

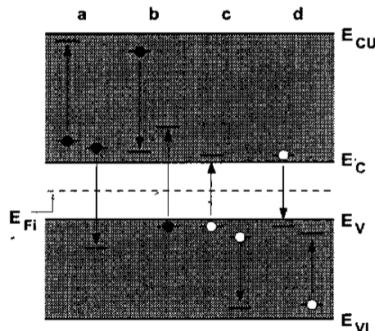
Lecture - 9

~~ఎంట్రో స్క్రేచ్ గట్టిస్ అనుమతి~~

→ In the last lecture we studied Thermal generation & Recombination terms. (FRH Theory)

In this lecture we will study other types of Generation & recombination terms. In some situations they may be important.

Auger recombination and impact ionization — I



$$U_n^{AI} = r_a - r_b = c_n n^2 p - I_n n ,$$

$$U_p^{AI} = r_c - r_d = c_p p^2 n - I_p p ,$$

where c_n, I_n are the transition coefficients for the Auger recombination and impact ionization started by electrons, and c_p, I_p are the transition coefficients for the Auger recombination and impact ionization started by holes; c_n, c_p are called "Auger coefficients". It is $[c_{n,p}] = \text{cm}^6 \text{s}^{-1}$, $[I_{n,p}] = \text{s}^{-1}$.

→ In the above figure we see a Generation & Recombination event that has the property that

the exchange of energy of the Electrons & Holes that make the transition occur due to collision with other electron or hole.

→ It is possible to classify '4' types of event

Event of Type(a) occurs when we have a collision b/w two electrons whose states initially belong to the CB.

During the collision one of the electron loses energy and occupies a state of the VB.

The other electron gains energy and occupies a state that is High up the Conduction Band. (CB)

→ It is Non-thermal because Energy is not given to the lattice it is given to another electron.

This type of transition is called Auger Recombination initiated by one electron.

→ There is also an other possibility of

Dual phenomenon i-e Auger Recombination initiated by Holes this is Type-C in the figure.

We have two holes initially in the VB due to the collision one hole makes a transition from VB to the CB. Of course, it is electron that goes the opposite way.

The other hole makes a transition of equal amount of energy towards the lower state of the VB.

Hole that goes Up loses Energy

Hole that goes Down Gains Energy

→ Type(b)

We have one electron which is in the VB and another electron for some reason has some high energy in the CB.

So, these two electrons are far away in Energy but they may come near in the physical

Space and have a collision at the conclusion after collision is that the Electron that was up in Energy loses energy and its final state is still in CB.

The energy released is taken by the ^{2nd} material electron in VB and it [^] transition from the VB into CB.

phenomenon ⑤ is called Impact Ionization initiated by Electrons.

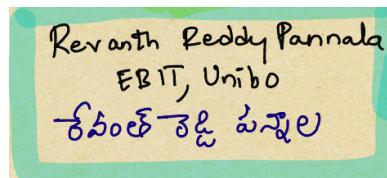
→ Similarly, we may have Impact Ionization initiated by Holes as we see in Type ① phenomenon ⑥ is a generation.

This is symbolized for Auger Recombination

$$U_n^{AI} = r_a - r_b = c_n n^2 p - I_n n,$$

$$U_p^{AI} = r_c - r_d = c_p p^2 n - I_p p,$$

where c_n, I_n are the transition coefficients for the Auger recombination and impact ionization started by electrons, and c_p, I_p are the transition coefficients for the Auger recombination and impact ionization started by holes; c_n, c_p are called "Auger coefficients" It is $[c_{n,p}] = \text{cm}^6 \text{s}^{-1}$, $[I_{n,p}] = \text{s}^{-1}$.



$$V_n^{AI} = \tau_a - \tau_b \quad \text{per unit volume in time}$$

τ_a : phenomenon (a) requires the presence of 2 electrons that collide and also the presence of Empty state in the valence Bond.

$$\tau_a \propto n^2 \quad \& \quad \tau_a \propto P$$

↓

because we
should have two
electrons in CB

One hole in
 vB

$$\Rightarrow \tau_a = C_n n^2 P$$

↓

transition coefficient for
Auger Recombination

III^b for phenomenon (b)

$\tau_b \propto n$ concentration of electrons
in conduction band

$$\boxed{\tau_b = T_n n}$$

→ The corresponding net Recombination Rate of the Auger Impact ionization phenomenon

$$U_n^{AI} = \gamma_a - \gamma_b \approx C_n n^2 p - I_n n$$

$$U_p^{AI} = \gamma_c - \gamma_d = C_p p^2 n - I_p p$$

→ There is no reason for U_n^{AI} to be equal to U_p^{AI} .

* The situation is completely different w.r.t to that of **THERMAL RECOMBINATION**

There is no special relationship b/w

$$U_n^{AI} \& U_p^{AI}$$

→ The total no. of net Recombinations is the sum of those initiated by e^- 's & initiated by Holes.

→ The total ^{Combined} Auger & Impact Ionization is the sum of the two

$$U_{AI} = U_n^{AI} + U_p^{AI}$$

→ Auger recombination and impact ionization — II

In equilibrium it is $U_n^{AI} = U_p^{AI} = 0 \Rightarrow$

$$I_n = c_n n^{\text{eq}} p^{\text{eq}}, \quad I_p = c_p n^{\text{eq}} p^{\text{eq}}.$$

The above are assumed to hold also in the general case, as long as the operating conditions are not too far from equilibrium; it follows

$$U_n^{AI} = c_n n (np - n^{\text{eq}} p^{\text{eq}}), \quad U_p^{AI} = c_p p (np - n^{\text{eq}} p^{\text{eq}}),$$

where in non-degenerate conditions it is $n^{\text{eq}} p^{\text{eq}} = n_i^2$. Referring to all recombinations as due to transitions of electrons, their rate is easily found to be $r_a + r_c$; similarly, the total generation rate is $r_b + r_d$. In conclusion, the net recombination rate due to the Auger and impact-ionization phenomena is given by

$$U_{AI} \doteq U_n^{AI} + U_p^{AI} = (c_n n + c_p p) (np - n^{\text{eq}} p^{\text{eq}}).$$

→ Now we will examine the last type of generation & recombination phenomenon

one of them is already mentioned. It is the Direct Generation & recombination phenomena induced by exchange of energy with lattice.

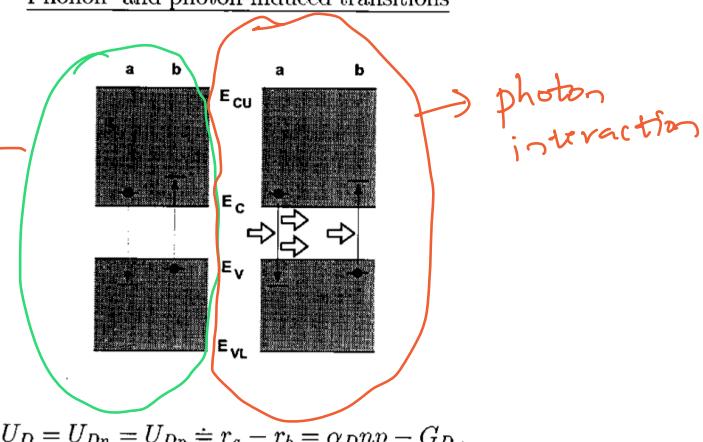
→ But, ^{Direct} Generation & recombination because of exchange of energy with lattice are **non-important** because in semiconductor we always have Traps.

∴ In practice, whenever consider the Generation & Recombination because of ^{charge} Energy of lattice

Direct recombinations and generations — I

Phonon- and photon-induced transitions

Generation
Recombination
because of
Energy of lattice
which is Generally
ignored.



$U_D = U_{Dn} = U_{Dp} \doteq r_a - r_b = \alpha_D n p - G_D$,
where α_D is the transition coefficient for the direct recombination, and G_D is the direct generation rate. The above must further be specified in the case of the phonon- or photon-induced transitions. It is $[\alpha_D] = \text{cm}^3 \text{s}^{-1}$, $[G_D] = \text{cm}^{-3} \text{s}^{-1}$.

- Much more important in semiconductor is Generation & Recombination in which the exchange of energy of the electrons occurs w.r.t. an external EMF (Electromagnetic field)
- EMF can be described from the point of view of QM using the concept of photon.
- So in practice, if we have an EMF, what we can do is to express the EMF in classical

Situation as a superposition of Monochromatic components

And each component is called a MODE of the EMF

Then each MODE has an energy and finally using QM, we find the Energy of the MODE i.e. of the Monochromatic Component of the EMF.

This energy is proportional to the Quantum of energy whose value is proportional to the frequency \times Planck's Constant

$$\nu \times h$$

$$E = h\nu$$

Is the energy of the individual Quantum of the Mode we are considering.

