بسمه تعالی

موضوع تکلیف جایزه:رسم نمودار چگالی الکترون بر حسب دما در یک مادهn-type سیلیکون،واثر فزایش ناخالصی دهنده بر ان

نام ونام خانوادگی:رحیم برومندی

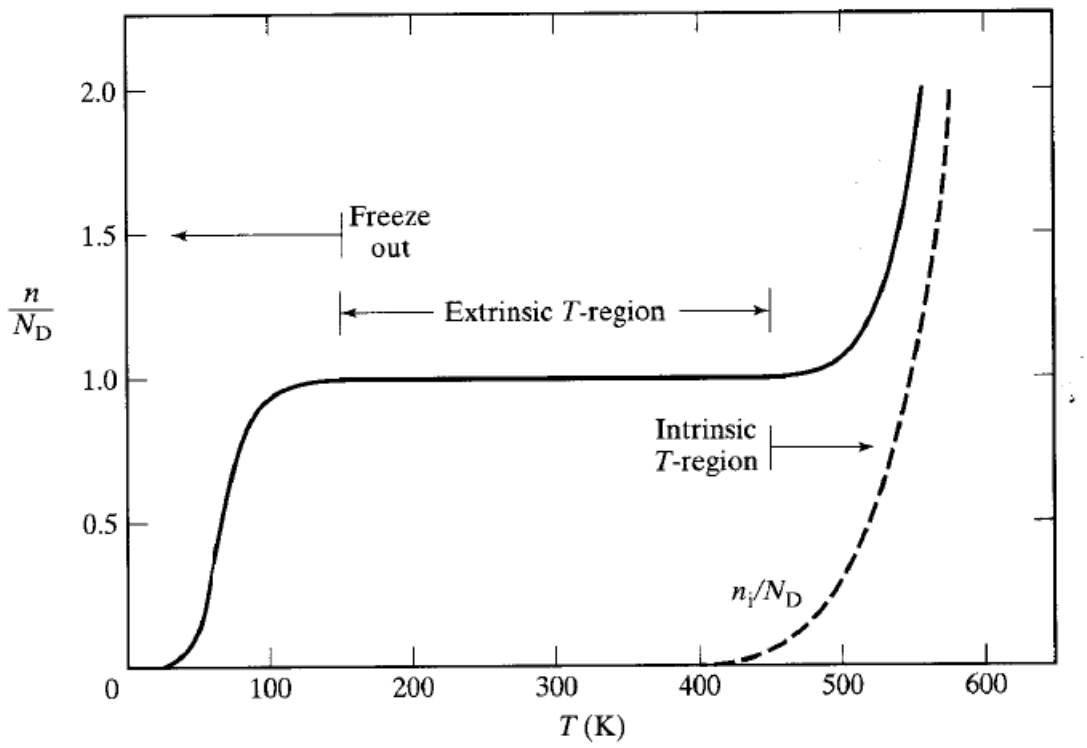
شماره دانشجویی:9431023

استاد درس:جناب اقای دکتر غیور

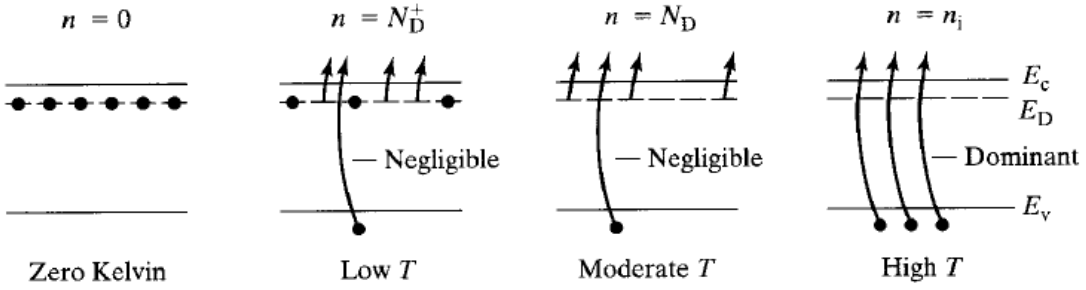
94/7/10

صورت مسیله این بود که باید در یک ماده نوع ان ،چگالی الکترون ها را که بر حسب

دما نمودار ان در کتاب ادوات یانگ داده شده بود باید معادلات ان را محاسبه کرده،برای سه ناحیه Freeze-out,Extrinsic,Intrinsic بعد ان را در متلب رسم کنیم.



