CHARGE CARRIERS
- GENERATION
AND RECOMBINATION
INJECTION LEVEL

\[ N_D = 10^{16} \]

Equilibrium: \( n_{n0}p_{n0} = n_i^2 = 10^4 \times 10^{16} = 10^{20} \)

Low injection level (e.g. due to light): \( \Delta n = \Delta p \ll N_D \)

Adding \( 10^{12} \) carriers /cm\(^3\)

\[ p_n = 10^4 + 10^{12} \approx 10^{12} \]
\[ n_n = 10^{16} + 10^{12} \approx 10^{16} \]

High injection level: \( \Delta n = \Delta p \approx N_D \) (not relevant)

Adding \( 10^{16} \) carriers /cm\(^3\)

\[ p_n = 10^4 + 10^{16} \approx 10^{16} \]
\[ n_n = 10^{16} + 10^{16} = 2 \times 10^{16} \]

Ref: Grove
Definitions:
\( G_{\text{th}} \): Dark (thermal) generation rate
\( R \): Recombination rate
\( U = R - G_{\text{th}} \): Net recombination rate
\( G_L \): Generation rate due to absorption of light

Uniformly illuminated semiconductor.
Net change in carrier concentration \( p_n \):
\[
\frac{dp_n(t)}{dt} = G_L + G_{\text{th}} - R = G_L - U \quad (2.1)
\]

Assuming \( U \) is proportional to excess carrier concentration (concentration beyond equilibrium).
Equilibrium concentration: \( p_{n0} \). Lifetime: \( \tau_p \)
\[
U = \frac{1}{\tau_p} (p_n(t) - p_{n0}) \quad (2.2)
\]

Combining these gives the differential equation:
\[
\frac{dp_n(t)}{dt} = G_L - \frac{p_n(t) - p_{n0}}{\tau_p} \quad (2.3)
\]

Steady state (\( G_L=U \)):
\[
\frac{dp_n(t)}{dt} = 0
\]
\[
p_n(t)|_{ss} = p_{n0} + \tau_p G_L \equiv p_L \quad (2.4)
\]

Turning light off:
\[
G_L = 0
\]
\[
\frac{dp_n(t)}{dt} = \frac{p_n(t) - p_{n0}}{\tau_p}
\]

Solving the differential equation. Initial condition \( p_n(0)=p_L \):
\[
p_n(t) = p_{n0} + (p_L - p_{n0})e^{-t/\tau_p} \quad (2.5)
\]
**Surface recombination:**

Charge carriers diffuse towards the surface.

Diffusion Flux:

\[ F_p = -D_p \frac{\partial p_n(x, t)}{\partial x} \]  \hspace{1cm} (2.6)

Concentration is given by the ‘transport equation’:

\[ \frac{\partial p_n(x, t)}{\partial t} = -\frac{\partial F_p}{\partial x} + G_L - U \]

\[ \frac{\partial p_n(x, t)}{\partial t} = D_p \frac{\partial^2 p_n(x, t)}{\partial x^2} + G_L - \frac{p_n - p_{n0}}{\tau_p} \]  \hspace{1cm} (2.7)

*Ref: Grove*

**Transport equation:**

\[ \Delta x \frac{\partial K}{\partial t} = F(x) - F(x + \Delta x) \]

\[ \frac{\partial K}{\partial t} = \frac{F(x) - F(x + \Delta x)}{\Delta x} \bigg|_{\Delta x \to 0} = \frac{\partial F}{\partial x} \]
Steady state and boundary conditions.

\[
\frac{\partial p_n(x, t)}{\partial t} = 0
\]

\[
p(x = \infty) = p_L = p_{n0} + \tau_p G_L
\]

\[
D_p \frac{\partial p_n}{\partial x} \bigg|_{x=0} = s_p [p_n(0) - p_{n0}]
\]

Carriers which reach the surface (x=0) recombine there.

\(s_p\) is a proportionality constant, surface recombination rate. Diffusion is proportional to the excess carrier concentration.

