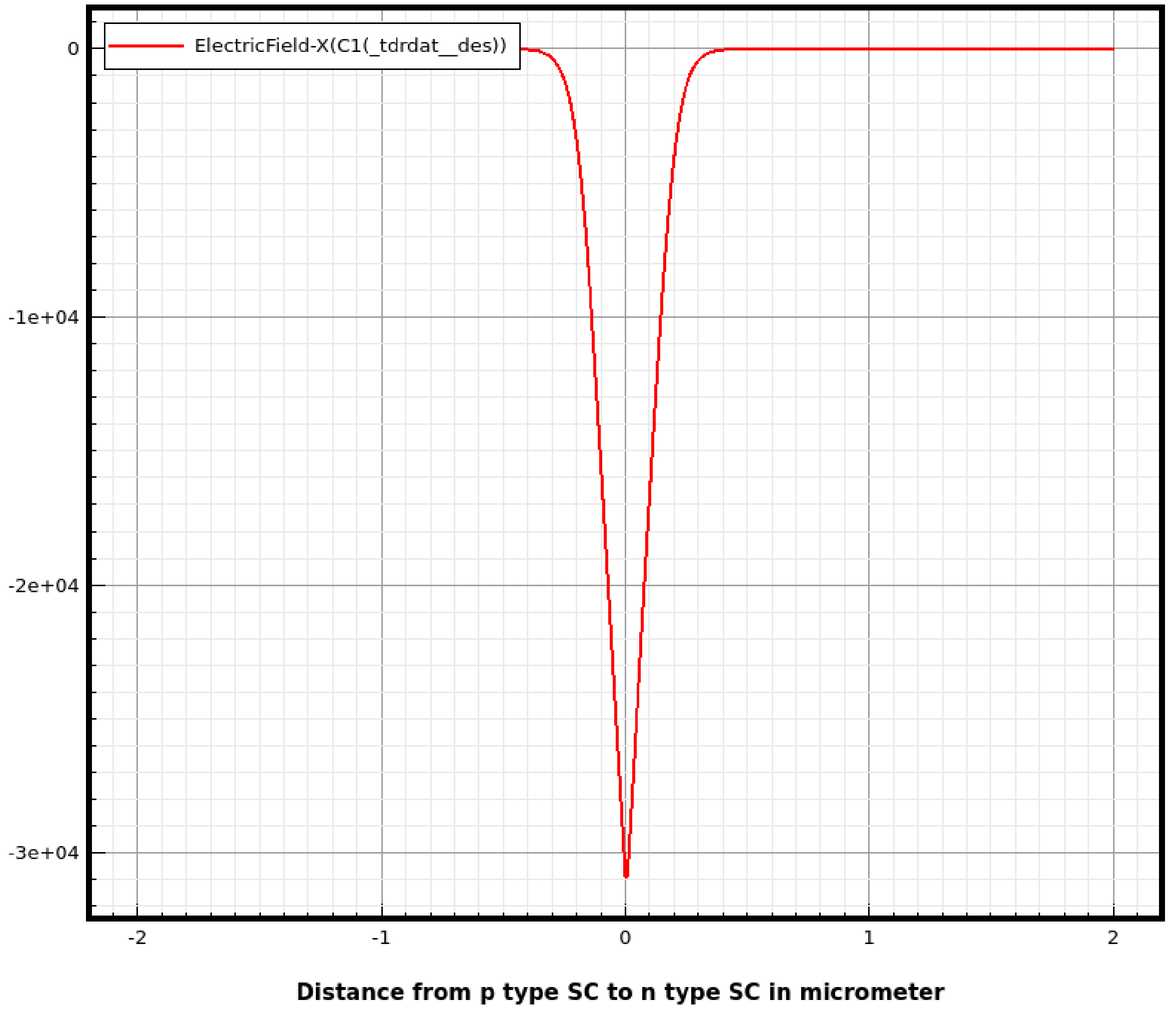
Ans:

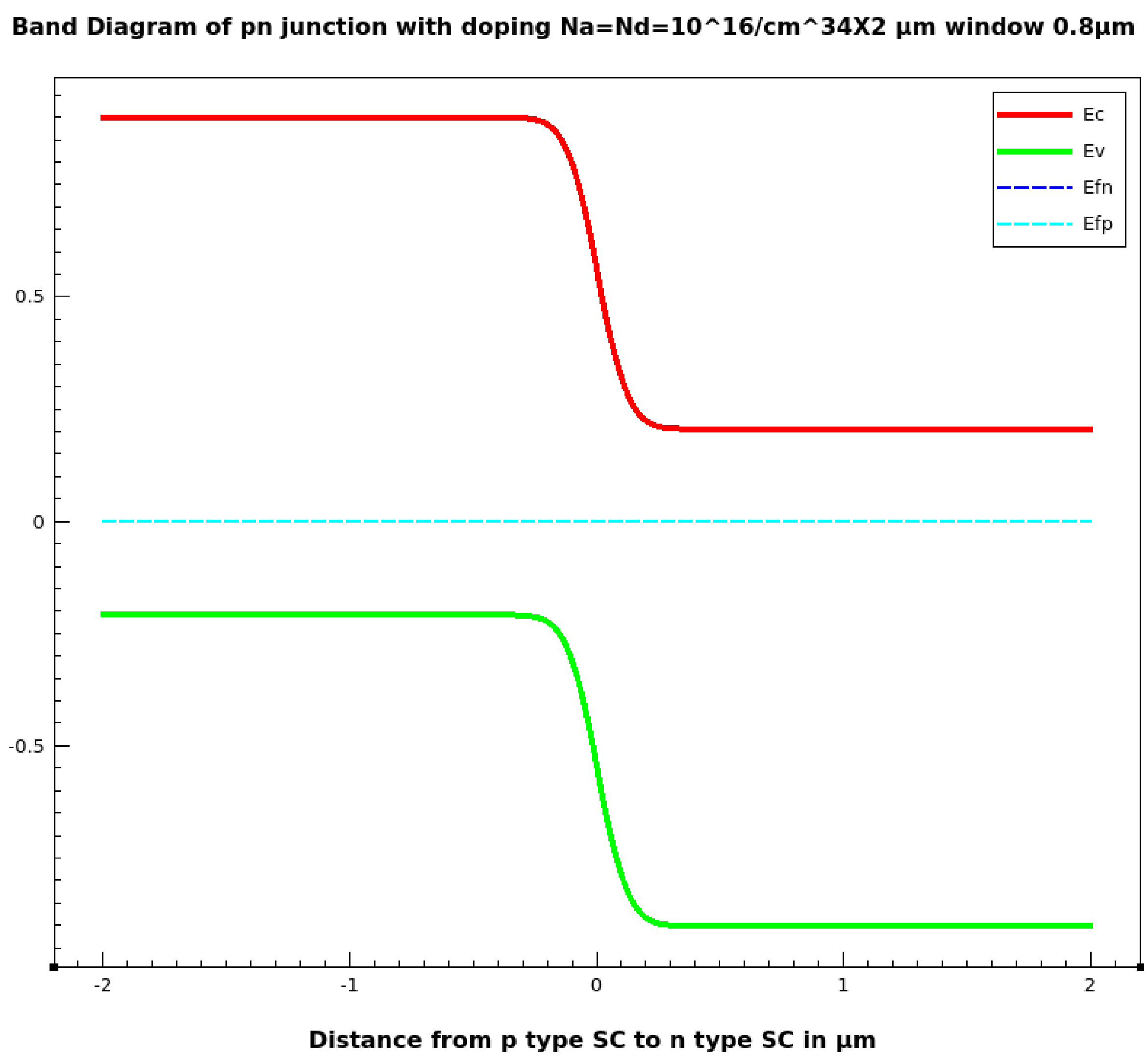
For Na=Nd=10^16/cm^3

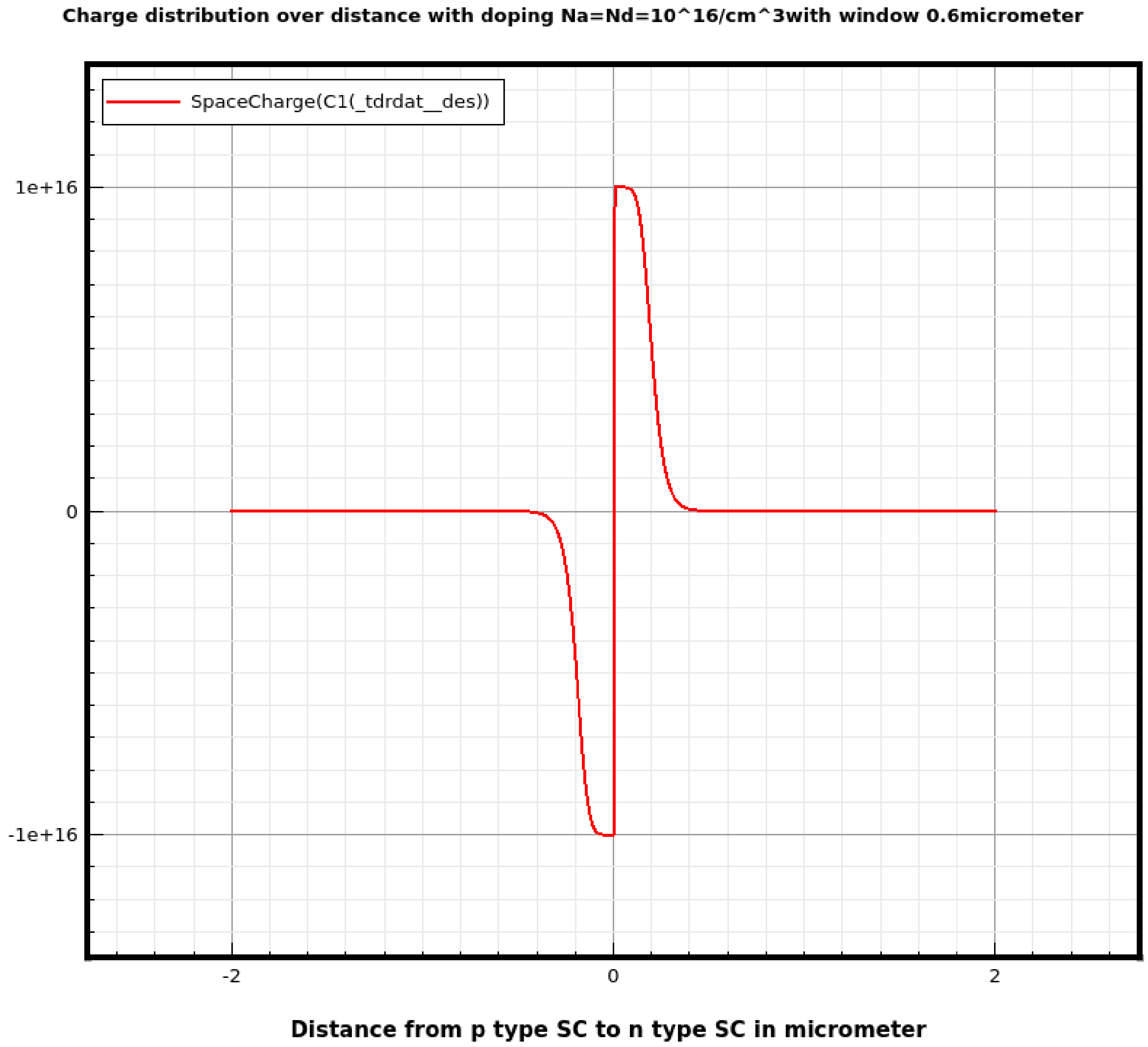

Sentaurus structure of pn junction with doping Na=Nd=10^16/cm^3 and dimension 4x2 micrometer with window 0.3,0.4micrometer
Y
-1
0
1
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer
DopingConcentration (cm^-3)
1.000e+16
0.000e+00
-3.684e+14
-1.000e+16


Electric Potential distribution in Y over distance with doping Na=Nd=10^16/cm^3with window 0.6micrometer
ElectrostaticPotential(C1(_tdrdat__des))
0.2
0
-0.2
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer

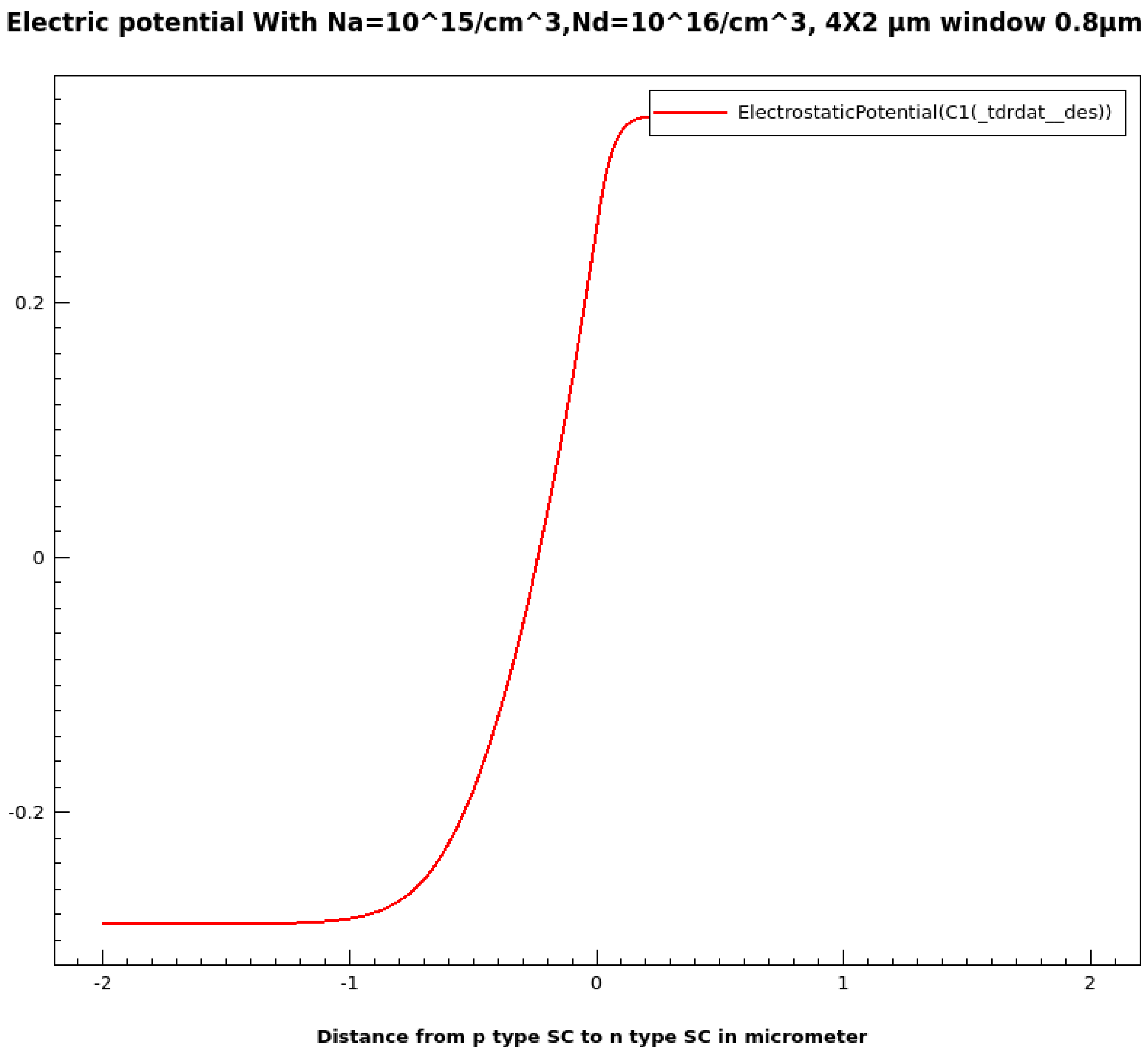
Electric field distribution in X over distance with doping Na=Nd=10^16/cm^3with window 0.6micrometer



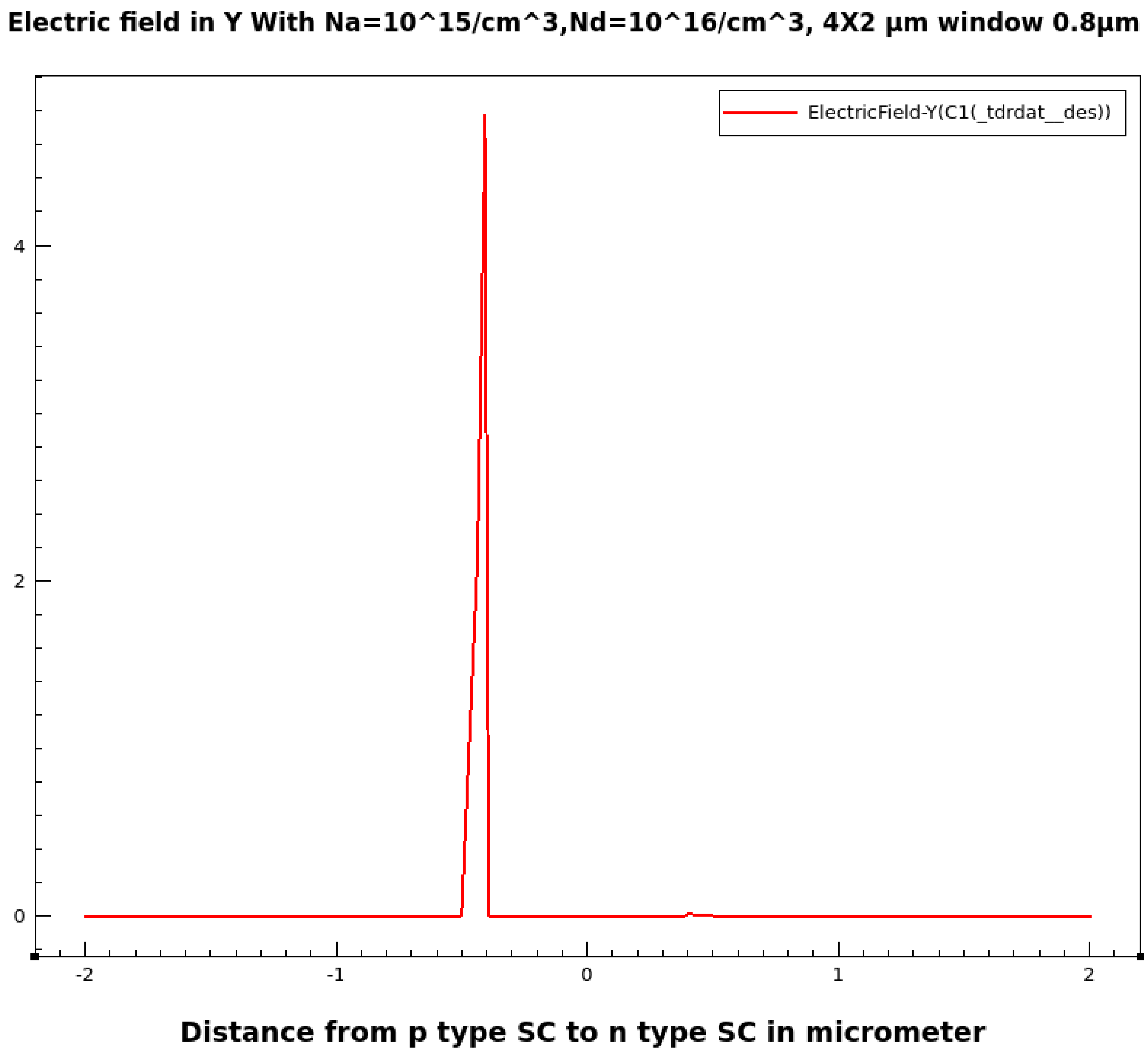

Band Diagram of pn junction with doping Na=Nd=10^16/cm^34X2 µm window 0.8µm
Ec
Ev
Efn
Efp
0.5
0
-0.5
-2
-1
0
1
2
Distance from p type SC to n type SC in µm

