# Electronic Devices and Circuits Lab : Report-2

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**Contents**



# 1 Aim :

The aim of the experiment was to understand the fundamental properties of semiconductors.

# 2 Procedure :

## 2.1 Problem-1 :

How does the occupation probability as a function of the energy varies with respect to time ? Under what circumstances does the Fermi-Dirac statistics reduce to Maxwell-Boltzmann statistics.

The **Fermi-Dirac statistics** say that the probability of an electron to occupy a particular energy level is

$$f(E) = \frac{1}{1 + exp\left(\frac{E - E_f}{k_B T}\right)}$$

For modelling purposes assume that $E_f = 0$,then we have

$$f(E) = \frac{1}{1 + exp\left(\frac{E}{k_B T}\right)}$$

where $k_B$ is Boltzmann constant. The expression has an exponential variation for energy levels referred with respect to the Fermi level along with temperature.For most of the practical purposes, calculations with Fermi statistics is often complicated and is often implemented using the Maxwell Boltzmann statistics which have the function as

$$f(E) = C \times exp(\frac{-E}{k_B T})$$

where C is a appropriate constant. We can observe that the Fermi function, in the conduction band where E is greater than $E_f$, i.e. when E - $E_f$ >> 0, we get exp[(E-$E_f$)/kT] >> 1 for a particular temperature(T), the function can be approximated to that of Maxwell Boltzmann as

$$f(E) \approx \frac{1}{exp(E/k_B T)} = exp(\frac{-E}{k_B T})$$

For practical purposes this approximation holds when E $\geq$ $E_f$ + $3k_B$T.

Similarly in the valence band, where $E_f$-E >> 0, the exp[(E-$E_f$)/kT] << 1, the probability of not finding an electron in the valence band i.e.[1 - f(E)] dies down similar to Maxwell Boltzmann curve.

$$1 - f(E) = 1 - \frac{1}{1 + exp(E/k_B T)} \approx exp(\frac{-E}{k_B T})$$

The above approximation is seemed to be valid when E $\leq$ $E_f$ - $3k_B$T.

## 2.2 Problem-2 :

How the 3D density of states changes with respect to the energy ?

The Density of States is the density of allowed energy levels is given by

$$D(E) = \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar}\right)^{1.5} E^{0.5}$$

in with unit $m^{-3}J^{-1}$ or $cm^{-3}eV^{-1}$. We assume here the effective mass to be same as the mass of electron and calculating the constants on a whole we get the value around $2.149 \times 10^{24}$ in $eV^{-3/2}\ cm^{-3}$. So the variation of our energy is done in eV.
The possible density of states is spread around 3-dimensions and each corresponding to a particular wave vector.

## 2.3 Problem-3 :

How the does the position of the Fermi energy changes with respect to doping ? (Use Maxwell-Boltzmann statistics for n-type semi conductor)

Generally, the fermi level lies slightly below the mid-gap of conduction and valence bands (due to the effective masses) in an intrinsic semiconductor. But when doped, the carrier concentration of one of the carrier increases, say for n-type, the electron concentration increases allowing the probability to occupy the levels in conduction band, hence pushing the $E_f$ line towards $E_c$ which can be seen as shown.

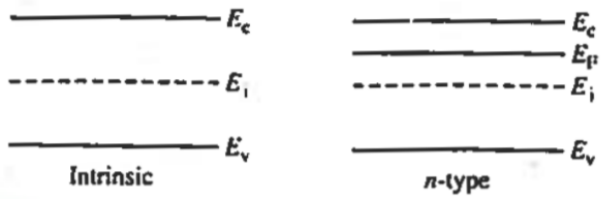


Figure 1: Fermi Level variation

Theoretically, the general position of fermi level in donor doped semiconductor assumed to be non-degenerate, in equilibrium and at temperatures where dopants are fully ionised is given as

$$E_f = E_i + k_B T ln(n/n_i) = E_i + k_B T ln(N_D/n_i)$$

where $E_i$ is the mid-gap, $n$ in the electron concentration which is almost equal to $N_D$, the dopant concentration in a n-type semiconductor. For silicon the $E_i$ value at temperature of 300K is 0.55270 eV. Varying the concentration of dopants we can observe the change in fermi level. Note that the room temperature is sufficiently high enough for ionising the dopants, so $n_i$ is almost $N_D$.