Differential equation has the solution:

\[
p_n(x) = p_L - (p_L - p_{n0}) \frac{s_p \tau_p L_p}{1 + s_p \tau_p L_p} e^{-x/L_p}
\]

\[
L_p = \sqrt{D_p \tau_p}
\]

\(L_p\): Diffusion length
LATTICE DISLOCATIONS

Dislocations deviates from the perfect periodicity. **The surface is an obvious example.** Energy states in the band gap becomes recombination centres, “stepping stones”. These increases the probability of recombination, i.e. reduce the lifetime of free charge carriers.

Probability of occupied centre at energy level $E_T$:

$$f(E_T) = \frac{1}{1 + e^{(E_T - E_F)/kT}} \quad (2.10)$$

$k$ is Boltzmanns constant and $T$ is absolute temperature.

Probability of an unoccupied centre: $1 - f$

$$v_{th} = \sqrt{3kT/m} \approx 10^{-5} \text{m/s} \quad \text{Termal velocity}$$

$$\sigma_n \approx 10^{-17} \text{m} \quad \text{capture cross section}$$

Transition rate $a$:

$$r_a = v_{th}\sigma_n n_t(1 - f(E_T)) \quad (2.11)$$

Transition rate $b$:

$$r_b = e_n N_t f(E_T) \quad (2.12)$$

Transition rate $c$:

$$r_c = v_{th}\sigma_p p_t f(E_T) \quad (2.13)$$

Transition rate $d$:

$$r_d = e_p N_t(1 - f(E_T)) \quad (2.14)$$

$k = 1.3805 \times 10^{-23} \text{ J/°K}$

Ref: Grove

e_n and $e_p$ are emission probability (depend on the distance to conduction band and valence band respectively)
Emission probability:

At equilibrium, process a and b have equal rate and $e_n$ and $e_p$ can be found by setting $r_a = r_b$:

$$v_{th}\sigma_n n N_t (1 - f(E_T)) = e_n N_t f(E_T)$$

$$e_n = v_{th}\sigma_n \frac{1 - f(E_T)}{f(E_T)} n = v_{th}\sigma_n e^{(E_T - E_F)/kT} N_c e^{-(E_C - E_F)/kT}$$

$$e_n = v_{th}\sigma_n N_c e^{-(E_C - E_T)/kT}$$ (2.15)

Corresponding result for $e_p$:

$$e_p = v_{th}\sigma_p N_v e^{-(E_T - E_V)/kT}$$ (2.16)

Ref: Grove
ILLUMINATED SEMICONDUCTOR

Uniform light and steady state *
Electrons enter and leave the conduction band at the same rate:
\[ \frac{dn_n}{dt} = G_L - (r_a - r_b) = 0 \]

Holes enter and leave the valence band at the same rate:
\[ \frac{dp_n}{dt} = G_L - (r_c - r_d) = 0 \]

No accumulation of electrons in the recombination centres:
\[ r_a - r_b = r_c - r_d \]

Solve for the occupation factor \( f \), using the expressions for the processes a, b, c, d [(2.11), (2.12), (2.13), (2.14)]
It follows the Fermi-model **

\[ f(E_T) = \frac{n\sigma_n + \sigma_p N_v e^{-(E_T - E_V)/kT}}{\sigma_n \left( n + N_c e^{-(E_C - E_T)/kT} \right) + \sigma_p \left( p + N_v e^{-(E_T - E_V)/kT} \right)} \] \( (2.17) \)

Ref: Grove

* Equilibrium = steady state without external influence

** Cannot use the expression for Fermi energy because this is based on equilibrium But we can use the model.
We have from chapter 1:

\[ n = N_c e^{-(E_C - E_F)/kT} \]
\[ n = n_i e^{(E_F - E_i)/kT} \]
\[ p = N_v e^{-(E_F - E_V)/kT} \]
\[ p = n_i e^{(E_i - E_F)/kT} \]
\[ n_i^2 = N_v N_c e^{-E_G/(kT)} \]