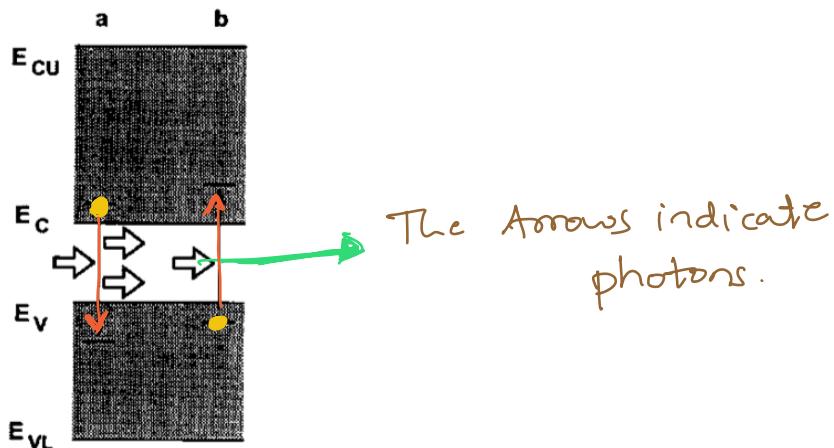
The Energy of the Mode is an Integer Number of these individual Quanta.

This gives rise to the concept of Photon. Photon is Quantum of EMF.

→ So, photons can be considered as particles and the interaction of EMF with semi conductor can be considered as a collision b/w one photon and one of the electron.

→ So, what happens when a photon interacts with an Electron that belongs to the valence Band of Semiconductor?

As



In the phenomenon b we see a white arrow symbolically means a Photon that comes in. This photon interacts with electron in VB and there is exchange of Energy such that photon releases completely each energy to the Electron. When this happens photon Disappears - Assume that Energy is sufficient for the transition i.e the initial Energy of the photon atleast equal to the Energy Gap. Then the Electron makes a transition from VB into the CB.

This is obviously called Absorption -

Because, light is absorbed (or) Electromagnetic Radiation is absorbed and the e^- 's become more energetic.

→ There is also another possibility that a photon interacts with an electron already in CB and this interaction induces a transition from CB to VB.

In this case, the photon that induces transition survives and continues its motion in the material and it may happen that the energy is released by e^- because of transition from CB to VB. This energy is also released in the form of EMF.

In that case we can say that the e^- emits another photon. This is illustrated phenomenon (a)

This type of transition is called Radiative.

→ Qualitatively we see immediately that if a Radiative transition occurs, we essentially have one photon coming in and two photons coming out and so calculations

Show that two photons coming out are coherent with each other -

i.e they have same Frequency
Direction
+
phase

→ Here we have a chance of coherent Amplification of the Monochromatic component of the Radiation inside the material.

→ Note:- In Electronic Circuits

In an Amplifier and we feedback suitably the o/p of the Amplifier into the

Inputs we may create an oscillator i.e circuit i.e able to produce by itself oscillation, offcourse energy of oscillation is taken from a Battery in case of a circuit

we can do the same thing in this case. If we are able to produce a coherent Amplification of the Radiation and if we are able to introduce a Feedback into the Material

eventually we obtain an oscillator i.e a device i.e able to produce Monochroma-

tic Radiation by itself.

A Feedback in optical case EM case is easy because at the end of the material we can put a Mirror and at the opposite end we can also put a Mirror. So we have ~~two~~ two mirrors that reflect to & fro the Radiation

& during these reflections we obtain an amplification. So eventually the material will oscillate and produce by itself a Monochromatic Radiation and this is the principle of LASER.

→ Of course one of the Two mirrors should be partially reflective so that we can extract from this a fraction of Radiation that can be used outside

→ So, we have two phenomena one is amplification of Radiation & the other is absorption.

Q Which of the two will prevail?

A It depends, If the Majority of electrons

are in VB ie material is close to an equilibrium state the No. of absorption will be prevailing.

Note: The probability of Absorption & Radiation are the same.

∴ No. of Absorption & Radiation depends on no. of electrons in VB & CB

In absorption case the material can be used as an optical detector because the transition of e^- s because of Absorption make CB rich of e^- s & VB rich of holes.

→ If Majority of e^- s are in CB then the transition e^- s from CB to VB will produce LASER

Not all materials emit Radiation on occasion of Recombination only Those whose gap is direct for instance GaAs are able to produce photons.

- This is the reason why semiconductor LASERS are manufactured with GaAs & never with silicon.
Silicon is an indirect semiconductor, it is no good for producing a LASER.
- Another reason for emissions (radiation) to prevail is we must have Majority of e^- 's in the CB which is very uncommon situation. Because, if we remember in Equilibrium majority of e^- 's are in VB.
- So, we must be able to bring Majority of electrons from VB into the CB. This is called Population Inversion. In order to do so we must provide Energy to the crystal and because of that this energy is converted into the LASER radiation.
- In order to describe mathematically the recombinations & Generations we call them V_D

$$U_D \rightarrow \text{Direct}$$

$$U_D = U_{Dn} = U_{Dp} = r_a - r_b = \alpha_D np - G_D,$$

where α_D is the transition coefficient for the direct recombination, and G_D is the direct generation rate. The above must further be specified in the case of the phonon- or photon-induced transitions. It is $[\alpha_D] = \text{cm}^3 \text{s}^{-1}$, $[G_D] = \text{cm}^{-3} \text{s}^{-1}$.

All the optical sensors are based on these phenomena

→ By the way, in semiconductors with Indirect gap like silicon has a very small probability of emitting Radiation upon Recombination of electron.

→ similarly, the probability of absorption is also not so high.

Q Why majority of most sensors are manufactured using silicon ?

A The reason is that in a SENSOR you need an enormous no. of pixels and all the circuitry that controls the signals and this is possible using only

Silicon Technology, because currently it is the most robust one. It's relatively easy and very well understood.

కాసిబిపి వాయికార్బన్ మా ఫలశ్రూ కండాచెంగా |
మా కామిపిలట్టుభూతీల్ నే ఐడ్సోఎస్‌ఎంబిపి |

క్రూహై వార్ధికార్బన్ మా ఫలశ్రూ కండాచెంగా.
మా క్రూఫులప్పుత్తు ర్షై తె సంగ్రహ్య కండాచెంగా.

" You have RIGHT to WORK but never to expect Results-

Let the Results of Action not be your Motive & don't let this attachment lead to INACTION."

Words to Go by when you prepare for Semiconductor Device physics.

→ Now, we must put all the information together
 When we described Mathematical Model of
 Semiconductor devices we had continuity Equations

In the continuity equation we have U_n, U_p
 are Shockley-Read-Holme net generation rate

G_n, G_p which are also equal to each other
 embed the combination of the Auger-Impact
 ionization, Direct optical phenomenon, Direct
 Thermal phenomenon.

Total Recombinations and Generations — I

In the carrier-continuity equations

$$\frac{\partial n}{\partial t} + U_n - G_n - \frac{1}{q} \operatorname{div} \mathbf{J}_n = 0, \quad \frac{\partial p}{\partial t} + U_p - G_p + \frac{1}{q} \operatorname{div} \mathbf{J}_p = 0$$

one finally finds, assuming that the different phenomena are uncorrelated, and taking the steady-state approximation for the trap populations,

$$U_n - G_n = U_p - G_p = U_{SRH} + U_{DT} + U_{AI} + U_{DO}$$

↑ Direct Thermal ↑ Direct Optical
 ↓ Auger-Impact Ionization

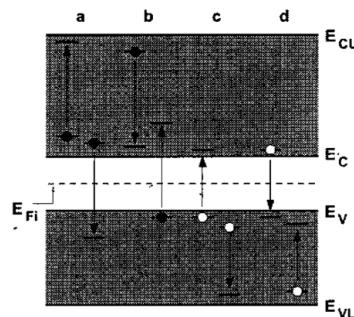
For the phonon-induced transitions, energy conservation implies $|\Delta E| = \hbar\omega$, where $\hbar\omega$ is the phonon energy, $\hbar \simeq 1.05 \cdot 10^{-34}$ Js. Taking the equilibrium distribution for the phonons, the number of phonons dN_{ph} in the interval $d\omega$ is

$$dN_{ph} = \frac{g_{ph}(\omega) d\omega}{\exp[\hbar\omega/(k_B T_L)] - 1}$$

It turns out that $dN_{ph}/d\omega$ is a rapidly decreasing function of ω , whence $U_{DT} \ll U_{SRH}$.

→ In most cases we don't have U_{DT} , U_{DO}
 But the cases for which we have to consider
 U_{AI} we will discuss it now.

Auger recombination and impact ionization — I



$$U_n^{AI} = r_a - r_b = c_n n^2 p - I_n n,$$

$$U_p^{AI} = r_c - r_d = c_p p^2 n - I_p p,$$

Auger impact ionization if we consider case (a)
 i.e. the recombination in order to have this
 phenomenon a collision b/w two electrons must
 occur. i.e. probability of an e^- to encounter an
 other electron must be high.

