N-I-N Heterjunction Structure

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Introduction

When initially getting into applications of semiconductors, generally there is a n-type material and a p-type material. Without getting into too much chemistry, one material donates electrons to the other material, this other material is often called the acceptor. The n-type material is the one the donates it's abundant electrons to the p-type material that has an abundant amount of holes. In this model, a Heterostructure semi-conductor is modeled. A Heterostructure semi-conductor is made of multiple doped materials of different types, but the energy gap will stay the same. Also, there are two different types of semiconductors that we can have. There are intrinsic semiconductors that are not doped and are considered poor conductors. Then there are extrinsic semiconductors that are considered to improve the conductivity.

Method

This N-I-N Heterjunction is made up of two n-type materials. In the middle of these two doped n-type materials is a undoped barrier. The n-typed materials are made of GaAs and the barrier is made from $Al_{0.3}Ga_{0.7}As$. Below is a diagram of the semiconductor we're looking at.

Cap 30nm $n^+, 2E18$ GaAs	Barrier (insulator) 500nm $Al_{0.3}Ga_{0.7}As$ undoped	Buffer 300nm $n^+, 2E18$ GaAs

Figure 1: N-I-N Heterjunction Structure.

In this junction, the cap and the buffer are extrinsic semiconductor materials since they are doped. Therefore the GaAs material has very different values and is a significantly better conductor than the intrinsic barrier. The effective mass of GaAs is $5.74 * 10^{-32} kg$ and the gap energy is given as $1.42eV$. To be able to find the Fermi Energy, the donor energy must first be found. The donor energy is given by

$$\frac{m_0^* * e^4}{8 * \epsilon * h^2} \tag{1}$$

where m_0^* is the effective mass of GaAs. The donor energy is found by taking the gap energy and subtracting it from equation 1. This yields

$$E_d = E_g - \frac{m_0^* * e^4}{8 * \epsilon * h^2} \tag{2}$$

which leads us to the Fermi energy for an extrinsic device,

$$E_f = 0.5 * (E_g + E_d) \tag{3}$$

The Fermi energy for GaAs is 1.4174. Now, $Al_{0.3}Ga_{0.7}As$ is an intrinsic and a different approach is used to find the Fermi energy. The value of x is found $Al_xGa_{1-x}As$, in this case x is just 0.3. This value is used to calculate the effective mass of an electron by

$$m_e^* = (0.063 + (0.083 * x)) * m_e \tag{4}$$

.

The effective mass of a hole,

$$m_h^* = (0.51 + (0.25 * x)) * m_h \tag{5}$$

.

Finally, the gap energy of an intrinsic device by

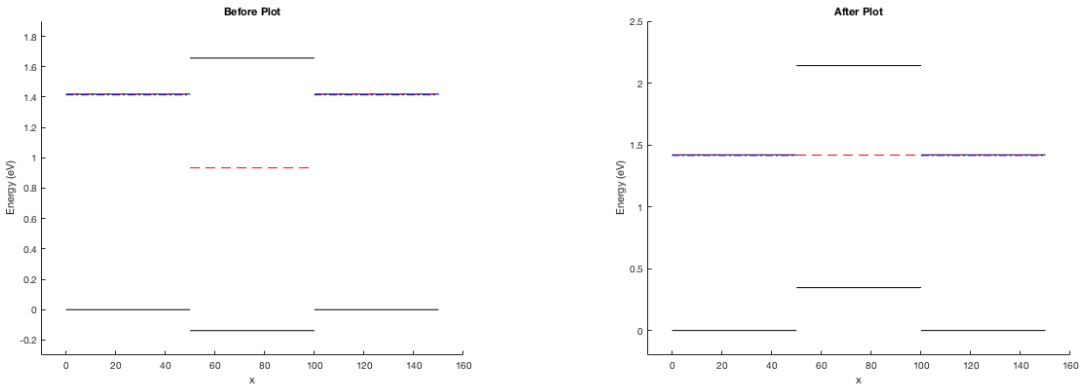
$$E_g = (1.42 + (1.247 * x)) \tag{6}$$

.

Once these values are found the Fermi energy can be found as

$$E_f = \frac{E_g}{2} + \frac{3}{4} * k_B * T * log(\frac{m_h^*}{m_e^*}) \tag{7}$$

where k_B is Boltzmann and T is temperature in kelvin. Once the valence bands, conductance bands, and Fermi energies are calculated the N-I-N Heterjunction Structure can be laid out. However, since this is a Heterjunction Structure the Fermi energies have to be lined up to be the same. Thus, a the below diagram is before the Fermi energy shift while the after diagram is dependent on the before diagram. This is unavoidable because this is the occurrence of the intrinsic and extrinsic materials being joined together. The shift is the extrinsic minus the intrinsic material. The valence and conductance bands were calculated for $Al_{0.3}Ga_{0.7}As$ by $-0.46 * x$ and $0.79 * x$ respectively.