\( E_F \) is valid at equilibrium only, but the model can be used for \( E_T \) and can be written as:

\[ f(E_T) = \frac{n \sigma_n + \sigma_p n_i e^{(E_i - E_T)/kT}}{\sigma_n \left( n + n_i e^{(E_T - E_i)/kT} \right) + \sigma_p \left( p + n_i e^{(E_i - E_T)/kT} \right)} \]  
\[ (2.18) \]

Replacing \( f(E) \) in the individual processes, get the net recombination rate: \( U = r_a - r_b = r_c - r_d \)

\[ U = \frac{\sigma_n \sigma_p v_{th} N_t [p n - n_i^2]}{\sigma_n \left( n + N_c e^{-(E_C - E_T)/kT} \right) + \sigma_p \left( p + N_v e^{-(E_T - E_V)/kT} \right)} \]  
\[ (2.19) \]

Alternatively:

\[ U = \frac{\sigma_n \sigma_p v_{th} N_t [p n - n_i^2]}{\sigma_n \left( n + n_i e^{(E_T - E_i)/kT} \right) + \sigma_p \left( p + n_i e^{(E_i - E_T)/kT} \right)} \]  
\[ (2.20) \]

(Recall that \( p n = n_i^2 \) in equilibrium only)
Special case: $\sigma_p = \sigma_n = \sigma$

\[
U = v_{th} \sigma N_t \frac{p_n - n_i^2}{n + p + 2n_i \cosh \left( \frac{E_T - E_i}{kT} \right)}
\] (2.21)

$p_n - n_i^2$ is the deviation from equilibrium and the driving force for recombination.

Maximum recombination rate when $E_T = E_i$, i.e. $E_T$ has the value in the middle of the energy gap.

\[
\cosh(x) = \frac{e^x + e^{-x}}{2}
\]

Ref: Grove
We have the expression for net recombination: (2.20)

\[ U = \frac{\sigma_n \sigma_p v_{th} N_t [p_n - n_i^2]}{\sigma_n n_n (E_T - E_i/kT) + \sigma_p (p + n_i e^{(E_i - E_T)/kT})} \]

Knowing that at low level injection in N-type semiconductor

\[ n_n \gg p_n \]

\[ n_n \gg n_i e^{[E_T - E_i]/(kT)} \]

we can simplify (2.20) for N-type such that:

\[ U \approx \frac{\sigma_n \sigma_p v_{th} N_t [p_n n_n - n_i^2]}{\sigma_n n_n} = \sigma_p v_{th} N_t [p_n - p_{n0}] \quad (2.22) \]

(Recall that both \( n_i \) and \( p_{n0} \) represent equilibrium).

Using (2.2):

\[ U = \frac{p_n - p_{n0}}{\tau_p} \]

Expression for minority carriers in N-type (holes):

\[ \tau_p = \frac{1}{\sigma_p v_{th} N_t} \quad (2.23) \]

Similar for P-type:

\[ U \approx \sigma_n v_{th} N_t [n_p - n_{p0}] \quad (2.24) \]

and lifetime for minority carriers (electrons):

\[ \tau_n = \frac{1}{\sigma_n v_{th} N_t} \quad (2.25) \]

Given these conditions, the recombination rate independent on the majority carrier concentration. That is, the minority carrier concentration determines the recombination rate.
EXAMPLES ON THE ORIGIN OF RECOMBINATION CENTRES

- Impurities from other groups than III and V in the periodic table gives energy states in the band gap.
- Surface states due to the lattice non-regularity.
  Approximately atoms/area ($\sim 10^{15}$ cm$^{-2}$). Lower density on oxidized surface ($\sim 10^{11}$ cm$^{-2}$)

Ref: Grove
THE DIODE AS PHOTO SENSOR
CURRENT - VOLTAGE CHARACTERISTICS

There are two sources of reverse biased current:

- **Generation current**
  Carriers generated in the depletion region. The field sweeps carriers out of the depletion region, electrons to the n-region and holes to the p-region.