In General this is not the case, The electrons
 have high probability of colliding with phonons
 so this is most important type of interaction
 that occurs.

The probability that $e^- \Delta e^-$ is not so high unless the concentration itself is very high.

So, Qualitatively we can say the need of considering Auger Recombination occurs only when Semiconductor Region are Highly doped of n-type.

Q what are the Regions of a semiconductor that are Highly Doped of n-type?

A They are Emitter Region of NPN BJT

and also the Source and Drain of the n-channel MOS Transistor.

→ Similarly, we have non negligible Auger Recombination initiated by Holes in a Region where population of Holes is more.

This again Happens in the Emitter Region of PNP BJT and also the Source and Drain of p-channel MOS Transistor.

→ Obviously, you can't have Auger Recombination happening for Holes & Electrons simultaneously only Majority carriers can produce Auger Recombination.

→ Impact Ionization

If, we consider phenomenon (b) in the figure in order to have phenomenon like (b) to occur we need to have one e^- with very High Energy. It is not easy for an e^- to acquire that High energy so easily. Because, e^- & holes have High probability of interacting with phonons, when they do so they release the energy to the Phonons. ∴ It is unlikely for an electron to acquire High Energy.

→ This is only possible if the region of Semiconductor we are considering has a very High electric Field in it. Then e^- & hole will gain High energy in a short interval of time & space

→ i.e. e^- & hole can reach High energy before interacting with a phonon before losing that energy.

After, this the e^- & hole are to have an Impact ionization.

In conclusion, Impact ionization occurs only in regions with high Electric Field.

This rules out those Regions where Auger Recombination occurs.

- The Regions in Semiconductor Device where we have High Electric Field are Reverse Biased Junctions
- For instance in a Bipolar device the Collector Junction in the Normal mode of operation is Biased in Reverse. Similarly, In the Drain Region of the MOS transistor that operates in Reverse.
- On the other Hand, Impact Ionization can produce chain Reaction & because of this Chain Reaction we might have condition
 - i-e Unwanted in a Semiconductor Device
 - i-e Avalanche Breakdown
- Now, continuing into a Special case where Impact Ionization is so strong to become most important Generation & Recombination phenomenon. even more important than the Thermal net Recombination Rate.

Total Recombinations and Generations — II

Limiting case of strong impact ionization

Very far from equilibrium the approximation $I_n = c_n n^{\text{eq}} p^{\text{eq}}$, $I_p = c_p n^{\text{eq}} p^{\text{eq}}$ is not valid, and the general expressions hold:

$$U_n^{AI} = c_n n^2 p - I_n n, \quad U_p^{AI} = c_p p^2 n - I_p p$$

Taking the steady-state case, if impact ionization dominates over the other generation-recombination processes; it follows $U_n - G_n = U_p - G_p \simeq U_{AI} \simeq -I_n n - I_p p$, whence

$$\operatorname{div} \mathbf{J}_n = -q I_n n - q I_p p, \quad \operatorname{div} \mathbf{J}_p = q I_n n + q I_p p$$

In a region where the transport is essentially ohmic it is $\mathbf{J}_n \simeq q \mu_n n \mathcal{E}$, $\mathbf{J}_p \simeq q \mu_p p \mathcal{E}$, whence $\mathbf{J}_n = J_n \mathbf{e}$, $\mathbf{J}_p = J_p \mathbf{e}$, where $\mathbf{e}(\mathbf{r})$ is the unit vector of the electric field: $\mathcal{E} = \mathcal{E} \mathbf{e} = \sigma |\mathcal{E}| \mathbf{e}$ with $\mathcal{E} \neq 0$ and $\sigma = \pm 1$. Replacing n and p one finds

$$-\sigma \operatorname{div} \mathbf{J}_n = k_n J_n + k_p J_p, \quad \sigma \operatorname{div} \mathbf{J}_p = k_n J_n + k_p J_p$$

where the impact-ionization coefficients are defined as

$$k_n \doteq \frac{I_n}{\mu_n |\mathcal{E}|} = \frac{I_n}{|v_n|}, \quad k_p \doteq \frac{I_p}{\mu_p |\mathcal{E}|} = \frac{I_p}{|v_p|}, \quad [k_{n,p}] = \text{cm}^{-1}$$

→ Assume we have strong Electromagnetic field and also assume we are in a steady state situation.

Now, taking the original continuity equation

In the carrier-continuity equations

$$\frac{\partial n}{\partial t} + U_n - G_n - \frac{1}{q} \operatorname{div} \mathbf{J}_n = 0, \quad \frac{\partial p}{\partial t} + U_p - G_p + \frac{1}{q} \operatorname{div} \mathbf{J}_p = 0$$

since, we are in steady state we make the Time derivative term equal to zero.

Then we assume that impact ionization dominates
Then we eliminate the other terms

$$\text{i.e. } U_n - G_n = U_p - G_p = U_{AI}$$

and near in steady state

→ So, continuity equation becomes

Very far from equilibrium the approximation $I_n = c_n n^{\text{eq}} p^{\text{eq}}$, $I_p = c_p n^{\text{eq}} p^{\text{eq}}$ is not valid, and the general expressions hold:

$$U_n^{AI} = \cancel{c_n n^2 p} - I_n n, \quad U_p^{AI} = \cancel{c_p p^2 n} - I_p p$$

This is Ignored When Impact Ionization is Dominant

Auger Recombination

Impact Ionization

Taking the steady-state case, if impact ionization dominates over the other generation-recombination processes; it follows $U_n - G_n = U_p - G_p \simeq U_{AI} \simeq -I_n n - I_p p$, whence

$$\text{div } \mathbf{J}_n = -q I_n n - q I_p p, \quad \text{div } \mathbf{J}_p = q I_n n + q I_p p$$

↓ ↓

New set of continuity
equations based on dominant Impact
Ionization.

→ If the Electric field is large Impact Ionization phenomenon is dominant that means that current densities are oriented with the field.

Because, the field is the dominant reason for the existence of current.

So, in general if we consider full form of drift-diffusion expression of current density there is no reason for Ohmic part of current density to be parallel to the diffusive part.

→ It's easy to find examples where they are not parallel to each other.

So, in general current densities neither parallel to the field nor parallel to the diffusion (to the gradient of concentration)

→ But, in this case since the field is dominant we may assume that current densities are mainly OHMIC.

→ So, we can say that J_n is equal conductivity times Electric field.

$$J_n \approx q \mu_n \cdot E$$

$$\rightarrow \text{Similarly } J_p \simeq q\mu_p \mathcal{E}$$

In a region where the transport is essentially ohmic it is $\mathbf{J}_n \simeq q\mu_n n \mathcal{E}$, $\mathbf{J}_p \simeq q\mu_p p \mathcal{E}$, whence $\mathbf{J}_n = J_n \mathbf{e}$, $\mathbf{J}_p = J_p \mathbf{e}$, where $\mathbf{e}(\mathbf{r})$ is the unit vector of the electric field: $\mathcal{E} = \mathcal{E}\mathbf{e} = \sigma|\mathcal{E}|\mathbf{e}$ with $\mathcal{E} \neq 0$ and $\sigma = \pm 1$. Replacing n and p one finds

$$-\sigma \operatorname{div} \mathbf{J}_n = k_n J_n + k_p J_p, \quad \sigma \operatorname{div} \mathbf{J}_p = k_n J_n + k_p J_p$$

where the impact-ionization coefficients are defined as

$$k_n \doteq \frac{I_n}{\mu_n |\mathcal{E}|} = \frac{I_n}{|v_n|}, \quad k_p \doteq \frac{I_p}{\mu_p |\mathcal{E}|} = \frac{I_p}{|v_p|}, \quad [k_{n,p}] = \text{cm}^{-1}$$

$$\hat{\mathbf{J}}_n = \overbrace{\mathbf{J}_n}^{\text{vector}} \underbrace{\mathbf{e}}_{\text{unit vector parallel to the Electric field}}$$

$$-\sigma \operatorname{div} \mathbf{J}_n = k_n J_n + k_p J_p, \quad \sigma \operatorname{div} \mathbf{J}_p = k_n J_n + k_p J_p$$

where the impact-ionization coefficients are defined as

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Here the continuity equation has been reduced to a form which has both vector & scalar current densities

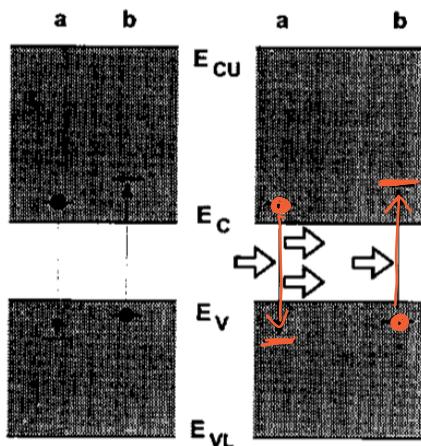
\mathbf{J}_n (vector)