(a) Before

(b) After

Figure 2: The before Fermi energy shift and after Fermi energy shift for the doped n-type materials and undoped barrier.

From the before and after diagram we see that the intrinsic material is shifted upwards to match it's Fermi energy with the extrinsic material. This results in the conductance and valance bands to shift to a higher level when they where previously at a lower level.

Results

To find current density a few things must first be defined. The equation for electron density is as follow

$$I_e \approx N_c * exp\left(\frac{-(E_g + eU_0 - E_f)}{k_B * T}\right) \tag{8}$$

where N_c is

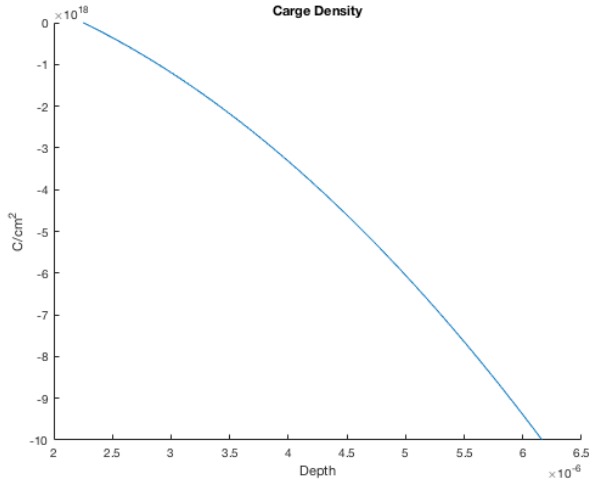
$$N_c = 2 * \left(\frac{2 * \pi * m_e^* * k_B * T}{h^2}\right)^{\frac{3}{2}}. \tag{9}$$

For the current density to be found the built in voltage is also needed. The built in voltage for this N-I-N junction can be calculated as follows,

$$U_0 = \frac{e(N_A x_p^2 + N_D x_n^2)}{2\epsilon} \tag{10}$$

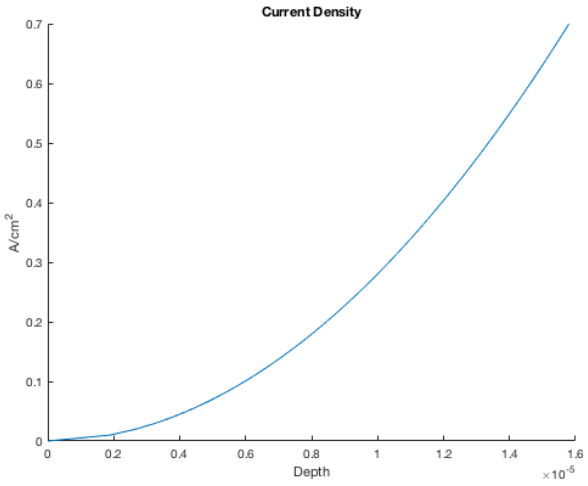
.

x_n and x_p are the depletion depths, N_A is the density of acceptors, N_D is the density of donors. To find the hole current density effective mass is changed to m_h^* and the charge e is changed to the mass of a hole. The following graphs are calculated with the equations listed above.



(a)

Figure 3: As the charge come further in it will deplete.



(a) Before

Figure 4: As the charge come further in it will deplete.

Conclusion

To check this models correctness, there are a few things to look through and prove true. The device in this model is very small, thus the region of depth should also be very small. In the figures looked at above this is true. The depth is in the correct orders of magnitude to be in nanometers, the correct length of the N-I-N device. Another good check is to calculate the units out and see if they are correct. In each figure nanometers were converted to centimeters. Therefore, every figure has an area in centimeters. Electron and hole densities have a correct order of magnitude. Finally, the last way is by comparing to the IV curves. The current density and the IV curves look similar in the way that make physical sense.