- **Diffusion current**
  Carriers generated outside the depletion region, but within a diffusion length from the depletion region. Minority carriers diffuse to the edge of the depletion region and swept across by the field.

Carriers that are swept across becomes majority carriers.

There are (almost) zero free carriers in the depletion region and therefore low probability for recombination there.
GENERATION CURRENT:

Carriers are quickly driven out of the depletion region.
- $p_n \ll n_i$
- No recombination
- $V_R >> kT/q$

Using (2.20), recombination = generation.

Generation rate is therefore ($p, n << n_i$):

$$U = \frac{-\sigma_n \sigma_p v_{th} N_t n_i^2}{\sigma_n n_i e (E_T - E_i)/kT + \sigma_p n_i e (E_i - E_T)/kT} \equiv -\frac{n_i}{2\tau_0} \quad (2.26)$$

$$\tau_0 \equiv \frac{\sigma_n e (E_T - E_i)/kT + \sigma_p e (E_i - E_T)/kT}{2\sigma_n \sigma_p v_{th} N_t}$$

For $\sigma_p = \sigma_n = \sigma$:

$$U = -\frac{\sigma v_{th} N_t n_i}{2 \cosh\left(\frac{E_i - E_T}{kT}\right)} \quad (2.27)$$

Generation current (dark current):

$$I_{gen} = q|U|W A_j \quad (2.28)$$

$$I_{gen} = \frac{1}{2} q\frac{n_i}{\tau_0} W A_j \quad (2.29)$$

$A_j$ is the cross section of the depletion region

We see that “step stones” close to $E_i$ gives the largest contribution to the generation current.

Ref: Grove
DIFFUSION CURRENT:

We apply the differential equation (2.7) for surface recombination on minority carriers.

- The concentration at the edge is 0 due to the field which sweeps the carriers across the junction.
- Steady state, no variation with time.

\[
D_p \frac{\partial^2 n_p}{\partial x^2} + G_L - \frac{n_p - n_{p0}}{\tau_n} = 0
\]

Far from the depletion region (2.4):

\[
n_p(\infty) = n_{p0} + \tau_n G_L
\]

At the edge of the depletion region:

\[
n_p(0) = 0
\]

Solution:

\[
n_p(x) = (n_{p0} + \tau_n G_L)(1 - e^{-x/L_n}) \quad (2.30)
\]

\[L_n= \text{diffusion length for the electron in the p-region.}\]

Diffusion current (differentiate):

\[
I_{\text{diff}, n} = -q \left( -D_n \frac{dn_p}{dx} \right)_{x=0} A_j = qD_n \frac{(n_{p0} + \tau_n G_L)}{L_n} A_j
\]

(2.31)

Corresponding for holes in n-region:

\[
I_{\text{diff}, p} = qD_p \frac{(p_{n0} + \tau_p G_L)}{L_p} A_j
\]

(2.32)

No injection (no light):

\[
I_{\text{diff}, n} = qD_n \frac{n_{p0}}{L_n} A_j = qD_n \frac{n_i^2}{N_A L_n} A_j
\]

(2.33)

\[
I_{\text{diff}, p} = qD_p \frac{p_{n0}}{L_p} A_j = qD_p \frac{n_i^2}{N_D L_p} A_j
\]
REVERSE CURRENT VS. TEMPERATURE

$V_R = 1V$

Circles: Generation current  
Squares: Diffusion current  
Solid line: Temperature dependence of $n_i$  
Dotted line: Temperature dependence of $n_i^2$

Generation current is proportional to $n_i$,  
Diffusion current is proportional to $n_i^2$

- Low temperature:  
The generation current dominates  
- High temperature:  
The diffusion current dominates.