(a)



(b)

بعد از جستجو به دنبال معادلات به کتاب Robert F. Pierret-Advanced Semiconductor Fundamentals-Prentice Hall (2002).pdf رسیدم که ان چند صفحه که این فرمول ها را محاسبه کرده اورده ام.(صفحات 121-126)

4.5.2 Equilibrium Carrier Concentrations

The starting point for all calculations is the charge neutrality relationship. Making only the assumption of nondegeneracy, one can substitute Eqs. (4.54) and (4.65) into Eq. (4.63) to obtain

$$N_V e^{(E_v - E_F)/kT} - N_C e^{(E_F - E_c)/kT} + \frac{N_D}{1 + g_D e^{(E_F - E_D)/kT}} - \frac{N_A}{1 + g_A e^{(E_A - E_F)/kT}} = 0 \quad (4.70)$$

In a given problem, the temperature, the material, the dominant dopant center or centers, and the dopant concentrations are all taken to be known quantities; the only unknown in Eq. (4.70) is E_F. Very generally, therefore, Eq. (4.70) can be numerically solved for E_F and the value of E_F substituted back into Eq. (4.54), thereby yielding n and p.

If the computation is limited to a range of temperatures, it is often possible to simplify the charge neutrality relationship and subsequently to obtain highly accurate closed-form solutions for the carrier concentrations. Specific examples of practical interest are considered below.

Freeze-Out/Extrinsic T ($N_D >> N_A$ or $N_A >> N_D$)

In a donor-doped semiconductor ($N_D \gg N_A$) maintained at temperatures where $N_D \gg n_i$, the electron concentration will always be much greater than the hole concentration. Likewise, N_D^+ will be much greater than N_A^- except in the extreme $T \rightarrow 0$ K limit where N_D^+ approaches N_A. Thus, excluding the $T \rightarrow 0$ K limit if $N_A \neq 0$, the charge neutrality relationship can be simplified to

$$n = N_D^+ \quad (4.71)$$

This result is of course in agreement with the previous qualitative discussion. Using Eqs. (4.65a) and (4.54a) we can also write

$$N_D^+ = \frac{N_D}{1 + g_D e^{(E_F - E_D)/kT}} = \frac{N_D}{1 + g_D (n/N_C) e^{(E_c - E_D)/kT}} \quad (4.72a)$$

$$= \frac{N_D}{1 + (n/N_\zeta)} \quad (4.72b)$$

where

$$N_\zeta \equiv (N_C/g_D) e^{-(E_c - E_D)/kT} \qquad \text{(a computable constant at a given } T\text{)} \quad (4.73)$$

Eliminating N_D^+ in Eq. (4.71) using Eq. (4.72b) and solving for n, one obtains

$$n = \frac{N_D}{1 + (n/N_\zeta)} \tag{4.74}$$

$$n^2 + N_\zeta n - N_\zeta N_D = 0 \tag{4.75}$$

and

$$n = -\frac{N_\zeta}{2} + \left[\left(\frac{N_\zeta}{2}\right)^2 + N_\zeta N_D\right]^{1/2} \qquad \begin{matrix}(+\text{ root chosen}\\ \text{because } n \geq 0)\end{matrix} \tag{4.76a}$$

or

$$n = \frac{N_\zeta}{2}\left[\left(1 + \frac{4N_D}{N_\zeta}\right)^{1/2} - 1\right] \tag{4.76b}$$

An analogous result can be obtained for acceptor-doped material.

Upon examining Eq. (4.76b), note that N_ζ will typically be much greater than N_D in the extrinsic temperature region and $n \rightarrow N_D$. For example, taking the semiconductor to be $N_D = 10^{15}/\text{cm}^3$ phosphorus-doped Si and $T = 300$ K, $E_c - E_D = 0.045$ eV, $g_D = 2$, $N_C = 3.226 \times 10^{19}/\text{cm}^3$, $N_\zeta = 2.829 \times 10^{18}/\text{cm}^3$, and from Eq. (4.76b) one computes $n = 0.9996N_D$. Since $n = N_D^+$, this result also tells us the phosphorus donor sites in $N_D = 10^{15}/\text{cm}^3$ Si are 99.96% ionized at room temperature and supports the usual total-ionization approximation for room-temperature operation. By way of comparison, the donor sites in the same semiconductor are only 73.4% ionized at liquid-nitrogen temperatures. ($N_C = 3.57 \times 10^{18}/\text{cm}^3$ and $N_\zeta = 2.02 \times 10^{15}/\text{cm}^3$ at 77 K if one employs the 4 K m_n^* for Si listed in Table 4.1.) It should also be mentioned that the entire low-temperature portion of the Fig. 4.18(a) plot was constructed using Eq. (4.76b).