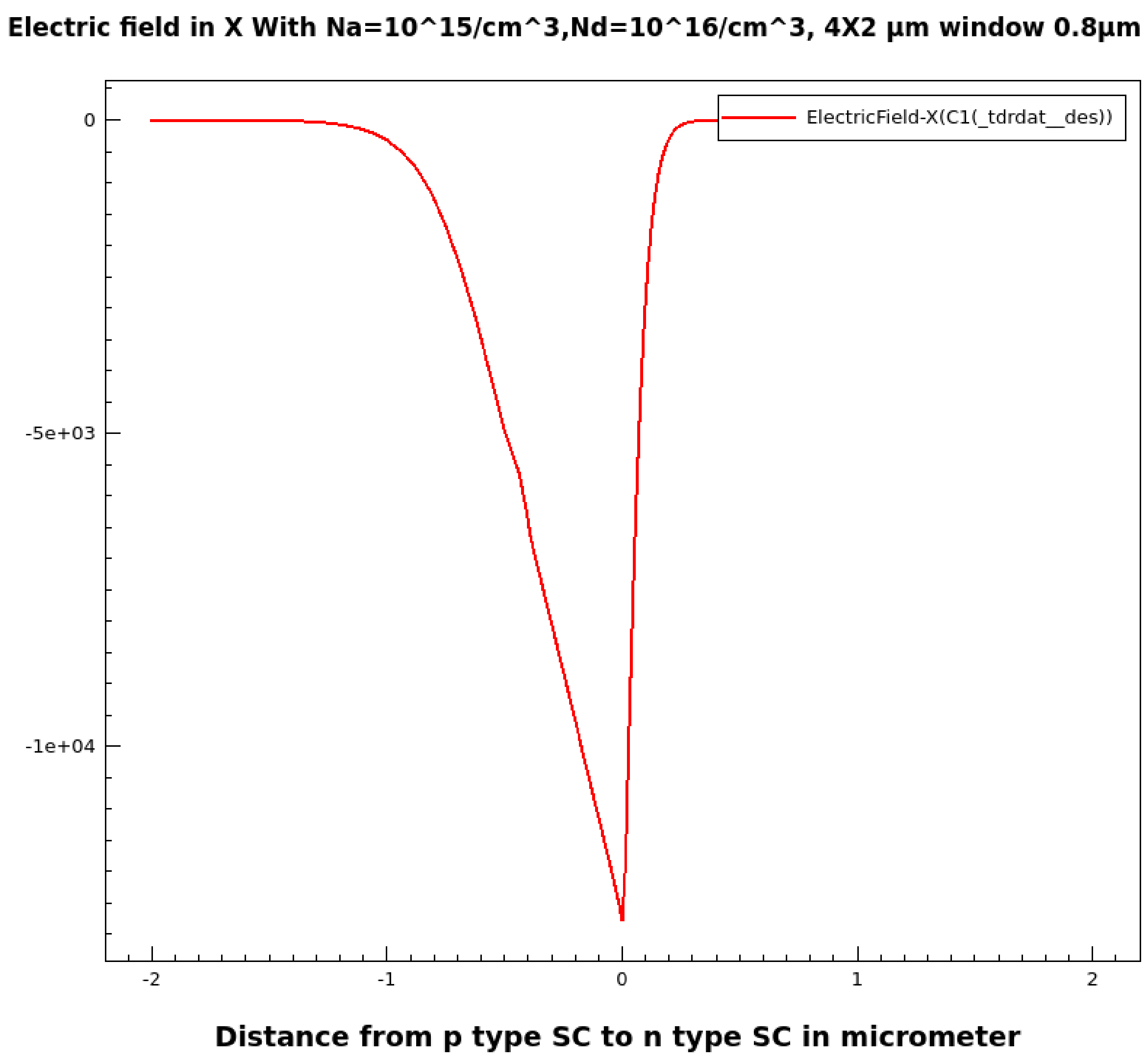


B)For Na=15/cm^3, Nd=10^16/cm^3

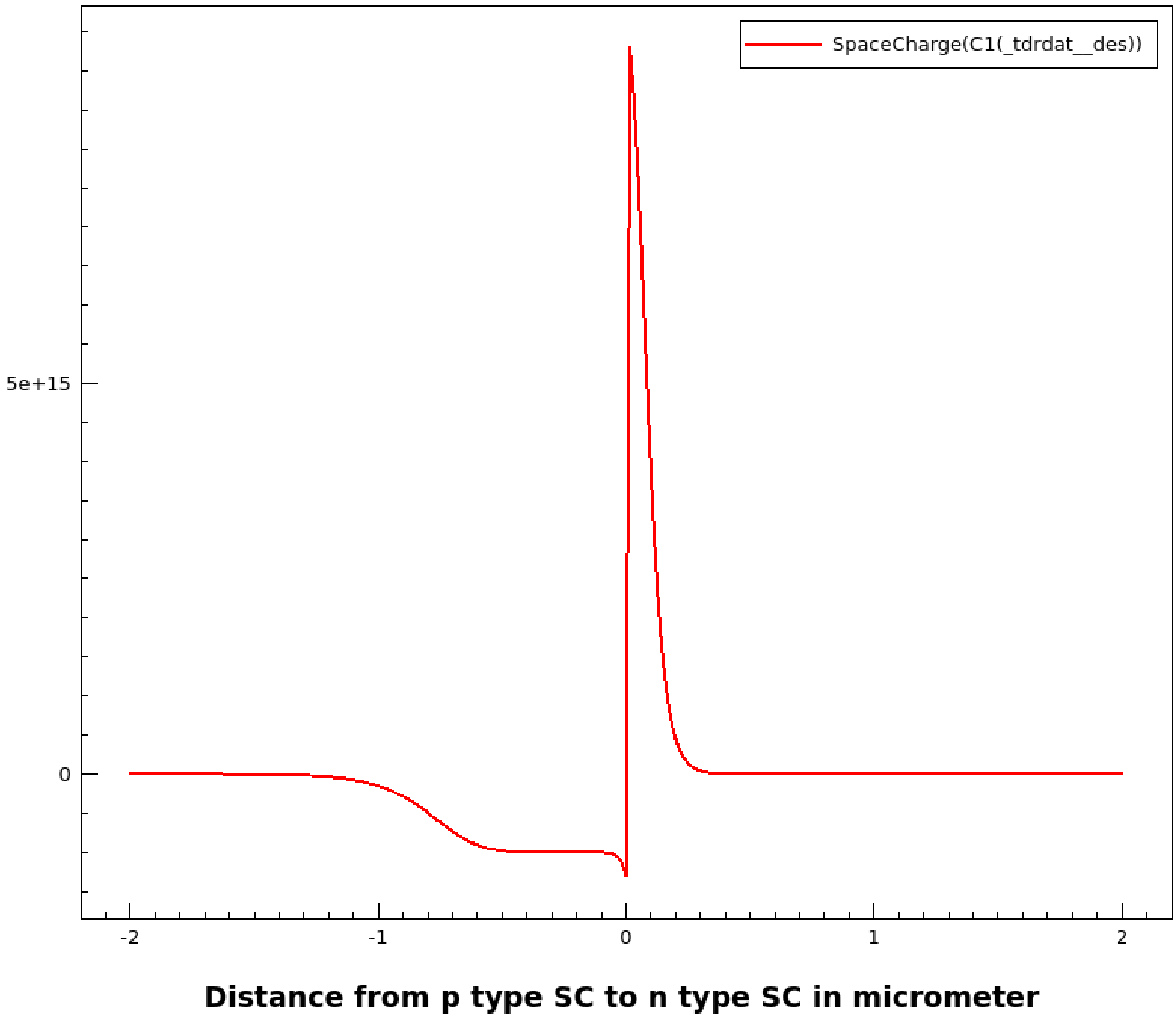


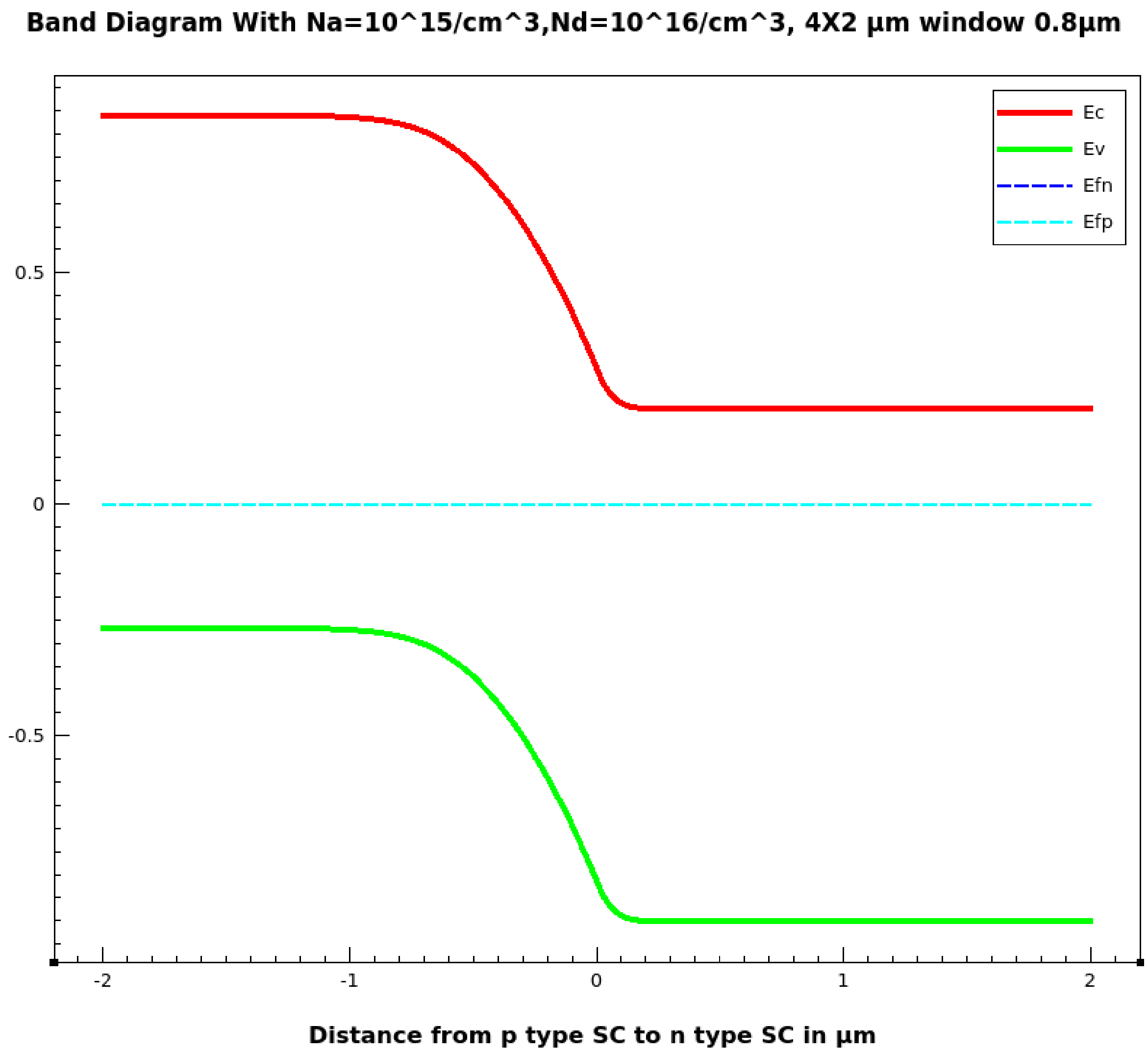
Electric potential With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm
ElectrostaticPotential(C1(_tdrdat__des))
0.2
0
-0.2
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer


Electric field in Y With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm
ElectricField-Y(C1(_tdrdat__des))
4
2
0
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer


Electric field in X With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm
ElectricField-X(C1(_tdrdat__des))
0
-5e+03
-1e+04
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer

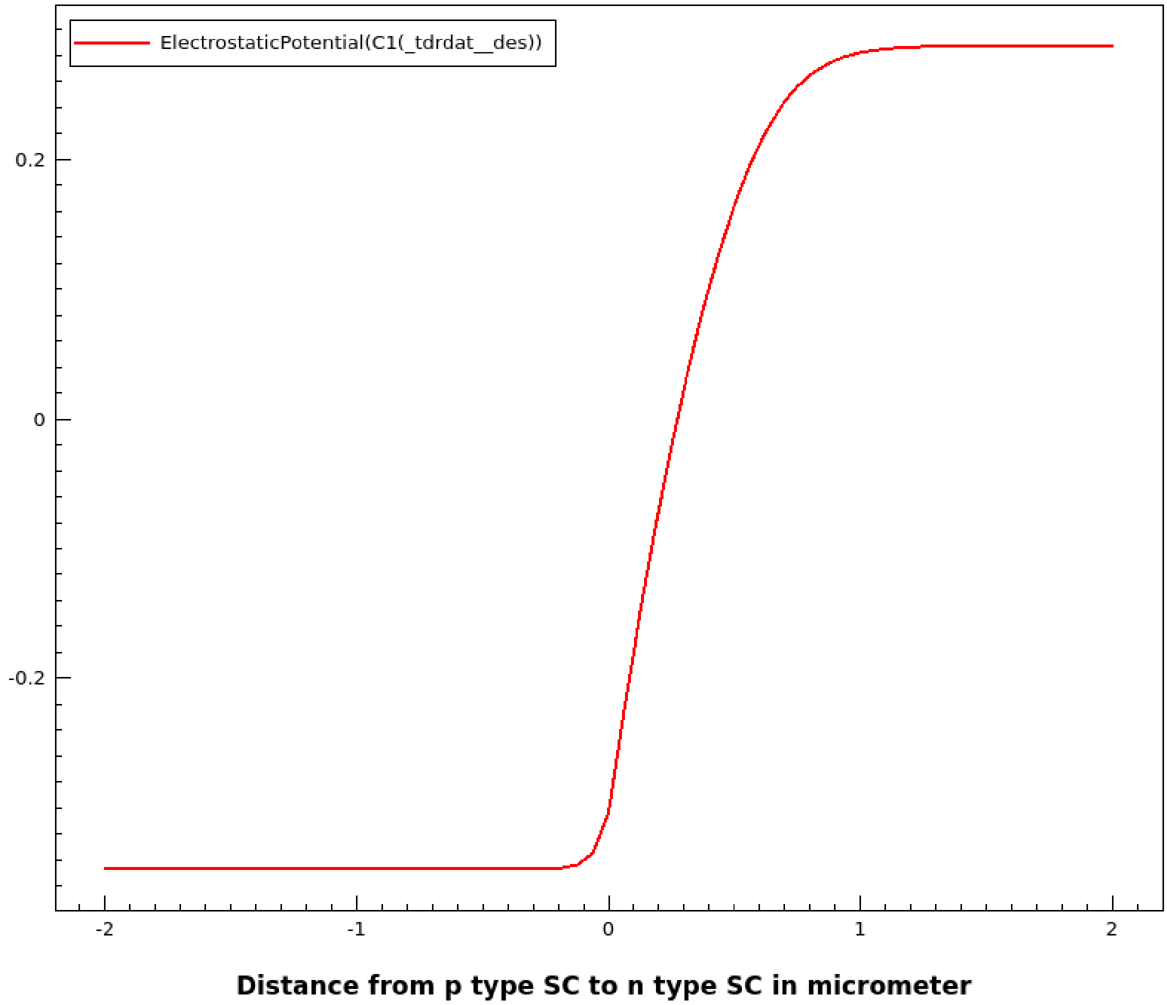
Charge density With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm

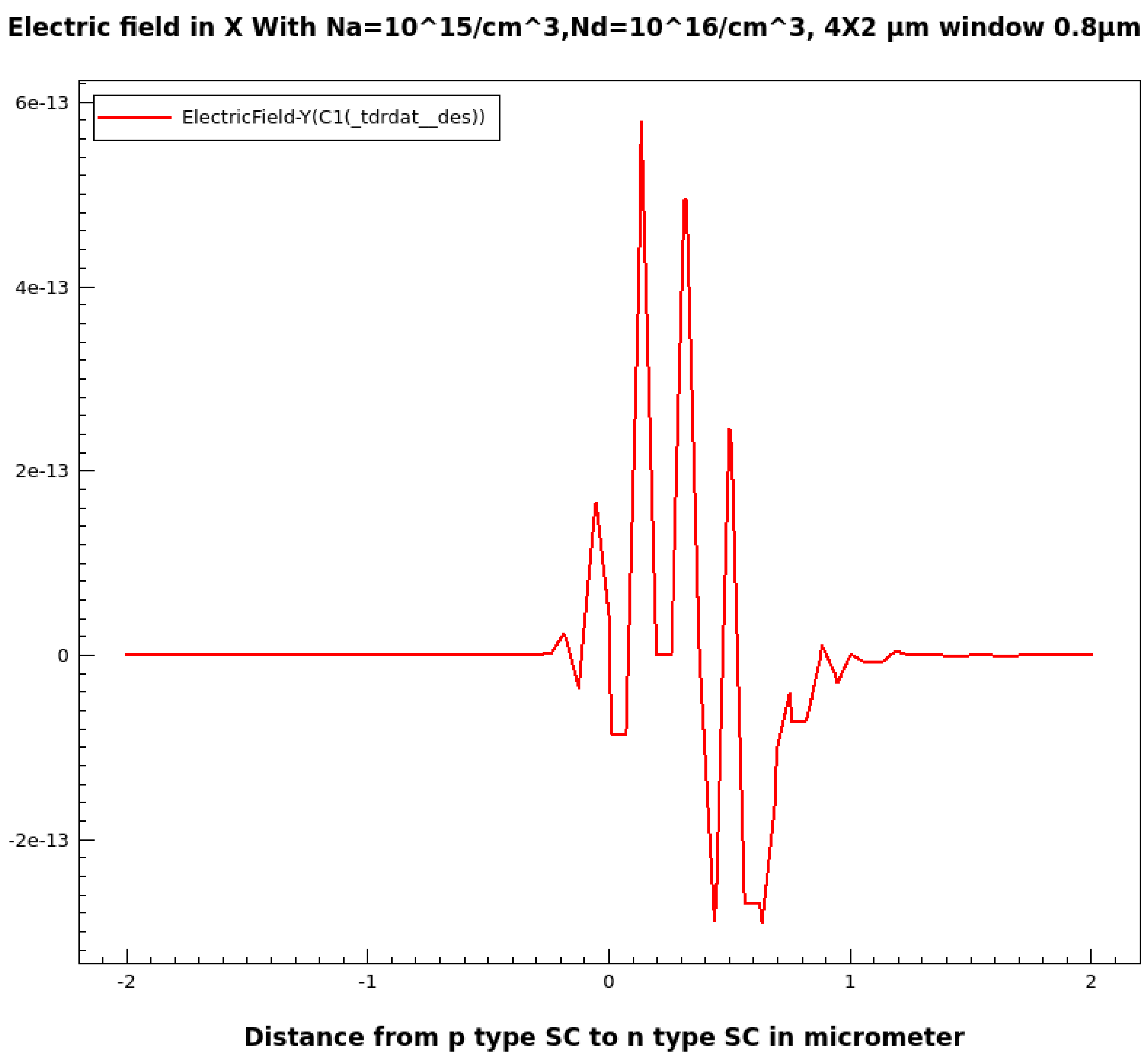


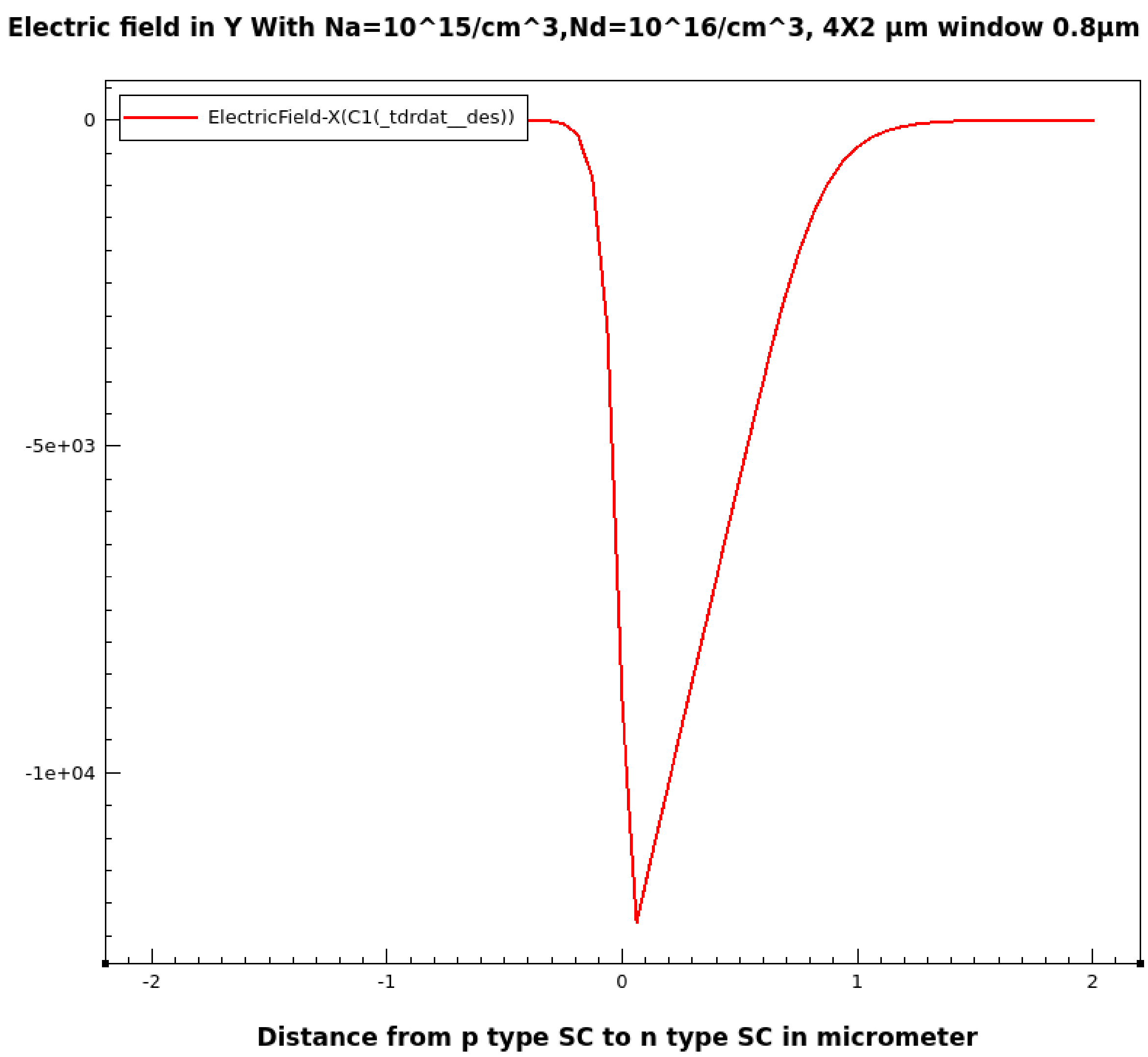


C)Na=10^16/cm^3,Nd=10^15/cm^3

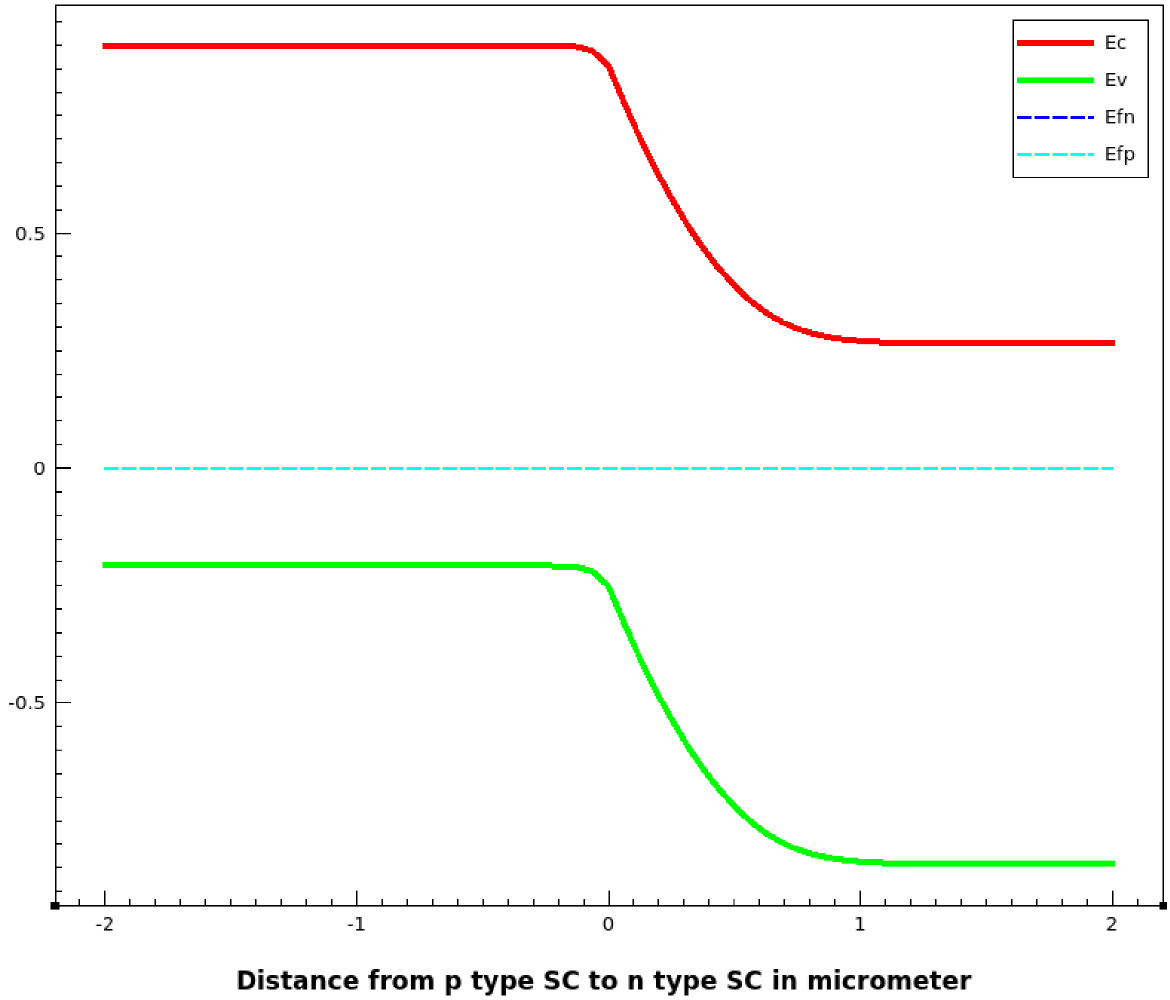
Electric Potential distribution With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm



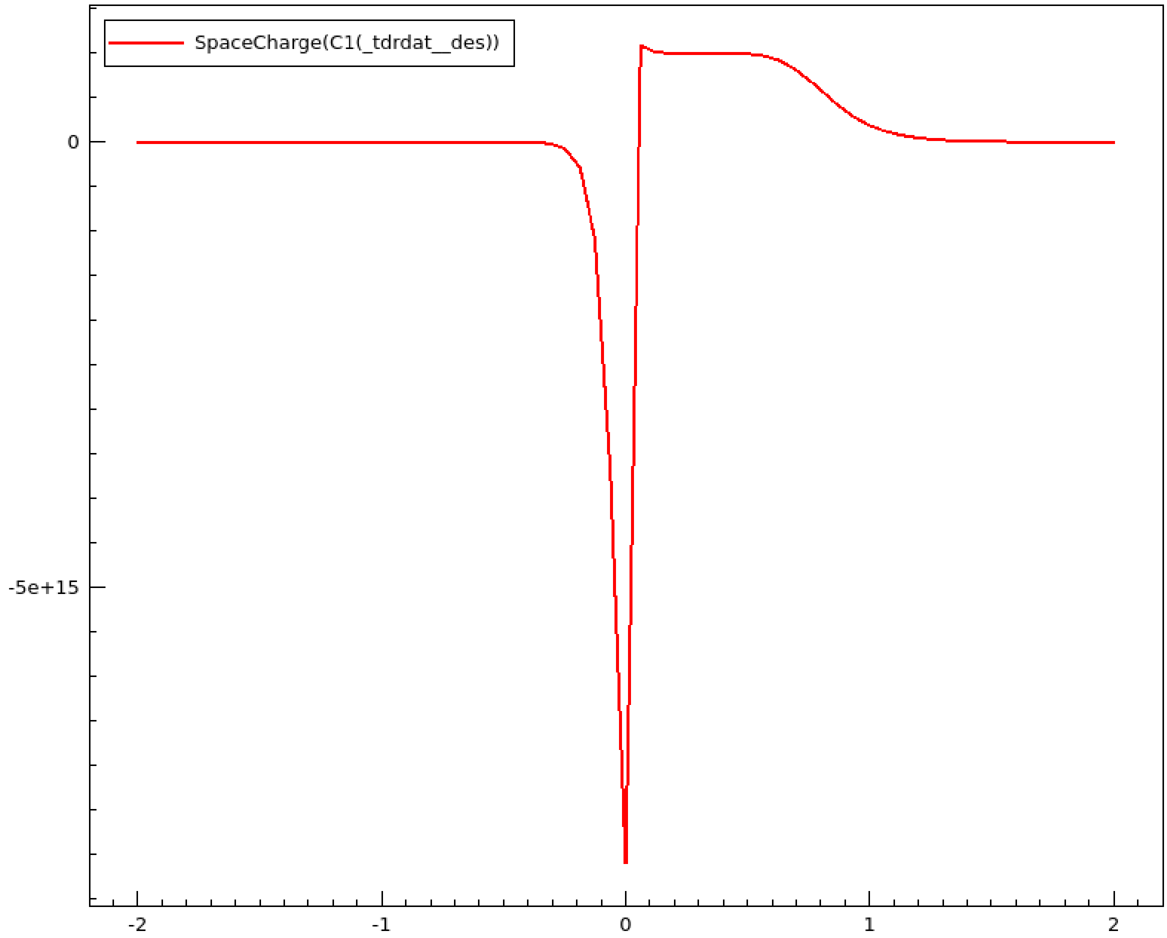

Electric field in X With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm
ElectricField-Y(C1(_tdrdat__des))
6e-13
4e-13
2e-13
0
-2e-13
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer


Electric field in Y With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm
ElectricField-X(C1(_tdrdat__des))
0
-5e+03
-1e+04
-2
-1
0
1
2
Distance from p type SC to n type SC in micrometer

Band Diagram With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm



charge density With Na=10^15/cm^3,Nd=10^16/cm^3, 4X2 µm window 0.8µm



Distance from p type SC to n type SC in micrometer