## 2.4 Problem-4 :

How does the intrinsic carrier concentration changes with respect to the temperature ? Assume effective density of states for conduction and valence band to be 2.8E19 $cm^3$ and 1.8E19$cm^{-3}$ . Assume doping to be 1E17 $cm^{-3}$ and comment on the nature of semiconductor. Plot $n_i$ on a semilog scale versus (1000/T) for n-type semiconductor.

So, Effective density of states for conduction band($N_C$) = $2.8 \times 10^{19}$ $cm^{-3}$
And Effective density of states for valence band($N_V$) = $1.8 \times 10^{19}$ $cm^{-3}$
Dopant Conceentration (n-type) = $1 \times 10^{17}$ $cm^{-3}$

The intrinsic carrier concentration is the number of electrons in the conduction band or the number of holes in the valence band in intrinsic material denoted by $n_i$. In an intrinsic material, the number of holes in conduction band is equal to the conduction band. Hence,

$$n = p = n_i$$

From the Fermi Dirac statistics and Density of states formula, we have

Electron concentration in conduction band: n = $N_C$ exp($\frac{E_f - E_c}{kT}$)

Hole concentration in valence band: p = $N_V$ exp($\frac{E_v - E_f}{kT}$)

So in an intrinsic semiconductor, we have

$$n \times p = n_i^2$$

$$n_i = \sqrt{N_C N_V} \times exp(\frac{-E_g}{2kT})$$

So, this number of carriers depends on the band gap of the material and on the temperature of the material and is independent of the doping done to the semiconductor . So, assuming the band gap($E_g$) independent of temperature(which actually varies) , calculating the constants and plotting the semilog graph of $n_i$ varying with 1000/T, we get its behaviour.

## 2.5 Problem-5 :

How does the electron density varies with energy (use Fermi-Dirac distribution) ?

The electron density(n) as function of energy is given by

$$n(E) = f(E) \times D(E)$$

where f(E) is the Fermi Dirac distribution given by

$$f(E) = \frac{1}{1 + exp\left(\frac{E-E_f}{k_B T}\right)}$$

And D(E) is the density of states given by

$$D(E) = \frac{1}{2\pi^2} \left(\frac{2m^*}{\hbar}\right)^{1.5} E^{0.5}$$

So,

$$n(E) = \frac{1}{1 + exp\left(\frac{E-E_f}{k_B T}\right)} \times \frac{1}{2\pi^2} \left(\frac{2m^*}{\hbar}\right)^{1.5} E^{0.5}$$

Assuming $E_f$=0 and varying the energy gives us the behaviour of the curve.