Extrinsic/Intrinsic *T*

For a semiconductor maintained at a temperature where the vast majority of dopant sites are ionized, the charge neutrality relationship simplifies to

$$p - n + N_D - N_A = 0 \tag{4.77}$$
(Same as 4.64)

In a nondegenerate semiconductor, however, $np = n_i^2$. Thus we have

$$n_i^2/n - n + N_D - N_A = 0 \tag{4.78a}$$

or

$$n^2 - (N_D - N_A)n - n_i^2 = 0 \tag{4.78b}$$

Solving the quadratic equation for n then yields

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2\right]^{1/2} \qquad \begin{matrix}(+\text{ root chosen} \\ \text{because } n \geq 0)\end{matrix} \tag{4.79a}$$

and

$$p = n_i^2/n = \frac{N_A - N_D}{2} + \left[\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2\right]^{1/2} \tag{4.79b}$$

When a semiconductor is maintained in the extrinsic temperature region, $N_D \gg n_i$ in a donor-doped ($N_D \gg N_A$) semiconductor and $N_A \gg n_i$ in an acceptor-doped ($N_A \gg N_D$) semiconductor. Thus for extrinsic temperature operation, which normally includes room temperature, Eqs. (4.79) reduce to

$$\boxed{\begin{matrix} n \simeq N_D \\ p \simeq n_i^2/N_D \end{matrix}} \qquad \begin{matrix}\text{donor-doped, extrinsic-}T \\ (N_D \gg N_A,\ N_D \gg n_i)\end{matrix} \qquad \begin{matrix}(4.80a) \\ (4.80b)\end{matrix}$$

$$\boxed{\begin{matrix} p \simeq N_A \\ n \simeq n_i^2/N_A \end{matrix}} \qquad \begin{matrix}\text{acceptor-doped, extrinsic-}T \\ (N_A \gg N_D,\ N_A \gg n_i)\end{matrix} \qquad \begin{matrix}(4.80c) \\ (4.80d)\end{matrix}$$

Likewise, in the intrinsic temperature region, where $n_i \gg |N_D - N_A|$, Eqs. (4.79) simplify to

$$\left[\begin{matrix} n \simeq n_i \\ p \simeq n_i \end{matrix}\right] \qquad \begin{matrix}\text{intrinsic-}T \\ (n_i \gg |N_D - N_A|)\end{matrix} \qquad \begin{matrix}(4.81a) \\ (4.81b)\end{matrix}$$

The results here are, of course, in total agreement with the earlier qualitative discussion. In the extrinsic temperature range, the majority carrier concentration is simply equal to the dominant doping concentration, and the minority carrier concentration equals n_i^2 divided by the dominant doping concentration; $N_D = 10^{15}/\text{cm}^3$ doped Si at $T = 300\,\text{K}$ would have $n \simeq 10^{15}/\text{cm}^3$ and $p \simeq 10^5/\text{cm}^3$. Moreover, regardless of the doping, all semiconductors ultimately become intrinsic at sufficiently elevated temperatures. Note that the complete expressions, Eqs. (4.79), need be employed only for temperatures where $n_i \sim |N_D - N_A|$.

Finally, to increase the resistivity, donors or acceptors are sometimes added to make $N_D - N_A \simeq 0$; in other materials, such as GaAs, N_A may be comparable to N_D in the as-grown crystal. When N_A and N_D are comparable and non-zero, the material is said to be *compensated*, with the effects of the dopants tending to negate each other. If this be the case, both N_D and N_A must be retained in the carrier concentration expressions.

4.5.3 Determination of E_F

The position of the Fermi level is often determined as an adjunct to carrier concentration calculations. For one, the Fermi level positioning is sometimes needed to confirm the validity of the nondegenerate assumption. Knowledge of the Fermi level positioning is also desired in drawing energy band diagrams. The precise nondegenerate positioning of E_F can always be computed, of course, from Eq. (4.70). (If it turns out that the semiconductor is degenerate, the E_F value thereby determined will extend further into the degenerate zone than the true E_F value.) Like the carrier concentrations, however, highly accurate closed-form solutions for E_F are possible in most practical cases of interest. Specific examples are considered below.