J_n (scalar)

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→ Another point important for optical sensors
is absorption of Electromagnetic Radiation

Phonon- and photon-induced transitions



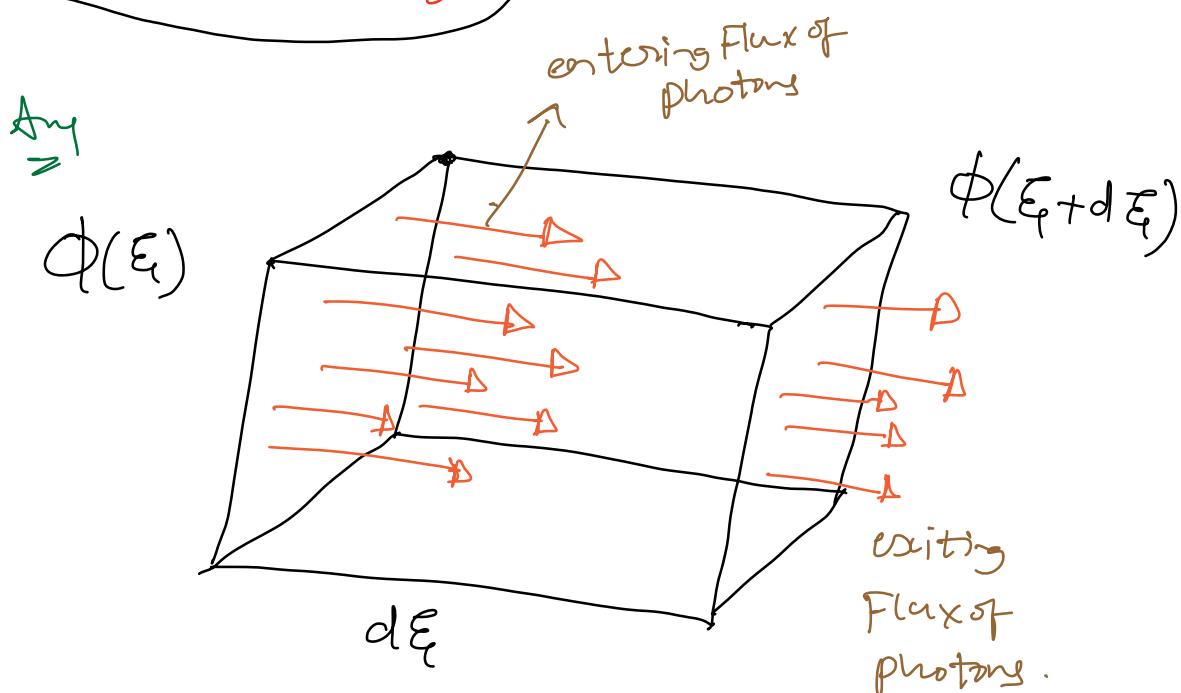
→ Here in case b if we have a photon it interacts with electron in VB and induces a generation of electron in CB and this photon disappears because it released energy to the Electron.

→ At the end of interaction there would be a photon less. If you consider many photons coming into the materials like an external light that impinges on the surface of the semiconductor then it's like a flux of photons. This flux of photons enter the semiconductor and some of the photons are absorbed, some

have a smaller no. of photons that continues the trajectory inside the semiconductor.

→ Essentially, the flux of photons decays while it proceeds inside the semiconductor

It's important to understand how photon flux decays while travelling through semiconductor?



' ξ ' is the axis along which the photon flux propagates. It is not necessarily along the common x, y, z axis. It depends on the angle at which the radiation impinges the semiconductor material.

→ $\phi(\xi) =$ flux entering the Infinitesimal Block on Left.

$\phi(\xi + d\xi) =$ Flux leaving the Infinitesimal block on Right

→ Now the objective is to calculate the variation of flux of photons inside the Block.

To calculate we make a reasonable assumption it is that the absorption events of photons are not correlated among each other.

i.e. each absorption event is independent of other absorption event.

We can say that no. of photons that are absorbed in the block is proportional to the no. of photons that are entering the block.

→ In general, we may define the absorption coefficient without making any assumptions.

$$k = -\frac{1}{\phi} \frac{\partial \phi}{\partial \xi} > 0 \quad f = \text{cm}^{-1}$$

$$\phi k = - \frac{\partial \phi}{\partial \xi}$$

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Here we can imply that

$$\frac{\partial \phi}{\partial \xi} \propto \phi$$

Rate of variation
of flux is
proportional to ϕ
itself

→ If ' χ ' is independent of ' ϕ ' we
are in the condition of absence of correlation
So we can say that the no. of photons
absorbed is proportional to incoming photons
with no correlation among these events.

But in general

$$k = k(\phi, \xi, \nu, T_L)$$

↓ ↓ ↗
 Flux position frequency of photon
 of photons

Temperature

As said, if absorption events are correlated
the flux lost per unit path $d\xi$ is proportional
to the Flux available at ξ . Then ' k ' is

independent of ϕ and if we integrate the expression

$$\phi \propto = -\frac{\partial \phi}{\partial \xi}$$

$$\Rightarrow k(\partial \xi) = -\frac{1}{\phi} (\partial \phi)$$

I.O.B.S
(Integrating on both sides)

$$\Rightarrow k \int \partial \xi = - \int \frac{1}{\phi} \partial \phi$$

$$\Rightarrow k \xi = - \log(\phi)$$

$$\Rightarrow k \xi = - \log(\phi) + C$$

$$\Rightarrow k \xi = - \log(\phi) + C$$

at $t=0$ $\xi=0$

$\Rightarrow C = \log(\phi_0)$

initial condition

$$\Rightarrow k \xi = - \log \phi + \log \phi_0$$

$$\Rightarrow k \xi = - (\log \phi - \log \phi_0)$$

$$\Rightarrow -K\xi = \log\left(\frac{\phi}{\phi_0}\right)$$

$$\Rightarrow \boxed{\phi = \phi_0 \exp(-K\xi)}$$

↓
exponential Decay

If 'f' also depends on position we must take the average of absorption coefficient

$$K_m = \frac{1}{\xi} \int_0^{\xi} K(\xi', \vartheta, T_2) d\xi'$$

Conclusion:- If the phenomenon is Non correlated we can say that Flux decays exponentially and the coefficient of the exponent is Absorption coefficient.

* Now, we have correlate the Flux with the optical generation.

$$h\nu G_{D0} = -\eta \frac{\partial u}{\partial t} = -\eta \frac{\partial (\mathcal{F}_{u_f})}{\partial t} = -\eta \frac{\partial I}{\partial \xi} = -\eta \frac{\partial (h\nu \phi)}{\partial \xi}$$

considering the chain of relations. Take G_{DO} This is the term we are interested in calculating.

G_{DO} : "No. of optical Transitions per unit volumed Time"

Each optical transition absorbs a photon of energy $\hbar\nu$.

So, if we multiply G_{DO} & $\hbar\nu$ we obtain Energy per unit volumed time associated to the optical generators.

Of course, this energy is subtracted from the energy of EMF. So, in the EMT there is a function called 'u'

'u': Spectral Energy density of the Radiation
Energy per unit volume & frequency
of the EM Radiation.

We use 'u' as a symbol we need not know how to calculate it.

→ So, if you take the Time derivative of the spectral energy density. You obtain the Time derivative of the energy of EMF per unit

Volume in Time & Frequency.

- In principle if each absorption of a photon corresponds to an opticle generation. Then the energy that the semiconductor takes from the radiation is equal to the Energy that Radiation is losing
- Actually, this is not so. Some photons may interact with electron that are already in the conduction band. Some may loose energy to nuclei.
∴ The energy that is lost by EMF that corresponds to Generation is larger.

→ So we need a efficiency constant η

Quantum efficiency

$$h\nu G_{DO} = -\eta \left(\frac{\partial u}{\partial t} \right) = -n \frac{\partial \left(\frac{I}{u_f} \right)}{\partial t}$$

$$\left(u = \frac{I}{u_f} \right)$$

(I): Intensity of EMF

(u_f): phase velocity of the Radiation velocity associated to frequency (n) inside the material.

it's the propagation velocity at frequency 2

$$\rightarrow -\eta \frac{\partial I}{\partial \epsilon_f dt} = -\eta \frac{\partial I}{\partial \epsilon} = -\eta \frac{\partial (h\nu \phi)}{\partial \epsilon}$$

Speed x time
elementary interval of space

$I = h\nu \phi$
energy Intensity

$$\therefore h\nu G_{DD} = -\eta \frac{\partial (h\nu \phi)}{\partial \epsilon}$$

$$h\nu G_{DD} \Rightarrow -\eta^{h\nu} \frac{\partial \phi}{\partial \epsilon}$$

$h\nu = \text{constant}$

$$\Rightarrow \boxed{G_{DD} = -\eta \frac{\partial \phi}{\partial \epsilon}}$$

$\phi = \phi_0 \exp(-k \xi)$

$$\Rightarrow G_{DD} = -\eta \frac{\partial}{\partial \epsilon} (\phi_0 \exp(-k \xi))$$

$$\Rightarrow -\eta \phi_0 E(\epsilon) \exp(-k \xi)$$

$$\Rightarrow \underline{(\eta \phi_0) \exp(-k \xi)}$$

$$\downarrow G_0$$

$$\Rightarrow G_{D0} = G_0 \exp(-kE)$$

Decay of optical generation rate

G_0 is inside the edge of semiconductor because photons which have entered into the surface are taken into consideration.