# 3 Results and Observation

## 3.1 Problem-1 :

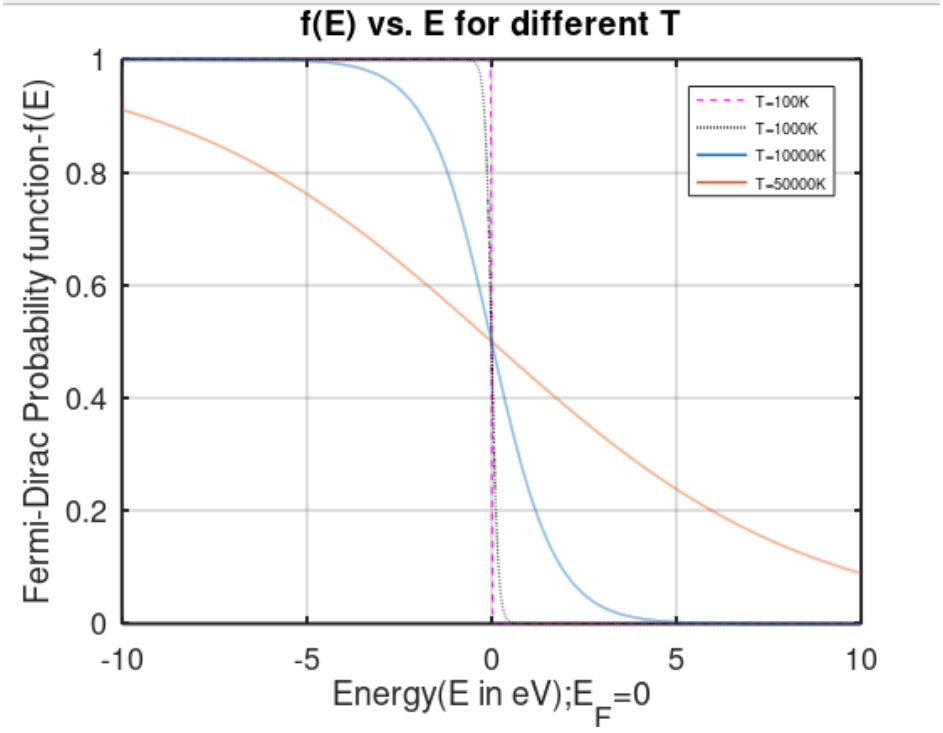


Figure 2: Variation of Fermi function with temperature

From the graph it can be observed that

- For T>0K, $f(E_f) = 0.5$ always and can be seen from equation also

$$f(E) = \frac{1}{1 + exp\left(\frac{E - E_f}{k_B T}\right)} \implies f(E_f) = \frac{1}{1 + exp\left(\frac{0}{k_B T}\right)} = \frac{1}{2}$$

- The probability for energy level to be filled in valence band is higher than that of conduction band.
- With increasing temperature, the probability for filling of energy levels in conduction band increases suggesting that the electrons gain more energy with increase in temperature, allowing them to escape valence band.
- The graph dies down quickly for greater energies similar to the exponential decay.