Exact Position of E_i

Given an intrinsic ($N_A = 0$, $N_D = 0$) semiconductor, one can write

$$n = p \tag{4.82}$$

or, making use of Eqs. (4.54),

$$N_C e^{(E_F - E_c)/kT} = N_V e^{(E_v - E_F)/kT} \tag{4.83}$$

Solving for $E_F = E_i$ yields

$$E_i = \frac{E_c + E_v}{2} + \frac{kT}{2} \ln (N_V/N_C) \tag{4.84}$$

and since

$$\frac{N_V}{N_C} = \left(\frac{m_p^*}{m_n^*}\right)^{3/2} \tag{4.85}$$

we conclude that

$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln (m_p^*/m_n^*) \tag{4.86}$$

Using the effective masses listed in Table 4.1, one finds E_i in Si is positioned 0.0073 eV below midgap and E_i in GaAs is positioned 0.0403 eV above midgap at 300 K. Thus, at 300 K, the energy displacement of E_i from midgap is 0.65% and 2.8% of the band gap energy for Si and GaAs, respectively.

Freeze-Out/Extrinsic T ($N_D >> N_A$ or $N_A >> N_D$)

In a donor-doped nondegenerate semiconductor where $N_D \gg n_i$, we know

$$n = N_C e^{(E_F - E_c)/kT} = (N_\xi/2)[(1 + 4N_D/N_\xi)^{1/2} - 1] \tag{4.87}$$

giving

$$E_F = E_c + kT\ln\{(N_\xi/2N_C)[(1 + 4N_D/N_\xi)^{1/2} - 1]\} \tag{4.88}$$

Equation (4.88) is particularly useful for low-temperature calculations. As can be verified using Eq. (4.88), E_F rises toward the conduction band edge when T is decreased, approaching a limiting value midway between E_c and E_D as $T \rightarrow 0$ K. (If $N_A \neq 0$, E_F approaches E_D.) Analogously, in acceptor-doped semiconductors, E_F approaches $(E_A + E_v)/2$ if $N_D = 0$ and E_A if $N_D \neq 0$ in the $T \rightarrow 0$ K limit.

Extrinsic/Intrinsic T

When the semiconductor temperature is maintained in the extrinsic/intrinsic temperature regions it is more convenient to work with the Eq. (4.57) n and p expressions involving n_i. Solving Eqs. (4.57) for $E_F - E_i$, one obtains

$$E_F - E_i = kT\ln(n/n_i) = -kT\ln(p/n_i) \tag{4.89}$$

Depending on the simplifications inherent in a particular problem, the appropriate extrinsic/intrinsic carrier concentration solution [Eqs. (4.79), (4.80), or (4.81)] can then be substituted into Eq. (4.89) to determine the positioning of E_F. Note that $E_F \rightarrow E_i$ in the intrinsic temperature region, as must be the case. Also, for typical device operating temperatures and semiconductor doping conditions,

$$\boxed{E_F - E_i = kT\ln(N_D/n_i)} \qquad \ldots N_D \gg N_A,\ N_D \gg n_i \tag{4.90a}$$

