Lecture 9

Photogeneration, Absorption, and Nonequilibrium

Reading:
Pierret 3.3-3.4
Photogeneration

Light with photon energy, $h\nu < E_g$ is not easily absorbed. A convenient expression for the energy of light is $E = 1.24/\lambda$ where $\lambda$ is the wavelength of the light in um.

Light with energy, $h\nu > E_g$ is absorbed with the “unabsorbed” light intensity as a function of depth into the semiconductor is $I(x) = I_o e^{-\alpha x}$

where $I_o$ is the initial light intensity, $x$ is distance and $\alpha$ is the absorption coefficient [1/cm].
Photogeneration

\[ \alpha (\text{cm}^{-1}) \]

\[ \lambda (\mu\text{m}) \]

- GaAs
- Si
- Ge
- GaP
- InP
Photogeneration

Each Photon with energy greater than Eg can result in one electron hole pair. Thus, we can say,

\[
\frac{\partial n}{\partial t}\bigg|_{\text{Light}} = \frac{\partial p}{\partial t}\bigg|_{\text{Light}} = G_L(x, \lambda) \quad \text{where} \quad G_L(x, \lambda) = G_{LO}e^{-\alpha} \quad \#/(cm^3 - Sec)
\]

If \( \alpha \) is small (near bandgap light), the generation profile can be approximately constant.

If \( \alpha \) is large (light with energy>> bandgap), the generation profile can be approximated as at the surface.
Important Nomenclature

$n_0, p_0 \ldots$ carrier concentrations in the material under analysis when equilibrium conditions prevail.

$n, p \ldots$ carrier concentrations in the material under arbitrary conditions.

$\Delta n \equiv n - n_0 \ldots$ deviations in the carrier concentrations from their equilibrium values.

$\Delta p \equiv p - p_0 \ldots$ $\Delta n$ and $\Delta p$ can be both positive and negative, where a positive deviation corresponds to a carrier excess and a negative deviation corresponds to a carrier deficit.

$N_T \ldots$ number of R−G centers/cm$^3$.

\[ n = \Delta n + n_0 \text{ and } p = \Delta p + p_0 \]

In Non-equilibrium, np does not equal $n_i^2$

Low Level Injection

$\Delta p = \Delta n \ll n_0 \text{ and } n \sim n_0 \text{ in n-type material}$

$\Delta p = \Delta n \ll p_0 \text{ and } p \sim p_0 \text{ in p-type material}$
Carrier Concentrations after a “Perturbation”

Steady State if perturbation has been applied for a long time
Non-Steady State, Nonequilibrium
Equilibrium

\[ \Delta p(t=0) > p_0 \]
\[ \Delta p(t=0) < p_0 \]

After the carrier concentrations are perturbed by some stimulus (leftmost case) and the stimulus is removed (center case) the material relaxes back toward its equilibrium carrier concentrations.
Material Response to “Non-Equilibrium”: Relaxation Concept

Consider a case when the hole concentration in an n-type sample is not in equilibrium, i.e., \( p_n \) does NOT equal \( n_i^2 \)

\[
\frac{\partial p}{\partial t} \bigg|_{thermal \ R-G} = -\frac{\Delta p}{\tau_p}
\]

where \( \tau_p \) is the minority carrier lifetime

\( c_p \) is a proportionality constant

\( N_T \) is the "trap" concentration

• The minority carrier lifetime is the average time a minority carrier can survive in a large ensemble of majority carriers.

• If \( \Delta p \) is negative \( \Rightarrow \) Generation or an increase in carriers with time.

• If \( \Delta p \) is positive \( \Rightarrow \) Recombination or a decrease in carriers with time.

• Either way the system “tries to reach equilibrium”

• The rate of relaxation depends on how far away from equilibrium we are.
Material Response to “Non-Equilibrium”: Relaxation Concept

Likewise when the electron concentration in an p-type sample is not in equilibrium, i.e., \( n_p \) does NOT equal \( n_i \)

\[
\frac{\partial n}{\partial t} \bigg|_{R\rightarrow G}^{\text{thermal}} = -\frac{\Delta n}{\tau_n} \quad \text{where} \quad \tau_n = \frac{1}{c_n N_T}
\]

where \( \tau_n \) is the minority carrier lifetime

\( c_n \) is a different proportionality constant

\( N_T \) is the "trap" concentration

More generally for any doping case:

\[
\frac{\partial n}{\partial t} \bigg|_{R\rightarrow G}^{\text{thermal}} = \frac{\partial p}{\partial t} \bigg|_{R\rightarrow G}^{\text{thermal}} = \frac{n_i^2 - np}{\tau_p (n + n_1) + \tau_n (p + p_1)}
\]

where...