## 3.2 Problem-2 :

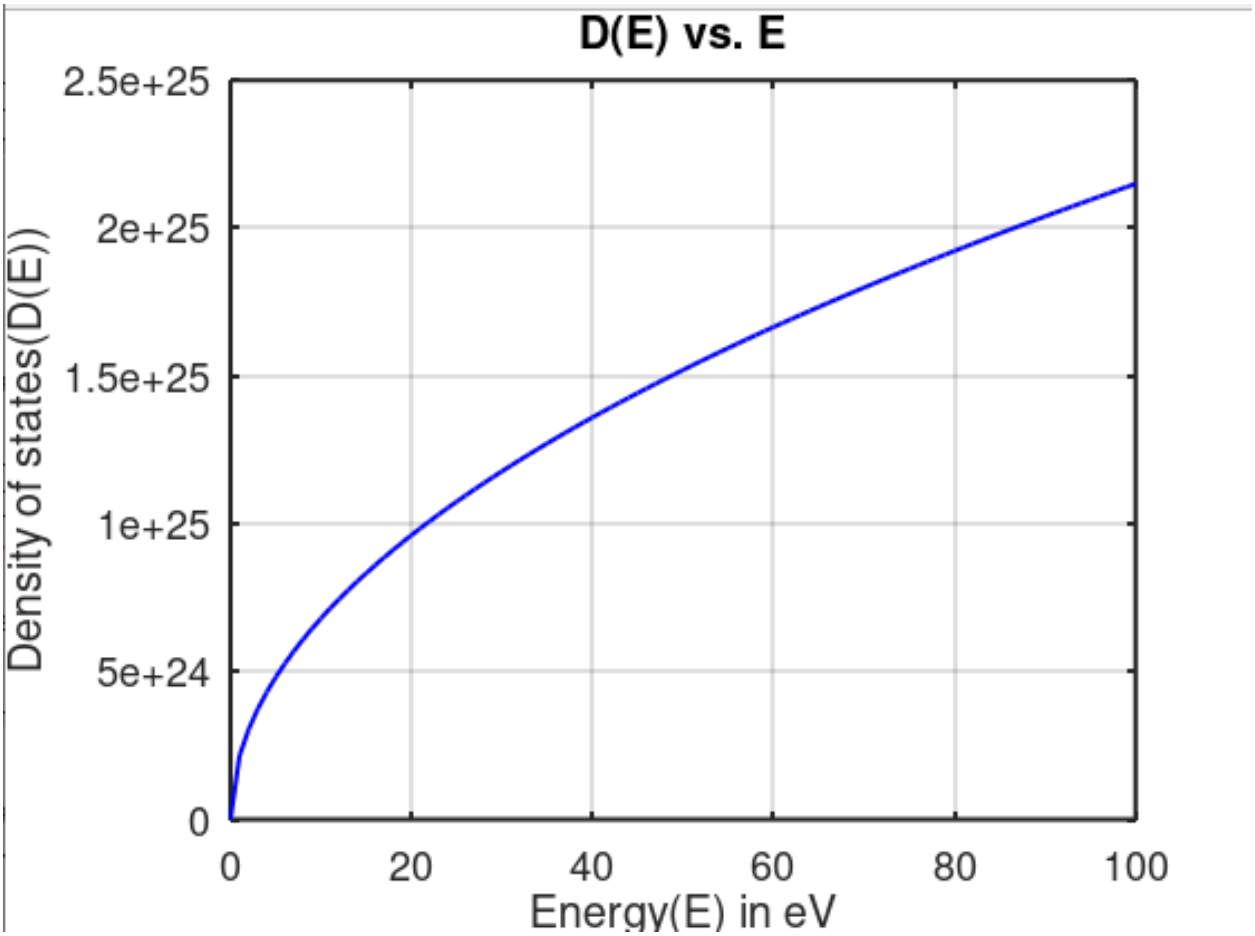


Figure 3: Variation of Density of states with Energy

From the above graph it can be observed that

- The density of states function varies with energy similar to a $\sqrt{x}$ graph.
- With increase in Energy, the density of states increases suggesting that the number of levels are higher at higher energies which is compatible with the theory of quantum numbers (n,l,m,s).
- It can also be inferred from the slope that the increase in density of states is more when energy changes in lower ranges than in higher ranges.

## 3.3 Problem-3 :

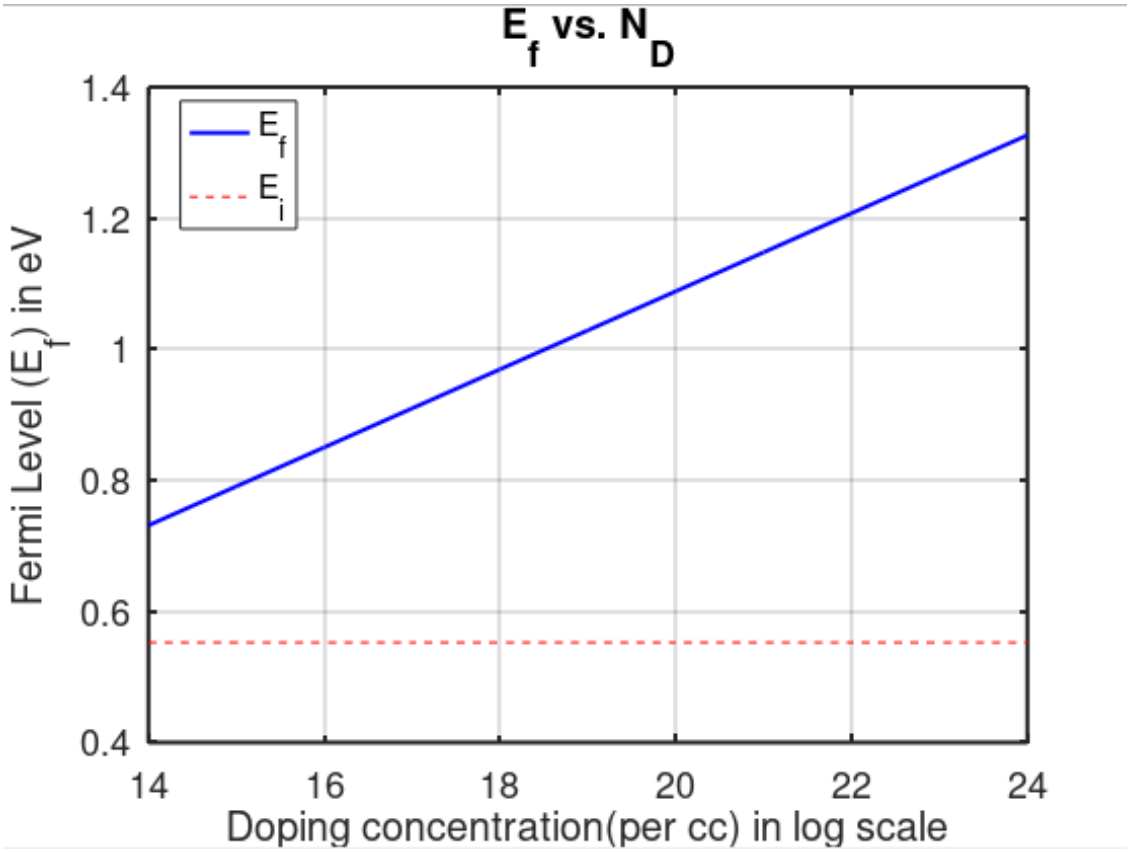


Figure 4: Variation of Fermi level with Doping Concentration(n-type)

From the above graph it can be observed that

- The $E_f$ level increases with increase in the doping concentration, which can be seen as it is moving towards conduction band($E_C$) away from the midgap.
- As the probability of filling of an energy level is at $E_f$ is always half, says that with increasing the dopants, more number of electrons fill the conduction band increasing the probability of occupying energy levels at conduction band, hence pusing $E_f$ towards $E_C$.
- As the variation is observed in log scale for doping concentration, with small changes in concentration the change in $E_f$ could be negligible.