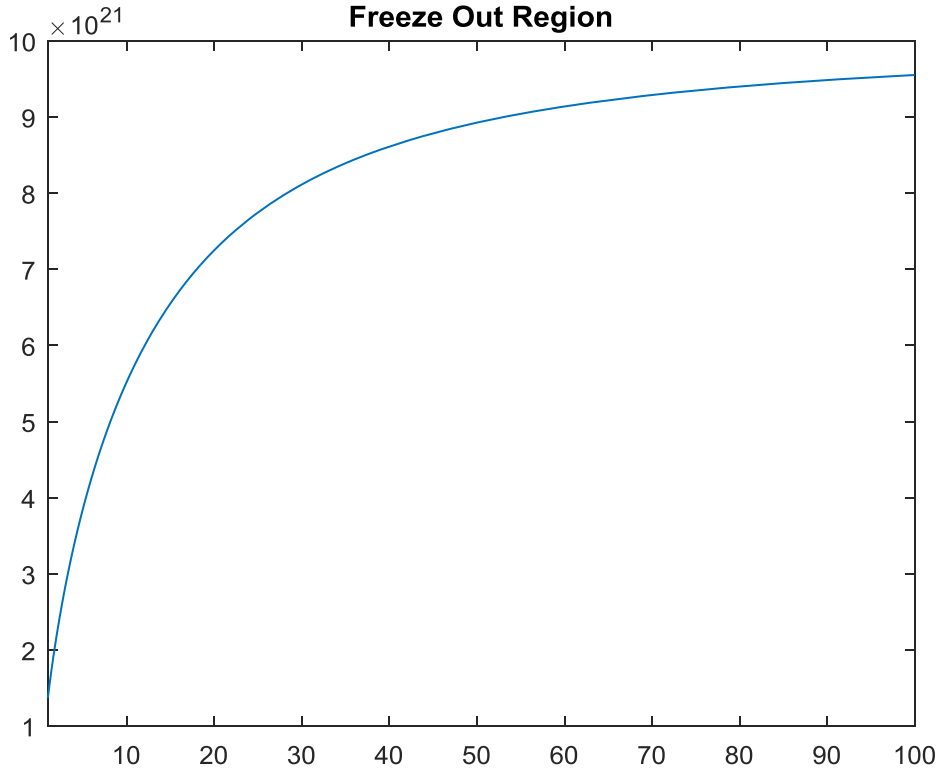
$$\boxed{E_i - E_F = kT\ln(N_A/n_i)} \qquad \ldots N_A \gg N_D,\ N_A \gg n_i \tag{4.90b}$$

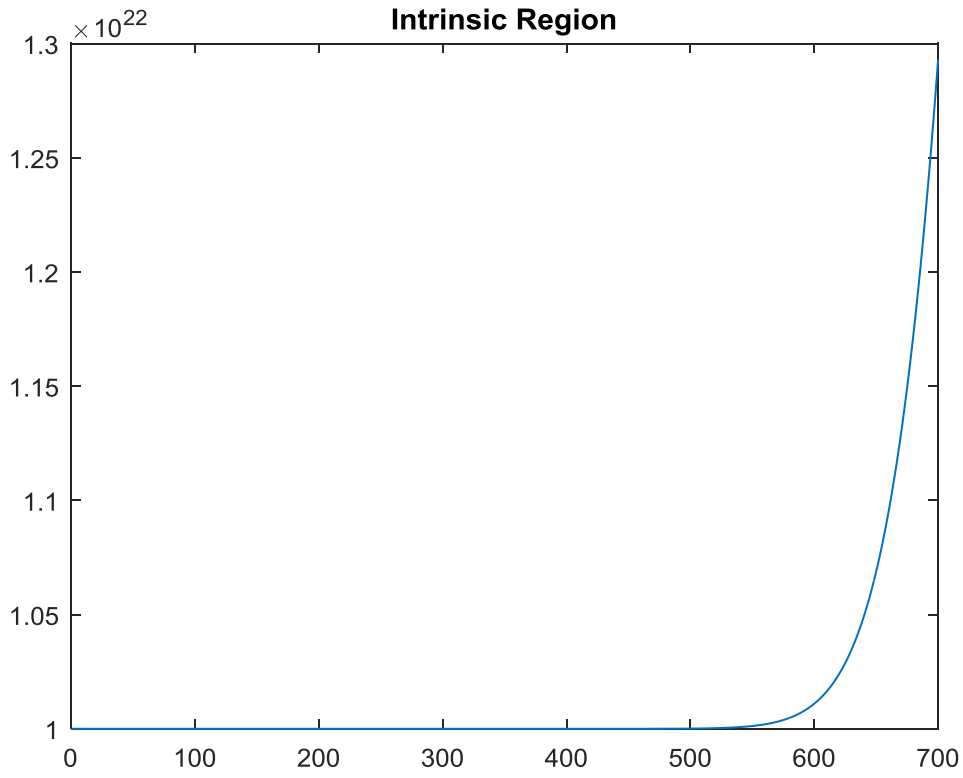
A plot of E_F versus T for select Si doping concentrations constructed using the relationships developed in this subsection is displayed in Fig. 4.19.