→ We remember that in the Model for Semiconductor we have TWO CLASSES of coefficients

- 1) Generation and Recombination Terms
- 2) Mobility

Due to Einstein relations the Diffusion coefficients are proportional to Mobility.

∴ In order to discuss remaining coefficients it is sufficient to discuss Mobility.

Mobility was found using a so called Heuristic reasoning.

Then we found the Mobility of e^- & holes

given by the formulas given below

Macroscopic Mobility Models — I

The carrier mobilities are defined in terms of the momentum-relaxation times as

$$\mu_n = \frac{q\tau_{pn}}{m_n}, \quad \mu_p = \frac{q\tau_{pp}}{m_p} \quad \Rightarrow \quad \frac{1}{\mu_n} = \frac{m_n}{q\tau_{pn}}, \quad \frac{1}{\mu_p} = \frac{m_p}{q\tau_{pp}}.$$

The inverse momentum-relaxation times are calculated from the scattering probability per unit time. When the collisions can be assumed uncorrelated, the following hold:

$$\frac{1}{\tau_{pn}} = \frac{1}{\tau_{pn1}} + \frac{1}{\tau_{pn2}} + \frac{1}{\tau_{pn3}} + \dots,$$

where the suffix indicates the specific collision mechanism. The same applies to holes. It follows

$$\frac{1}{\mu_n} = \frac{1}{\mu_{n1}} + \frac{1}{\mu_{n2}} + \dots, \quad \frac{1}{\mu_p} = \frac{1}{\mu_{p1}} + \frac{1}{\mu_{p2}} + \dots,$$

which is also referred to as *Mathiessen's Rule*. Each μ_{ni} , μ_{pi} is then expressed in terms of a macroscopic parameter related to the scattering mechanism at hand.

$$\mu_n = \frac{q\tau_{pn}}{m_n}$$

Average relaxation time for momentum of e^-
effective mass of e^-

Similarly

$$\mu_p = \frac{q\tau_{pp}}{m_p}$$

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m_n, m_p are given and constant

q is universal constant

∴ we can say μ is dependent on T
 Relaxation time

→ It is convenient for our discussion to consider inverse of Mobility.

$$\frac{1}{\mu_p} = \frac{m_p}{q \tau_{pn}}, \quad \frac{1}{\mu_n} = \frac{m_n}{q \tau_{pp}}$$

The inverse momentum-relaxation times are calculated from the scattering probability per unit time. When the collisions can be assumed uncorrelated, the following hold:

$$\frac{1}{\tau_{pn}} = \frac{1}{\tau_{pn1}} + \frac{1}{\tau_{pn2}} + \frac{1}{\tau_{pn3}} + \dots,$$

∴ The larger the probability of collision The smaller is the Mobility because it's proportional to relaxation.

→ The larger is the No. of collisions The larger is the friction. So, it opposes the motion.

→ The information that Inverse Relaxation time is related to the probability per unit time of the collision is useful it makes it possible to separate different types of collisions.

- Because we assume that collision events are not correlated among each other that means if the e^- or hole undergoes a collision it is not dependent on other types of collisions that also may occur.
- So, if the collisions are correlated then the ^{Global}_~ probability of collision per unit Time is equal to the sum of probabilities of a collision per unit associated per individual collision types.

i.e for electrons

$$\frac{1}{\tau_{pn}} = \frac{1}{\tau_{pn1}} + \frac{1}{\tau_{pn2}} + \dots$$

Collisions of Type 1

↓ implies

Inverse Mobility \propto Inverse Relaxation Time

$$\boxed{\frac{1}{\mu_n} \propto \frac{1}{\tau_{pn}}}$$

$$\Rightarrow \frac{1}{\mu_n} = \frac{1}{\mu_{n1}} + \frac{1}{\mu_{n2}} + \dots$$

$$\frac{1}{\mu_p} = \frac{1}{\mu_{p1}} + \frac{1}{\mu_{p2}} + \dots$$

Qualitatively conductivity \propto Mobility
 (σ) (μ)

$$\Rightarrow \frac{1}{\mu} \propto \frac{1}{\sigma}$$

$$\Rightarrow \frac{1}{\mu} \propto \text{Resistivity}$$

These formulas look strikingly similar to resistances connected in parallel.

→ So, what do we mean by collisions of Type 1 & Type 2 and so on?

Any They could be collisions with PHONONS
 collisions with Impurities
 " " Surfaces
 (Interface between semiconductor &

other matter)

→ many more.

∴ we can calculate separately the Mobility or contribution to mobility each type of collision for instance phonon impurities surfaces and soon.

$$\frac{1}{\mu_p} = \frac{1}{\mu_{p1}} + \frac{1}{\mu_{p2}} + \dots$$

This kind of relation is called Matthiessen's Rule.

→ In order to determine expression of Type 1, 2, 3 the calculation is very tedious ∴ it is preferable to identify Microscopic Models that connect each kind of Mobility to some microscopic parameters of the semiconductor.

→ We will consider primarily 3 Types of collisions, collisions are also called scattering mechanisms.

The 3 collisions are devidecd into two groups.

(i) Bulk Transport (ii) Surface Transport

Macroscopic Mobility Models — II

The most important scattering mechanisms, and the related macroscopic parameters entering the mobility models, are listed below:

- Bulk transport:

- ▷ Phonon scattering: the model depends on the lattice temperature T_L and on $|\text{grad } \varphi_n|$ (for electrons) or $|\text{grad } \varphi_p|$ (for holes).
- ▷ Ionized-impurity scattering: the model depends on the total ionized-impurity concentration $N_I = N_D^+ + N_A^-$.

- Surface transport (typically, at the Si-SiO₂ interface). In addition to the above, the following is also important here:

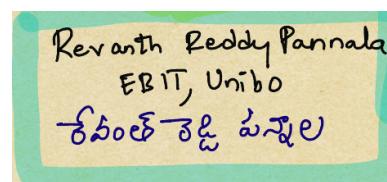
- ▷ Surface scattering: the model depends on the component of the electric field normal to the surface, \mathcal{E}_\perp .

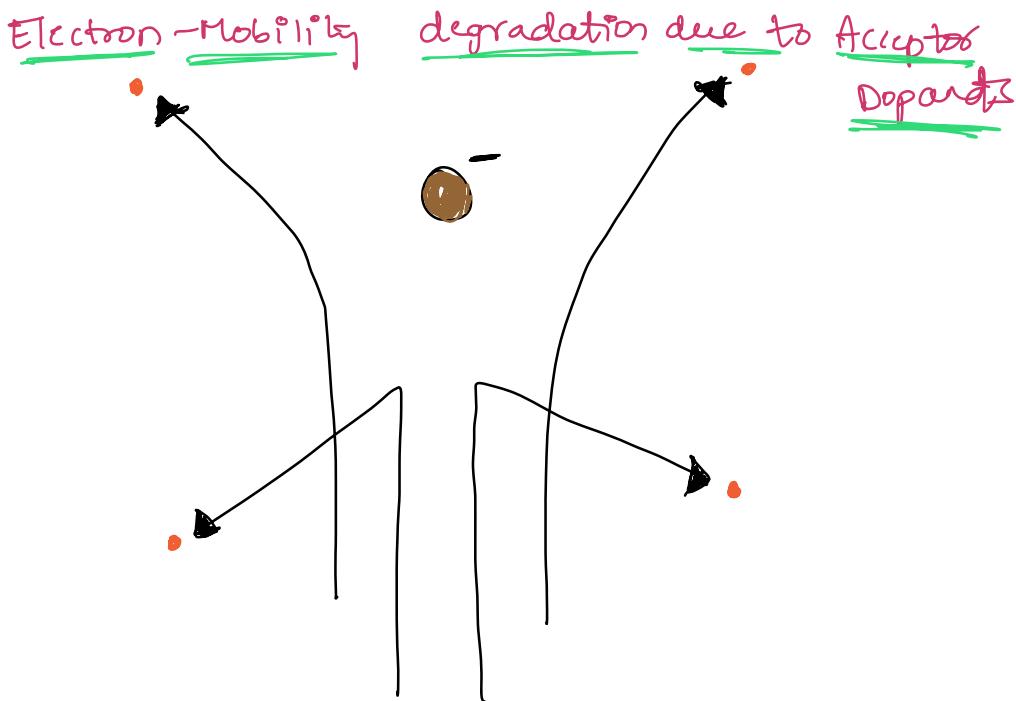
By way of example, the electron mobility may read

$$\frac{1}{\mu_n} = \frac{1}{\mu_{n1}(T_L)} + \frac{1}{\mu_{n2}(|\nabla \varphi_n|)} + \frac{1}{\mu_{n3}(N_I)} + \frac{1}{\mu_{n4}(\mathcal{E}_\perp)},$$

where each term is provided in table form or analytically.