## 3.4 Problem-4 :

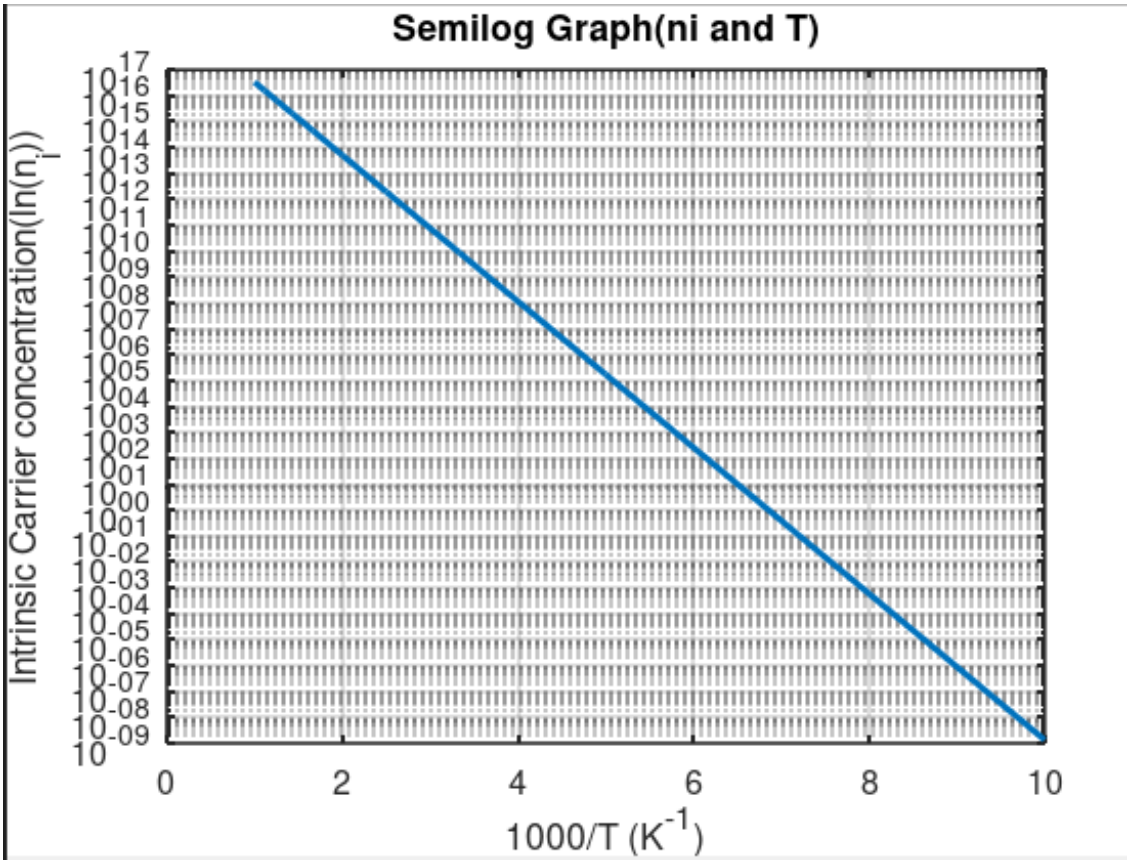


Figure 5: Semilog graph of Intrinsic Concentration with 1000/T

From the above graph it can be observed that

- The Intrinsic carrier concentration increases with increase in temperature which can infer that at higher temperatures the energy of the Silicon atom ($\times$ $k_B$T) increases which helps in its ionisation by overcoming energy barrier($E_g$), increasing number of carriers.
- Even for significant change in temperature, say 25K, $n_i$ increases hugely, here by $10^5$ times (graph is for semilog-y).
- As the temperature keeps on increasing, the intrinsic carrier concentration keeps on increasing, and should actually saturate at a point where all atoms have ionised.
- Here we did not consider the physical changes happening to the semiconductor, but if considered the semiconductor might change its phase.