بعد از ان شروع به نوشتن معادلات در متلب کردیم،که برای ND=10^22 1/m3 (برحسب سانتی متر مکعب می شه 10^16)

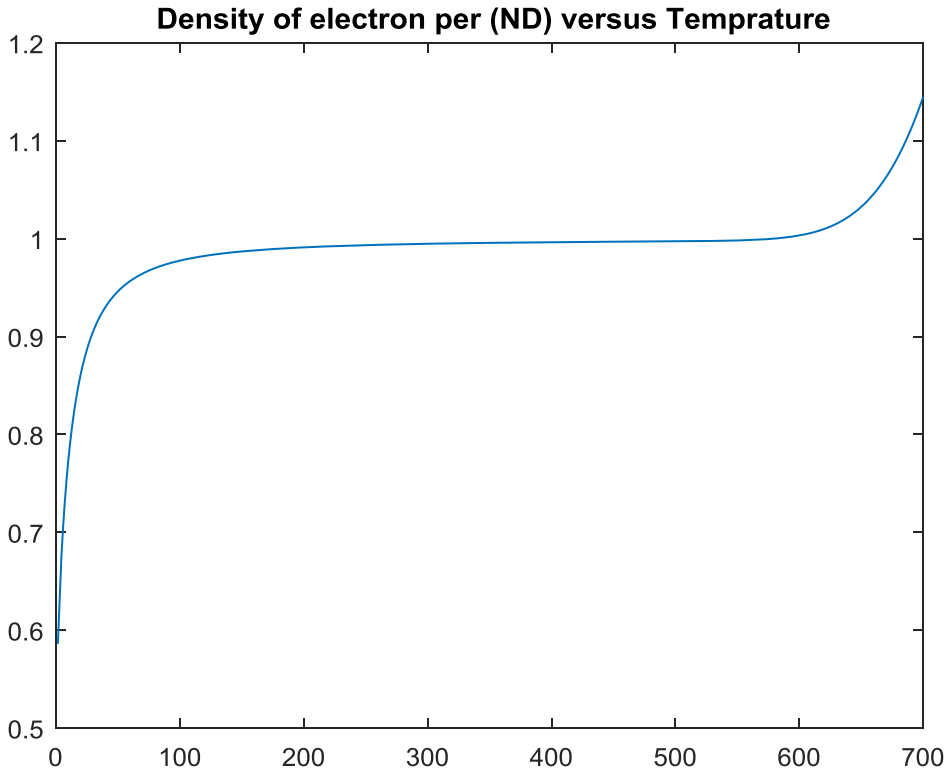
حال سورس ان و نتایج ان به شرح زیر است:

```
%R.Borumandi(alias name in net stackprogramer)
clc
clear
disp('plot');
msgbox('programed by R.Borumandi rahim.bormandi71@gmail.com or
stackprogramer@gmail.com');
%definition of constant
ND=10^22;%1/m^3
qe=1.602*10^(-19);
Eg=1.11*qe;%ev
K=1.38*10^(-23);%ev
h=6.63*10^(-34);%ev
m0=9.109*10^-31;
me=1.08*m0;
mh=.56*m0;
gD=25;
Ec=1.00000005*qe;
ED=1*qe;
%Defintion of Freeze Out Region
n=@(T)(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1);
fplot(n,[1,100]);
title('Freeze Out Region')
%Defintion of Intrinsic Region
figure;
n_intrinsic=@(T)
ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(-
1*Eg/(K*T))))^.5;
fplot(n_intrinsic,[0,700]);
title('Intrinsic Region')
%Defintion of Density of electron per ND versus Temprature
figure
n_final=@(T) [[(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1)]+...

[ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(
-1*Eg/(K*T))))^.5]]/(2*ND);
fplot(n_final,[0,700]);
title(' Density of electron per (ND) versus Temprature')
```