→ we will examine few pictures that qualitatively explain the effects of the ionized dopants and later on the surfaces on the mobility degradation.





అల్కోలు చేసి చెరుకున మహు కొబాల్!

“ విజ్ఞానం నుండి విశ్వం ప్రాణం రాలేదు !

విశ్వం నుండి విజ్ఞానం ప్రాణం ఏచ్చింది ! ”

- In the figure let's assume 'y' electrons are moving upwards towards an acceptor Impurity atom.

Assume The Avg. velocity of these Electrons is similar to the individual electrons. All these 'y' electrons contributes Current Density oriented in vertical direction.

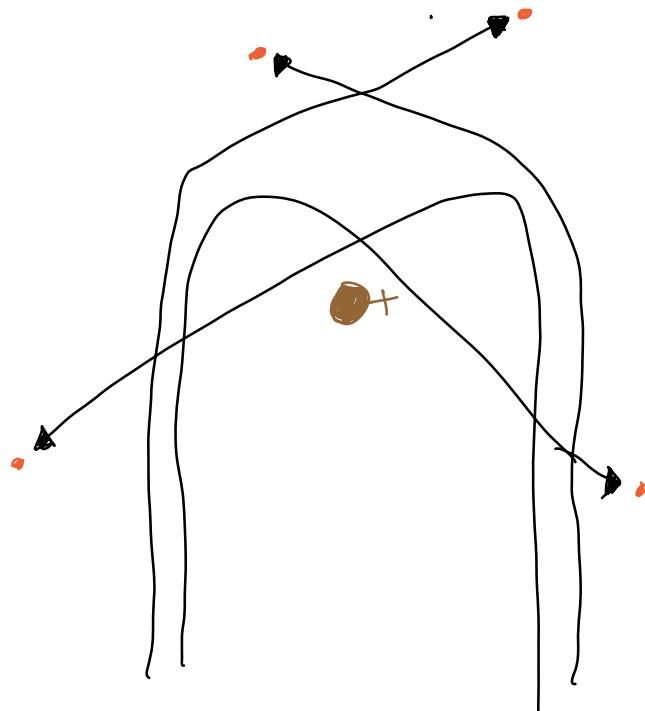
- obvious will be deviated because of Acceptors Impurity as shown Above.

because similar charges repel each other.

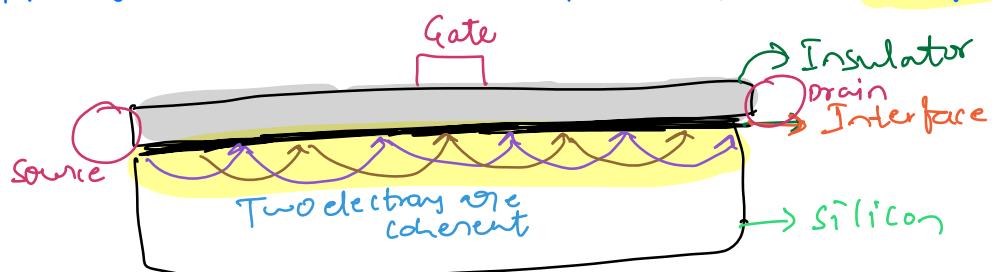
இதை இரண்டு மின் கால்கள் என
Two Electrons are called Coulomb.
ஒன்று ஒன்று பிரிவதாகவே.

→ This deviation randomizes the motion of
Electrons

* Same type of analysis can be done for
positive Impurity



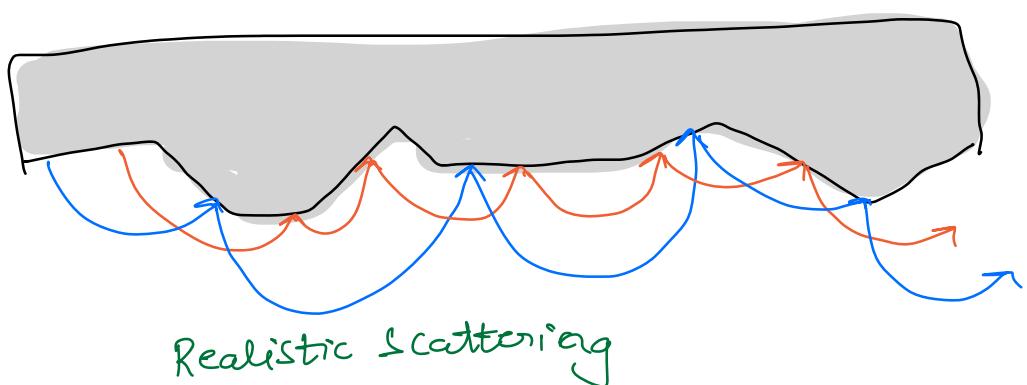
→ Now we will discuss the effects of the surface.



Assume this is an MOS transistor
and electrons are travelling from Source to
Drain

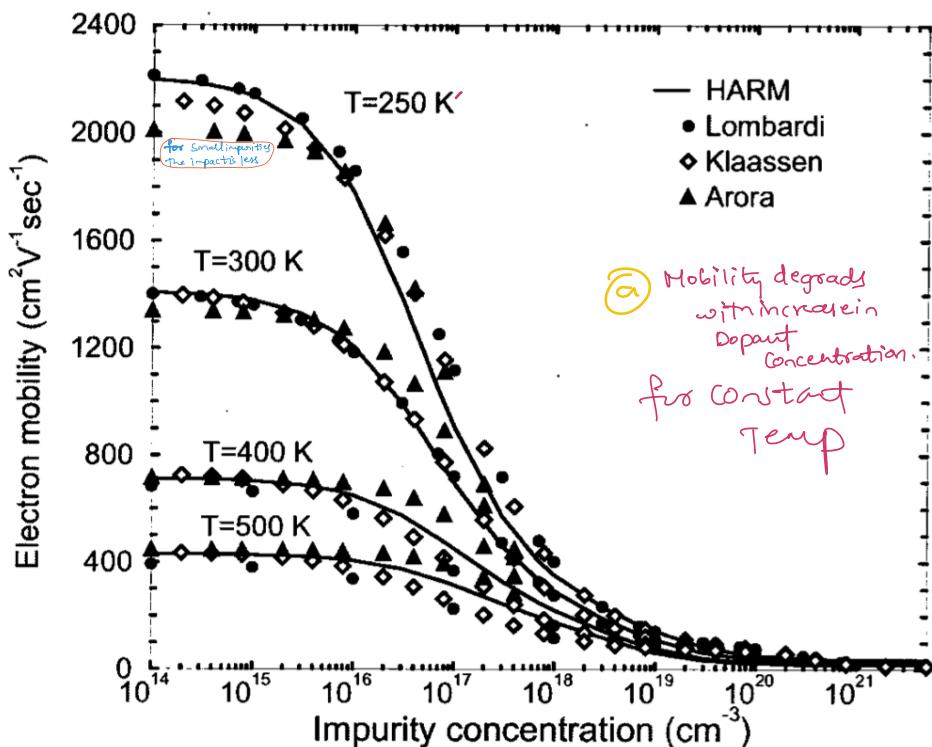
But, they are also attracted by the Gate voltage
so they travel as highlighted above. This Ideal
case

Realistic case would look like



In contrast to the Ideal case in which Horizontal component of the Motion is preserved, Here in the Realistic case Horizontal component of motion is not preserved.

T. 27.15: Mobilità degli elettronni in funzione della temperatura e del drogaggio.



(b) For a constant impurity concentration if temperature \uparrow mobility degrades.

This is it further Model of semiconductor devices.