## 3.5 Problem-5 :

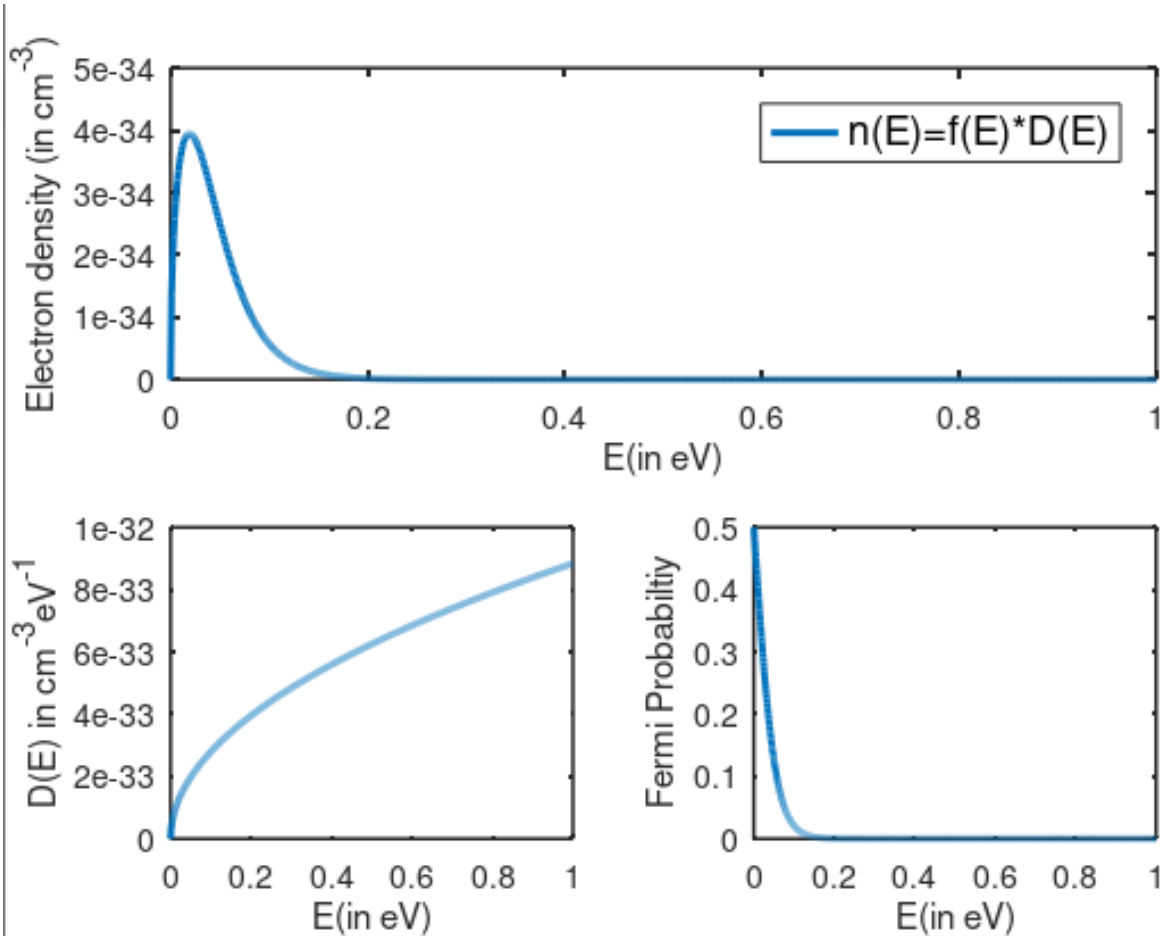


Figure 6: Electron density variation with energy in the Conduction band

The energy referred in the above graph is with respect to conduction band. From the above graph it can be observed that

- The electron density is concentrated near the lower energy levels of the conduction band, the place where probability is high and dies down very quickly for higher energy levels.
- The electron density can be seen as the product of the graphs of density of states and Fermi probability function.
- It suggests that for filling higher energy levels, the lower energy levels have to be filled first.

# 4 Conclusions

From the above all simulations, the conclusions we can draw are

1. The probability function according to Fermi Dirac statistics, widens with increase in temperature.

2. The probability function according to Fermi Dirac statistics decays similar to Maxwell Boltzmann statistics when the energy difference is significantly higher.

3. The density of states increase with increase in energy similar to a $\sqrt{x}$ curve.

4. The fermi level changes with the change in doping concentration. For a n-type doping, it moves towards $E_C$ and similarly for p-type doping it moves towards $E_V$.

5. The intrinsic carrier concentration is independent of the doping done to the semiconductor and depends majorly on band gap,temperature.

6. The variation of intrinsic carrier concentration increases with temperature.

7. The electron density is concentrated near the lower energy levels of the conduction band.

8. The hole density on similar grounds, can be concluded that it is concentrated near the higher energy levels of valence band.( as higher energy level electrons transit to coduction band).

*The octaves scripts are attached separately.