Freeze Out Region
×10^21
10
9
8
7
6
5
4
3
2
1
10
20
30
40
50
60
70
80
90
100



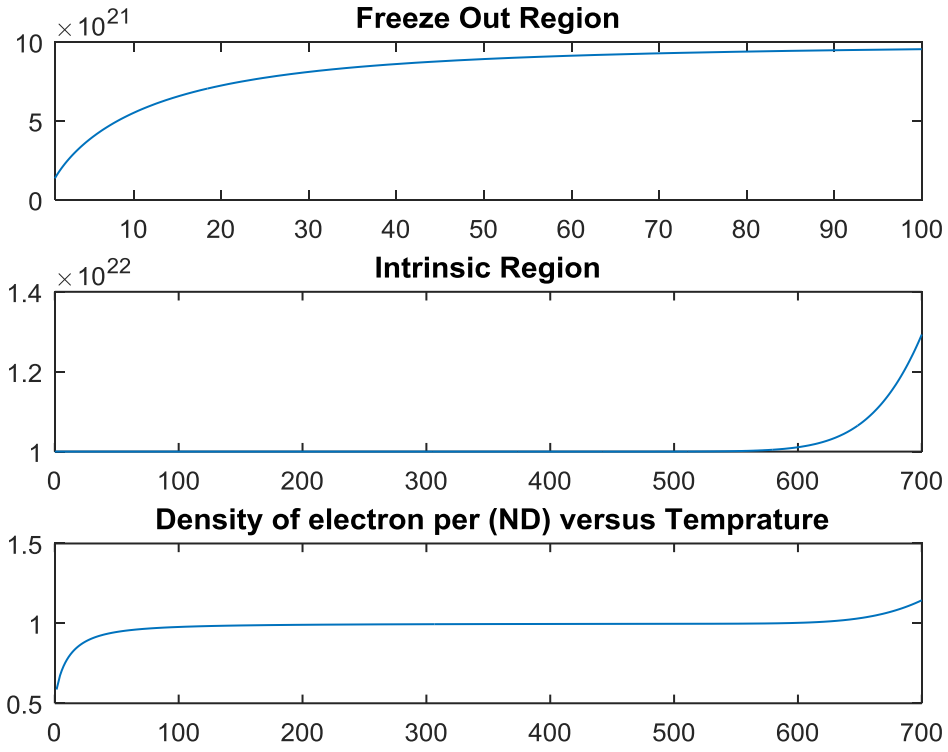
جمع این دو نمودار به ما مشخصه اصلی یعنی چگالی الکترون تقسیم بر ND بر حسب دما می دهد.



اگر نمودار های قبل را بخواهیم باهم بکشیم ،از کد زیر استفاده می کنیم.

```
%R.Borumandi(alias name in net stackprogramer)
clc
clear
disp('plot');
msgbox('programed by R.Borumandi rahim.bormandi71@gmail.com or
stackprogramer@gmail.com');
%definition of constant
ND=10^22;%1/m^3
qe=1.602*10^(-19);
Eg=1.11*qe;%ev
K=1.38*10^(-23);%ev
h=6.63*10^(-34);%ev
m0=9.109*10^-31;
me=1.08*m0;
mh=.56*m0;
gD=25;
Ec=1.00000005*qe;
ED=1*qe;
%Defintion of Freeze Out Region
n=@(T)(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1);
subplot(3,1,1);
fplot(n,[1,100]);
title('Freeze Out Region')
%Defintion of Intrinsic Region
```

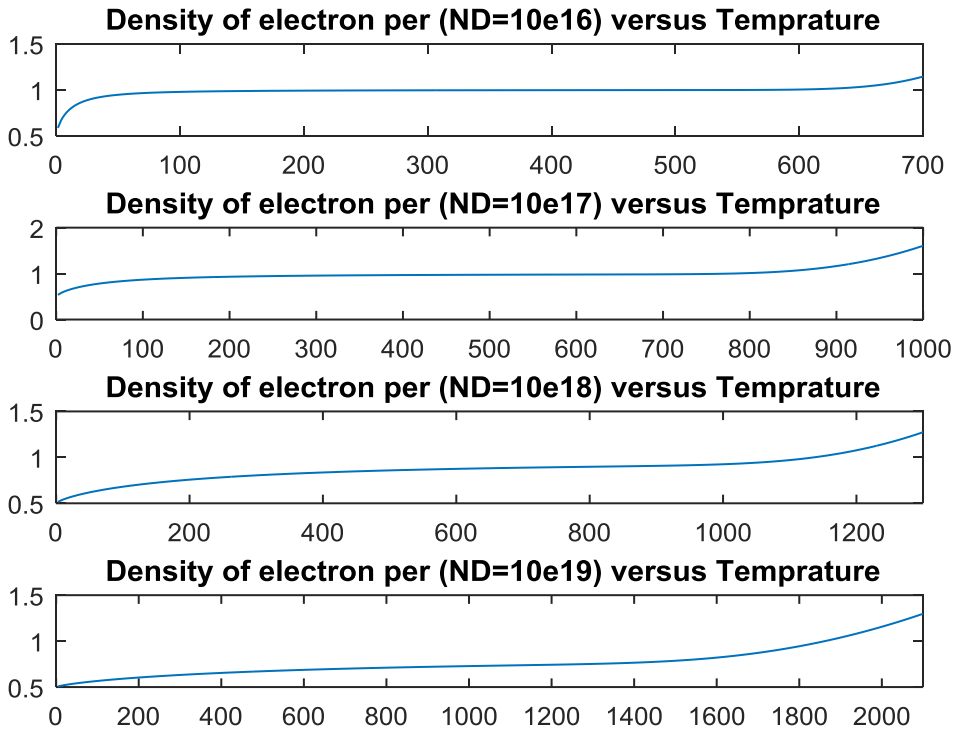
```
n_intrinsic=@(T)
ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(-
1*Eg/(K*T))))^.5;
subplot(3,1,2);
fplot(n_intrinsic,[0,700]);
title('Intrinsic Region')
%Defintion of Density of electron per ND versus Temprature

n_final=@(T) [[(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1)]+...

[ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(
-1*Eg/(K*T))))^.5]]/(2*ND);
subplot(3,1,3);
fplot(n_final,[0,700]);
title(' Density of electron per (ND) versus Temprature')
```