From now on we will consider Individual devices and we start with PN Junction

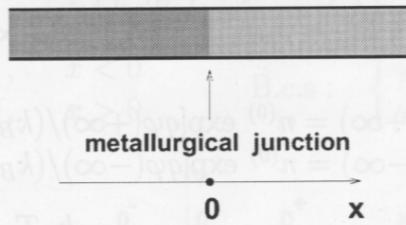


PN Function

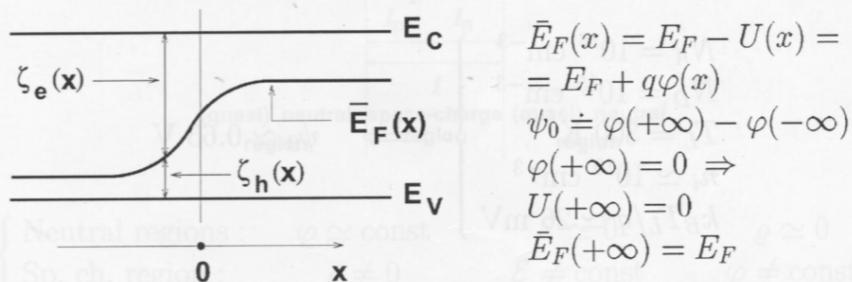
p-n Junction in Equilibrium — I

One-dimensional case

p-type, $N_A = \text{const}$ n-type, $N_D = \text{const}$



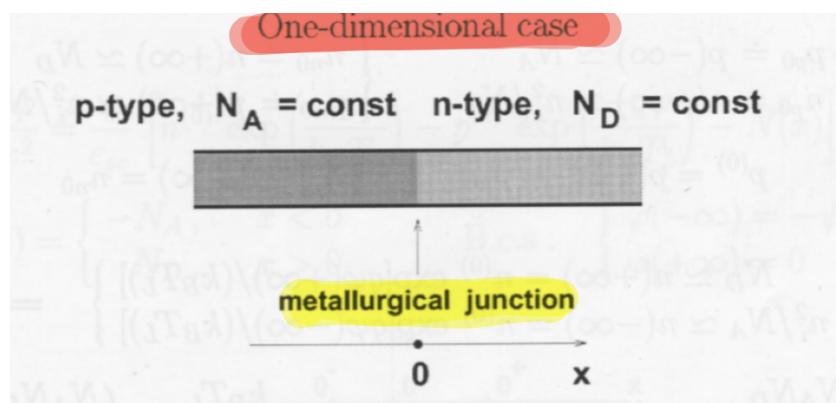
Hyp: $N_A > N_D$, non-degenerate and completely ionized



ψ_0 : "built-in potential" (indicated also by ψ_B)

→ we take a simple case of PN Junction
 i.e one-dimensional case that is not
 so realistic which is convenient for
 Analysis.

so that one part of device (p-type) (left) is doped with constant of Acceptor Atom and the other part (Right) (n-type) is doped with a constant concentration of Donor atom. and Both concentrations are same which is Technologically not possible. But, on paper we can do it.



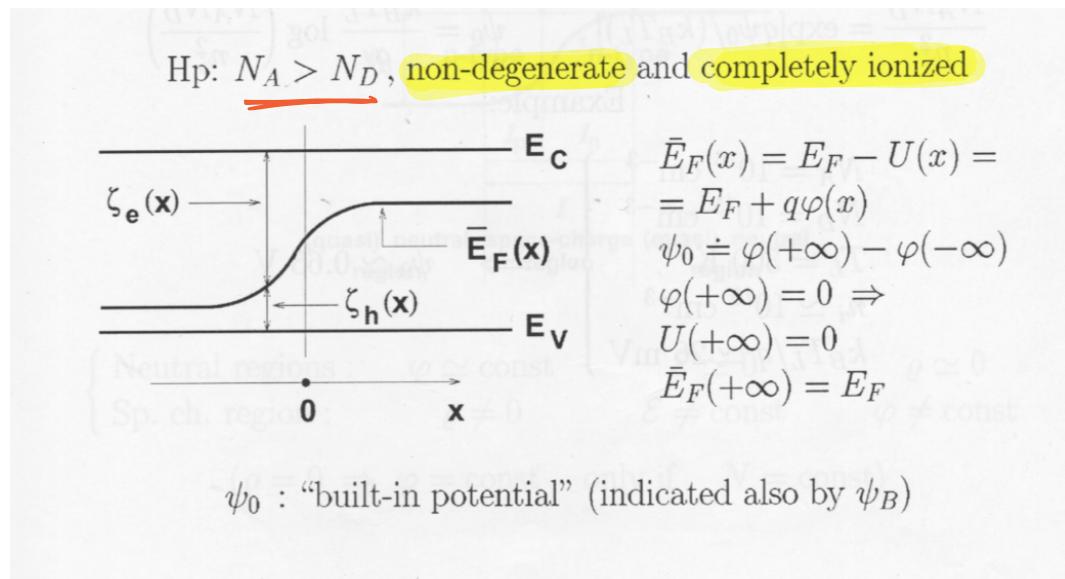
Therefore, at the Junction we have an abrupt change in dopants i-e (p-type to n-type) as we go from Left to Right.

Abrupt Junction → Non Realistic Junction



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→ we assume



→ Now we know what happens, when we have a semiconductor where dopant concentration depends on position.

We can not use the Fermi level any more we need to use \bar{E}_F function i-e

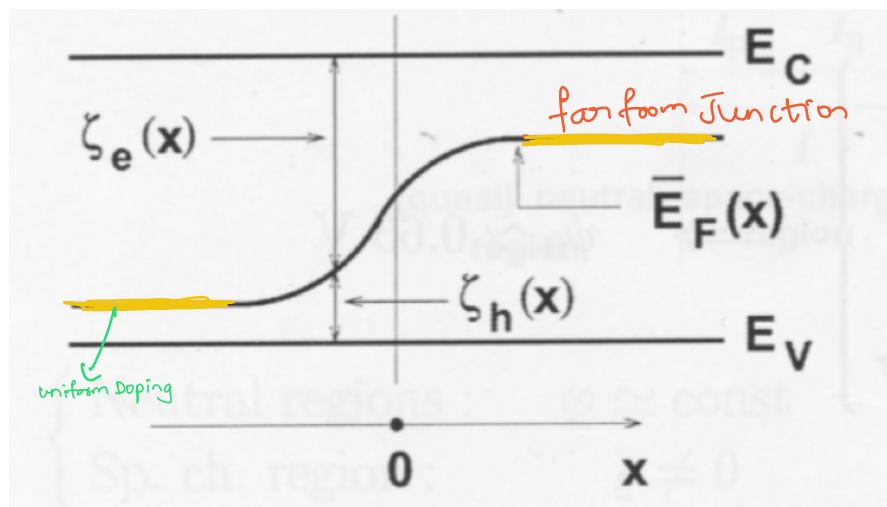
$$\bar{E}_F(x) = E_F - U(x) = E_F + q\varphi(x)$$

Electrostatic potential Energy

Q How can we calculate the properties of the function?

Any we assume the two sides of PN Junction are unlimited in space.

At a point far from the Junction we will reach a point where the N-type side behaves like a Uniform N-type Semiconductor



Similarly, if we go Far to the left in the p-type Junction we can assume a Uniformly Doped Semiconductor.

\bar{E}_F has two Asymptotic values

$$\rightarrow \bar{E}_F(\infty) = E_F + q\phi(\infty)$$

$$\text{by } \bar{E}_F(-\infty) = E_F + q\phi(-\infty)$$

obviously $\bar{E}_F(\infty) \neq \bar{E}_F(-\infty)$ are different

and $\therefore \phi(\infty) \neq \phi(-\infty)$

"This is present only due to the presence of Non uniform Dopeant concentration."

$$\Psi_0 = \phi(-\infty) - \phi(\infty) = \Phi_B$$

\hookrightarrow Barrier potential

This potential is only due to Non uniform Dopeant concentration.

→ The zero of electric potential arbitrarily. So we will choose Electric potential at ∞ to be zero.

$$\phi(+\infty) = 0 \Rightarrow V(+\infty) = 0$$

Electric potential

electro static potential energy

\therefore At Infinity

$$\boxed{\bar{E}_F(+\infty) = E_F}$$

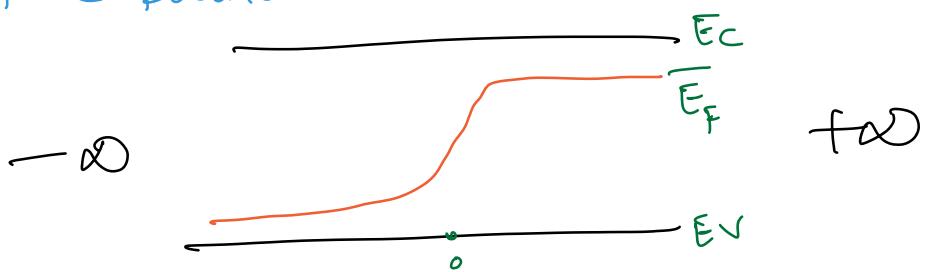
Now we will consider the **Equilibrium case** and we remember that the **Model Mathematical of Semiconductor device** Reduces to **Poisson's Equation**.

→ So, we formally solve poisson's equation to analyze PN Junction.

of course, we cannot solve it analytically because it's non-linear.

But, at least state the form of poisson equation and we can also find the boundary condition for poisson equation.