Appendix

```
function AlGaAs
%% constants
x = 0.3;                %constant for AlGaAs
m_0 = 9.11*10^-31;      %electron mass in kg
e_r = 12.9;             %rel perm of GaAs
e_0 = 8.85*10^-12;      %perm in F/m
h = 6.63*10^-34;        %Planck's constant in J*s
hev = 4.14*10^-15;      %Planks's constant in eV
eps = e_r*e_0;          %perm
Kb = 8.6173*10^-5;      %eV * K^-1
T = 300;                %Temperature 300K
e = 1.6*10^-19;         %elec charge in coulombs


%% AlGaAs

m_e_Al = (0.063+(0.083*x))*m_0; %Effective electron mass in kg
m_h_Al = (0.51+(0.25*x))*m_0; %Effective hole mass in kg
EgAl = (1.42 + (1.247*x)); %Eg in eV
EfAl = (EgAl/2)+((3/4)*(Kb)*(T)*log(m_h_Al/m_e_Al)); %Fermi energy
```

```
%% GaAs

m_e_Ga = 0.063*9.11*10^-31; %Effective electron mass in kg
Eg = 1.42; %band gap in eV
est = ((m_e_Ga*e^4)/(8*eps^2*h^2));
conv_eV = est * 6.242E18;
Ed = Eg - conv_eV;
Ef = 0.5*(Eg+Ed);
N_d = 2*10^18;
N_e = N_d*(1+exp((Ef-Ed)/(Kb*T))^(-1));

%% Conductance and Valence Bands

Delta_E_c = 0.79*x;
Delta_E_v = -0.46*x;

%% Density for AlGaAs
Nc = 2*((2*pi*m_e_Al*Kb*T)/h^2)^(3/2);
Ne = Nc*exp(-(1.794-0.9338)/(Kb*T)); % electron density for AlGaAs
Nv = 2*((2*pi*m_h_Al*Kb*T)/h^2)^(3/2);
Nh = Nv*exp(-0.9338/(Kb*T)); % Hole density for AlGaAs

%% Outputs
shift = Ef - EfAl;
fprintf('The value of EfAl: %f\n',EfAl);
fprintf('The value of Ef: %f\n',Ef);
fprintf('The value of the shift: %f\n',shift);
%% Before Plot
figure(1)
hold on;
    plot([0 50],[Ed Ed],'b-.') %Eg
    plot([0 50],[Ef Ef],'r--') %Ef
    plot([0 50],[0 0],'k') %E_v
    plot([0 50],[Eg Eg],'k') %E_c
    plot([50 100],[EfAl EfAl],'r--') %E_f
    plot([50 100],[Delta_E_v Delta_E_v],'k') %E_v
    plot([50 100],[Eg + Delta_E_c Eg + Delta_E_c],'k') %E_c
    plot([100 150],[0 0],'k') %E_v
    plot([100 150],[Eg Eg],'k') %E_g
    plot([100 150],[Ef Ef],'r--') %Ef
    plot([100 150],[Ed Ed],'b-.') %Ec
title('Before Plot')
axis([-10, 160, -0.3, 1.9])
ylabel('Energy (eV)')
xlabel('x')
legend('Ef','Eg')

%% After Plot
figure(2)
hold on;
    plot([0 50],[Ef Ef],'r--') %Ef
    plot([100 150],[Ed Ed],'b-.') %Ef
    plot([0 50],[Ed Ed],'b-.') %Ef
    plot([0 50],[0 0],'k') %E_v
    plot([50 100],[Delta_E_v + shift Delta_E_v + shift],'k') %E_v
```

```
    plot([100 150],[0 0],'k') %E_v
    plot([0 50],[Eg Eg],'k') %E_c
    plot([50 100],[Eg + Delta_E_c + shift , Eg + Delta_E_c + shift],'k') %E_c
    plot([100 150],[Eg Eg],'k') %E_c
    plot([100 150],[Ef Ef],'r--') %Ef
    plot([50 100],[EfAl+shift EfAl+shift],'r--') %E_c
title('After Plot')
axis([-10, 160, -0.2, 2.5])
ylabel('Energy (eV)')
xlabel('x')
legend('Ef','Eg')

%% Intrinsic semi conductors
Nc = 2*((2*pi*me*Kb*T)/(h^2));
Nv = 2*((2*pi*mh*Kb*T)/(h^2));
Ne = Nc*exp(-((Ec-Ef)/(Kb*T)));
Nh = Nv*exp(-Ef/(Kb*T));

%% Extrinsic Semiconductors
figure(2)
hold on;
title('Carge Density')
xlabel('Depth')
ylabel('C/cm^2')
plot(xd,a)
% %Brett's Equation
% % Ni2 = Ne*Nh; %only true for elec nue
Nc = 2*(((2*pi*m_e_Ga*Kb*T)/(hev^2))^1.5);
Nh = Nv*exp(-Ef/(Kb*T);
Nv = 2*((2*pi*m_h*T)/h^2)^(3/2);
Na = 2E18;
xp = [0:0.5E-9:30E-9];
xp2 = [0:0.5E-9:300E-9];
xn1 = [0:0.5E-9:30E-9]; %nm
xn2 = [0:0.5E-9:300E-9]; %nm
u01 = (e*((Na*(xp.^2)) + (Nd*(xn1.^2))))/(2*eps);
u02 = (e*(Na*xp2.^2 + Nd*xn2.^2))/(2*eps);
Ie = Nc*exp(-((Eg+(e.*u0)-Ef)/(Kb*T)));
Ie2 = Nc*exp(-((Eg+e*u0-Ef)/(Kb*T)));
xxn1 = ((2*eps*u0*Na)/(e*Nd*(Nd+Na))).^0.5;
xxn2 = ((2*eps*u0*Na)/(e*Nd*(Nd+Na))).^0.5;
figure(3)
hold on;
title('Current Density')
xlabel('Depth')
ylabel('A/cm^2')
plot(xxn1, u0)
```