این برای سیلیسیوم برای ND=10^161/cm^3بود حالا برای چندین مقدار افرایشی ND با سورس زیر می کشم.

```
      %R.Borumandi(alias name in net stackprogramer)
clc
clear
disp('plot');
msgbox('programed by R.Borumandi rahim.bormandi71@gmail.com or
stackprogramer@gmail.com');
%definition of constant
ND=10^22;%1/m^3
qe=1.602*10^(-19);
Eg=1.11*qe;%ev
K=1.38*10^(-23);%ev
h=6.63*10^(-34);%ev
m0=9.109*10^-31;
me=1.08*m0;
mh=.56*m0;
gD=25;
Ec=1.00000005*qe;
ED=1*qe;
%Defintion of Density of electron per ND versus Temprature

n_final=@(T) [[(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1)]+...

[ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(
-1*Eg/(K*T))))^.5]]/(2*ND);
subplot(4,1,1);
fplot(n_final,[0,700]);
title(' Density of electron per (ND=10e16) versus Temprature')
%Defintion of Density of electron per ND versus Temprature
ND=10^23;%1/m^3
n_final=@(T) [[(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1)]+...

[ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(
-1*Eg/(K*T))))^.5]]/(2*ND);
subplot(4,1,2);
fplot(n_final,[0,1000]);
title(' Density of electron per (ND=10e17) versus Temprature')


%Defintion of Density of electron per ND versus Temprature
ND=10^24;%1/m^3
```

```
n_final=@(T) [[(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1)]+...

[ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(
-1*Eg/(K*T))))^.5]]/(2*ND);
subplot(4,1,3);
fplot(n_final,[0,1300]);
title(' Density of electron per (ND=10e18) versus Temprature')
%Defintion of Density of electron per ND versus Temprature
ND=10^25;%1/m^3
n_final=@(T) [[(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T))/2*((1+4*ND/(((2*((2*pi*me*K*T)/h^2)^1.5)/gD)*exp(-1*(Ec-
ED)/K*T)))^.5-1)]+...

[ND/2+((ND/2)^2+((2*((2*pi*me*K*T)/h^2)^1.5)*(2*((2*pi*mh*K*T)/h^2)^1.5)*exp(
-1*Eg/(K*T))))^.5]]/(2*ND);
subplot(4,1,4);
fplot(n_final,[0,2100]);
title(' Density of electron per (ND=10e19) versus Temprature')
```



نتیجه گیری:هرچه NDرا افزایش می دهیم نمودار کمی به سمت راست شیفت پیدا می کند،وناحیه خطی هم کمتر می شود،علت اینکه به سمت راست شیفت پیدا می کند این است،که چون ND زیادتر شده زمان بیشتری برای یونوزاسیون یعنی دمای بیشتری لازم است اما برای غلبه niنیز چون حامل ها بیشتر اند در دمای بالاتری اتفاق می افتد،البته با افزایش NDمشاهده می شود ناحیه خطی کاهش می یابد.

موفق باشید