→ The boundaries at the moment are





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p-n Junction in Equilibrium — II

$$\begin{cases} p_{p0} \doteq p(-\infty) \simeq N_A \\ n_{p0} \doteq n(-\infty) \simeq n_i^2/N_A \end{cases} \quad \begin{cases} n_{n0} \doteq n(+\infty) \simeq N_D \\ p_{n0} \doteq p(+\infty) \simeq n_i^2/N_D \end{cases}$$

$$p^{(0)} = p(+\infty) = p_{n0}, \quad n^{(0)} = n(+\infty) = n_{n0}$$

$$\left. \begin{array}{l} N_D \simeq n(+\infty) = n^{(0)} \exp[q\varphi(+\infty)/(k_B T_L)] \\ n_i^2/N_A \simeq n(-\infty) = n^{(0)} \exp[q\varphi(-\infty)/(k_B T_L)] \end{array} \right\} \Rightarrow$$

$$\frac{N_A N_D}{n_i^2} = \exp[q\psi_0/(k_B T_L)], \quad \psi_0 = \frac{k_B T_L}{q} \log \left(\frac{N_A N_D}{n_i^2} \right)$$

Example:

$$\left. \begin{array}{l} N_A = 10^{16} \text{ cm}^{-3} \\ N_D = 10^{15} \text{ cm}^{-3} \\ T_L = 300 \text{ K} \\ n_i \simeq 10^{10} \text{ cm}^{-3} \\ k_B T_L / q \simeq 26 \text{ mV} \end{array} \right\} \Rightarrow \psi_0 \simeq 0.65 \text{ V}$$

P-side

→
 $P_{p0} = p(-\infty) \doteq N_A$
(Majority)
 $n_{p0} = n(-\infty) \doteq \frac{n_i^2}{N_A}$
(minority)

When we go to $-\infty$ near in a P-region i.e uniformly doped.

We assume that the dopant concentration is large wrt the intrinsic concentration and we remember in the uniform equilibrium case it is very easy to calculate the concentrations.

The concentrations are written above.

p_{p0} : Asymptotic concentration of Holes in P-side

n_{p0} : " " " " e⁻'s in "

→ n-side

Then on the n-side; if we go to infinity (∞)
and offcourse the concentration of Majority carriers
i.e. e⁻'s is

$$n_{n0} = n(+\infty) \cong N_D$$

& That of Holes is

$$p_{n0} = p(+\infty) \cong \frac{n_i^2}{N_D}$$

Now we have stated above that $+\infty$ is the place where Zero of the potential is assumed.

We remember at this point another symbol

$$p^{(0)} = p(+\infty) = p_{n0}, \quad n^{(0)} = n(+\infty) = n_{n0}$$

concentration of holes
when the electric potential
is ZERO in our case
this is at $+\infty$

∴ Now we know for Non-Degenerate case
we can use the exponential expressions.

$$\left. \begin{array}{l} N_D \simeq n(+\infty) = n^{(0)} \exp[q\varphi(+\infty)/(k_B T_L)] \\ n_i^2/N_A \simeq n(-\infty) = n^{(0)} \exp[q\varphi(-\infty)/(k_B T_L)] \end{array} \right\} \Rightarrow$$

$$\frac{N_A N_D}{n_i^2} = \exp[q\psi_0/(k_B T_L)] \Rightarrow \boxed{\psi_0 = \frac{k_B T_L}{q} \log \left(\frac{N_A N_D}{n_i^2} \right)}$$

Built in potential

Ex:-

$$\frac{N_A N_D}{n_i^2} = \exp[q\psi_0/(k_B T_L)], \quad \boxed{\psi_0 = \frac{k_B T_L}{q} \log \left(\frac{N_A N_D}{n_i^2} \right)}$$

Example:

$$\left. \begin{array}{l} N_A = 10^{16} \text{ cm}^{-3} \\ N_D = 10^{15} \text{ cm}^{-3} \\ T_L = 300 \text{ K} \\ n_i \simeq 10^{10} \text{ cm}^{-3} \\ k_B T_L / q \simeq 26 \text{ mV} \end{array} \right\} \Rightarrow \psi_0 \simeq 0.65 \text{ V}$$

This is typical threshold voltage of a P-N junction

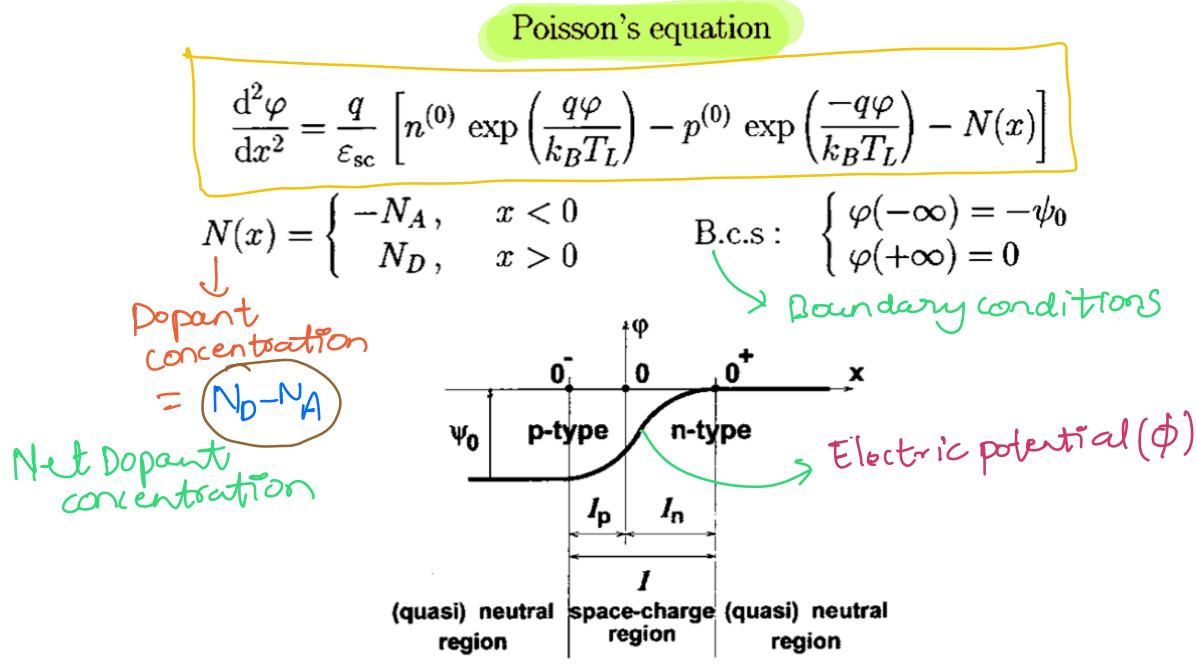
do

→ An other issue is we must now solve the Poisson's equation

of course it should be done numerically and it is relatively easy.

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p-n Junction in Equilibrium — III



$$\begin{cases} \text{Neutral regions : } & \varphi \approx \text{const} & \mathcal{E} \approx 0 & \rho \approx 0 \\ \text{Sp. ch. region : } & \rho \neq 0 & \mathcal{E} \neq \text{const} & \varphi \neq \text{const} \end{cases}$$

$(\rho = 0 \Rightarrow \varphi = \text{const} \text{ only if } N = \text{const})$

→ From the graph the electric potential (ϕ) is positive '0' on the right and goes towards +∞ and is negative on the left and is equal to

$$\phi(-\infty) = -\psi_0$$



What is the important information we can derive from the figure?

→ Essentially we can see that the PN Junction can be separated into ② different regions as shown figure.

(i) (Quasi) neutral Region Left

(ii) Space-charge Region

(iii) (quasi) neutral Region Right

→ Now we remember that Electric field is the derivative of potential with -ve sign

$$E = -\frac{d\phi}{dt}$$

∴ If the Electric potential is practically constant then the Electric field is practically zero.

→ The charge density is the derivative of Electric field apart from the permittivity.

∴ If Electric field is practically zero then the charge density is also practically zero.

- In conclusion, the two external regions the charge densities are practically equal to zero. for this reasons they are called Neutral (or) Quasi Neutral Regions where Electric field is almost equal to zero.
- Instead there is an intermediate region where the Electric potential goes from 0 to $-\psi_0$.
 \therefore in the space charge region the Electric field is also not zero \Rightarrow The charge density is also non zero.
- O^- & O^+ are at a finite distance from the origin
- l_p, l_n are lengths of distance of O^- & O^+ from origin.
- $\lambda = l_p + l_n$ Total length of space charge Region.

- Since we are in the equilibrium case
 the only unknown in the mathematical model
 of semiconductor device is the electric potential
- If we succeed in calculating Electric potential
 by solving the poisson's equation then we
 know the value of the Electric potential at
 each position 'x' in the semiconductor as a
^{at each position}
 consequence we can calculate the concentration
 of electrons & holes.
- We can also see

Poisson's equation

$$\frac{d^2\varphi}{dx^2} = \frac{q}{\varepsilon_{sc}} \left[n^{(0)} \exp\left(\frac{q\varphi}{k_B T_L}\right) - p^{(0)} \exp\left(\frac{-q\varphi}{k_B T_L}\right) - N(x) \right]$$

↓ ↓

Concentration Concentration
of Electrons of Holes

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