Ref: Grove
**Photo Diode**

**Light intensity**

Illuminance (light flux) has the unit [Lux]=[Lumen/m²]
vs.
Irradiance (power) has the unit [W/m²]

<table>
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<th>Wave length (nm)</th>
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<th>Wave length (nm)</th>
<th>Photopic conversion</th>
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<td>W/Im</td>
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**Sensor efficiency**

- Photons with energy larger than the bandgap can generate e-h pair.
- Some of the photons are reflected at the surface and do not contribute.
- Some of the photons are reflected at the silicon oxide surface or Passivation surface and do not contribute.
- Some of the generated charge carriers that are collected recombine fast, and are therefore lost.
Photo Diode

Reflection factor:

\[ R = \frac{\text{Reflected intensity}}{\text{Incoming intensity}} = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad (2.34) \]

where \( n_1 \) and \( n_2 \) is the refractive index to the interfacing materials.

Example: SiO\(_2\) (n=1.45) and Si (n=4) result in R=22%

Efficient light = incoming light \( \times (1-R) \)
Fill Factor

Ratio photosensitive area to total pixel area

\[
FF = \left( \frac{A_{PD}}{A_{\text{pixel}}} \right) \times 100\%
\]
Photo Diode

Photon energy

Plank and black body radiation:

Atoms in a heated body behaves like harmonic oscillators, each oscillator can absorb or emit energy, in an amount proportional to its frequency:

\[ E = \hbar \nu \]  

(2.35)

where \( \nu \) is the frequency, \( \hbar \) is Planck's constant: \( 6.626 \times 10^{-34} \) Js

The energy is quantized:

\[ E_n = n \hbar \nu \]

where \( n \) is a positive integer: Number of photons.

Photon wavelength \( \lambda = \frac{c}{\nu} \)

Visible light: \( 450nm-700nm \)

\[ E(\nu) = \frac{8\pi \hbar c}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \]

Ref. Alonso-Finn
Absorption

The flux of photons, with energy higher than the band gap, decreases as the photons are absorbed and e-h pair are generated. Thus, the photon flux, \( \Phi(x) \), decreases with the penetration depth.

\[
d\Phi = \alpha \Phi dx
\]

\[
\Phi_{ph}(x) = \Phi_0 e^{-\alpha x}
\]

Absorption coefficient \( \alpha \) depends on the energy, i.e. is larger for shorter wave lengths.

**Photons in the blue range of the spectrum**
- Short wave length - high energy
- High probability of e-h pair generation.
- Easily absorbed
- Short penetration depth.

**Photons in the red range of the spectrum**
- Long wave length - low energy
- Low probability of e-h pair generation.
- Passes more material before absorption take place.
- Long penetration depth.
Foveon principle

A Foveon X3 direct image sensor features three separate layers of pixels embedded in silicon. Since silicon absorbs different colors of light at different depths, each layer captures a different color. As a result, only Foveon X3 direct image sensors capture red, green, and blue light at every pixel location.

In conventional systems, color filters are applied to a single layer of pixels in a tiled mosaic pattern. The filters let only one wavelength of light—red, green, or blue—pass through to any given pixel, allowing it to record only one color. As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

www.foveon.com
Photo Diode

Foveon (cont.)
Response limits

The responsivity has a lower limit.

The band gap must be exceeded (excitation of electrons).
Lower limit is given by the wave length. Apply (2.35):

\[ h \nu \geq E_g \quad \frac{hc}{\lambda} \geq E_g \]

\[ E_{g, Si} = 1,11 \text{ eV} \quad 1 \text{ eV} = 1,602 \cdot 10^{-19} \text{ J} \]

\[ \lambda_{\text{max}} = \frac{hc}{E_g} = \frac{6,626 \cdot 10^{-34} \text{ [Js]} \cdot 10^8 \text{ [m/s]}}{1,11 \cdot 1,602 \cdot 10^{-19} \text{ [J]}} = 1,06 \mu \text{m} \]

(2.37)

The Responsivity has an upper limit given by the penetration depth.