\( n_1 = n_i e^{(E_T - E_i)/kT} \) and \( p_1 = n_i e^{(E_i - E_T)/kT} \)

Same unit as above
Example: After a long time on, a light is switched off

\[ \frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n} \quad \text{has a solution} \]

\[ n(t) = n_o + \Delta n_o e^{-\left(\frac{t}{\tau_n}\right)} \quad \text{where } \Delta n_o = \text{initial excess electron concentration} \]
Material Response to “Non-Equilibrium”: Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Given: \( \Delta n = \Delta p, \quad n = n_o + \Delta n, \quad p = p_o + \Delta p \)

Low Level Injection \( \Longrightarrow \Delta n << N_a \) and High Level Injection \( \Longrightarrow \Delta n >> N_a \)

- Recombination Rate, \( R = B np \text{ [#/cm}^3\text{ sec.]} \) (depends on number of electrons and holes present)
- In Thermal Equilibrium,
  \( np = n_i^2 \) where \( n_i^2 \) is the n-p product due to thermal generation (intrinsic generation)
  Recombination rate, \( R = B n_i^2 = G, \) Generation Rate where \( B \) is a constant

Under Illumination (Non-thermal equilibrium), \( np \not\approx n_i^2 \)

Net Recombination Rate, \( -\frac{dn}{dt} = R - G = B(np - n_i^2) \)

but,
\[
-\frac{dn}{dt} = B(np - n_i^2)
\]
\[
= B((n_o + \Delta n)(p_o + \Delta p) - n_i^2)
\]
\[
= B( n_o p_o - n_i^2 + \Delta p n_o + \Delta n p_o + \Delta n \Delta p )
\]
\[
= B \Delta n( 0 + n_o + p_o + \Delta n)
\]
\[
= B \Delta n(n_o + p_o + \Delta n)
\]

Thus, using our lifetime definition,

\[
-\frac{dn}{dt} = -\frac{\Delta n}{\tau_e}
\]

\( \tau_e = \frac{1}{B(n_o + p_o + \Delta n)} \)
Material Response to “Non-Equilibrium”: Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Special cases:

Low Level Injection: $\Delta n \ll \text{majority carrier density}$

$$\tau_e = \frac{1}{B(n_o + p_o)}$$

and if the material is n-type:

$$\tau_e = \frac{1}{Bn_o}$$

or p-type:

$$\tau_e = \frac{1}{Bp_o}$$

High level injection: $\Delta n \gg \text{majority carrier density}$

$$\tau_e = \frac{1}{B\Delta n}$$
Electron Capture and Emission

Electron Capture Rate:
\[ c_e = v_{th,e} \sigma_n n N_t (1-f(E)) \]

- How many electrons are available for capture
- Number of empty defect sites
- Capture cross section: Effective size of the defect. Units of area
- Thermal velocity: How fast the electrons are moving

Electron Emission Rate:
\[ e_e = e_n N_t f(E) \]

- Number of filled defect sites
- \( e_n = v_{th,e} \sigma_n N_c e^{-(E_c-E_t)/K_T} \)
Hole Capture and Emission

Hole Capture Rate
- How many holes are available for capture
- Number of filled defect sites
- Capture cross section: Effective size of the defect. Units of area
- Thermal velocity: How fast the holes are moving

Hole Emission Rate
- Number of empty defect sites

\[ c_p = v_{th,p} \sigma_p p N_t f(E) \]
where \( c_p \) = the hole capture rate
\( v_{th,p} \) = the thermal velocity of holes
\( \sigma_p \) = the capture cross section
\( p \) = the hole concentration
\( N_t \) = the total number of defect sites
\( f(E) \) = the hole distribution function

\[ e_p = e_h N_t (1 - f(E)) \]
where \( e_p \) = the hole emission rate
\( e_h \) = the hole emission velocity
\( N_v \) = the number of available sites
\( f(E) \) = the hole distribution function

\[ e_h = v_{th,p} \sigma_p N_v e^{-(E_t-E_v)/kT} \]
Electron and Hole Capture and Emission

Recombination:
- electron capture / hole capture
- hole capture / electron capture

Generation:
- hole emission / electron emission
- electron emission / hole emission

Recycling of carriers into bands:
- hole capture / hole emission
- electron capture / electron emission
Carrier Concentrations after a “Perturbation”

\[ \frac{\partial p}{\partial t} \bigg|_{Re\ combination} = -c_p N_T p \quad \text{and} \quad \frac{\partial p}{\partial t} \bigg|_{Generation} = c_p N_T p_o \]

Plenty of Electrons

R-G Center Concentration \( N_T \)

Filled with Electrons

Very few Holes
Electron and Hole Capture and Emission

In steady state non-equilibrium, the number of electrons and holes are constant:

\[
G - (c_e - e_e) = \frac{dn}{dt} = 0
\]

\[
G - (c_p - e_p) = \frac{dp}{dt} = 0
\]

"The net recombination/generation rate is,"

This equation can be used to solve for \(f'(E)\), the non-equilibrium fermi distribution function (which does NOT equal \(f(E)\), then calculated as,"