Recombination rate is high at the surface, where short wave photons are absorbed, due to high density of energy levels in the band gap at the surface. (typically \( N_{ts}=10^{11} \text{ s}_o \sim 150 \) results in \( t_s = 1/s_o \sim 0.7 \mu \text{s/ \mu m} \))
Photo Diode

Sensitivity vs. wave length

![Graph showing sensitivity vs. wavelength for human eye and silicon. The graph plots wavelength (nm) on the x-axis and relative response on the y-axis. The peaks for human eye and silicon are indicated.]
Quantum Efficiency (QE) 

One definition [ref. Sze]:
Number of generated electron-hole pair per photon hitting the sensor (pixel).

\[
\eta = \frac{I_{ph}/q}{P_{opt}/h\nu} \quad \left[ \frac{\text{elektrons per time unit}}{\text{photons per time unit}} \right]
\] (2.38)

Common definition of QE: Number of collected electrons per photon.

Responsivity: The ratio photo current to optical input power [ref. Sze]

\[
R = \frac{I_{ph}}{P_{opt}} = \frac{\eta q}{h\nu} = \frac{\eta \lambda}{1.24 \times 10^6} \quad \left[ \frac{A}{W} \right]
\] (2.39)

\[
\left( \frac{q}{h\nu} = \frac{q\lambda}{hc} = \frac{1.602 \times 10^{-19}}{6.626 \times 10^{-34}} \frac{\lambda}{3 \times 10^8} = \frac{\lambda}{1.24 \times 10^{-6}} \right)
\]

Responsivity is proportional to the wave length.
**Conversion gain**

\[
C = \frac{dQ}{dV} \\
V = \frac{q}{C} \cdot \text{number of electrons}
\]

Voltage per collected electrons is defined as “Conversion Gain”:

\[
CG = \frac{q}{C} \left[ \frac{\mu V}{e} \right] 
\]  

(2.40)

From optical power to voltage:

\[
V = CG \cdot QE \cdot t \cdot \frac{P_{\text{opt}}}{hv} 
\]  

(2.41)

**Full Well**

Maximum number of electrons that can be stored in the pixel:

\[
N_{\text{sat}} = \frac{1}{q} \int_{V_{\text{Reset}}}^{V_{\text{max}}} C_{PD}(V)dV
\]  

(2.42)
Pinned Photo diode

n-region buried in a p-substrate.
Reduces the effect of surface recombination
  • Improved response in blue range
  • Reduced dark current.

Pinned voltage = the voltage that results in a complete depletion of the n-region.

Pinning voltage depends on doping concentration and implantation range.

Added process step to standard CMOS process.
Patented: Eastman-Kodak/Motorola (ImageMOST™).
Example 1 - photo diode

Incoming light 550nm (green). Exposure time: 10 ms. External reverse bias $V_R = 2V$.

- Dark current and signal from a non illuminated sensor?
- Responsivity?
- Required intensity to achieve a signal of 1 V?
**Physical data**

<table>
<thead>
<tr>
<th>$N_A$</th>
<th>$10^{16}$ cm$^{-3}$</th>
<th>$\sigma_p, \sigma_n$</th>
<th>$10^{-15}$ cm$^2 = 10^{-19}$ m$^2$</th>
<th>$k$</th>
<th>$1.38 \times 10^{-23}$ J / °K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_D$</td>
<td>$10^{18}$ cm$^{-3}$</td>
<td>$\mu_e$</td>
<td>0.135 m$^2$/Vs</td>
<td>$q$</td>
<td>$1.602 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>$N_t$</td>
<td>$3 \times 10^{11}$ cm$^{-3}$</td>
<td>$\mu_p$</td>
<td>0.048 m$^2$/Vs</td>
<td>$\varepsilon_0$</td>
<td>$8.85 \times 10^{-12}$ C$^2$/Nm$^2$</td>
</tr>
<tr>
<td>$E_t$</td>
<td>$E_i$</td>
<td></td>
<td></td>
<td>$\varepsilon_{r, Si}$</td>
<td>11.7</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>0.3 (reflection coefficient)</td>
<td></td>
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</table>
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