



FORMATION : INTRODUCTION A LA SIMULATION DE CELLULES PHOTOVOLTAÏQUES

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FORMATION : INTRODUCTION A LA SIMULATION DE CELLULES PHOTOVOLTAÏQUES

A. Darga,

Group of Electrical Engineering of Paris (GeePs)

Plan

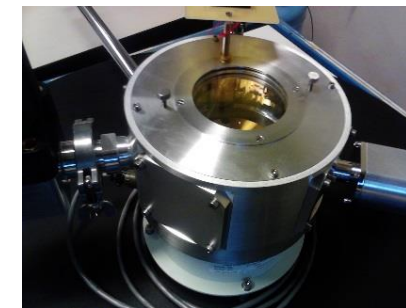
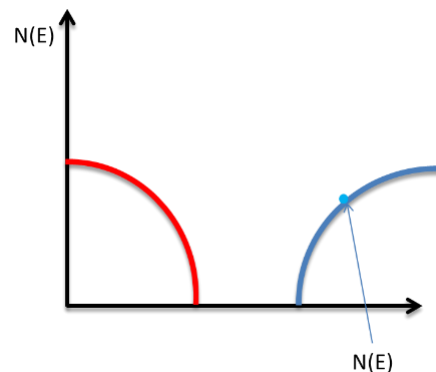
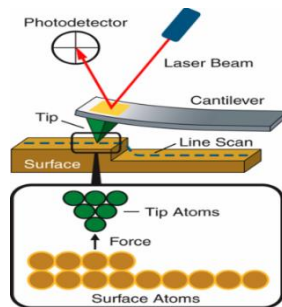
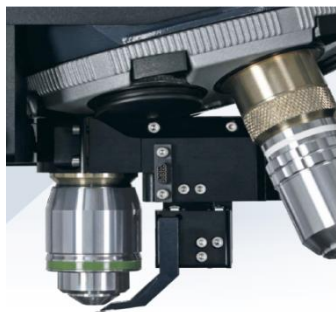
- Introduction
 - Objectifs de la formation
 - Organisation
- Séance 1
 - SCAPS et quelques rappels
 - Début projets
 - ZnO/CdS/CIGSe
 - HIT
 - PIN
 - Homojonction
- Séance 2 : suite projets
- Conclusion

GeePs (Head : Prof. C. Marchand)
Semiconductor Modelling and Characterization
Head : Prof. J. P. Kleider

Materials-Interfaces-Devices
Nano / Micro properties

Characterization
Modelling/Simulation

Materials-Interfaces-Devices
Macroscopic properties



Co-localized characterization
confocale Microscopy:

- ✓ μ PL, μ Raman,
- ✓ AFM, C-AFM
- ✓ Resiscope (CP-AFM)

Softwares :

[DeOST : electronic transport properties:](#)

AFORS-HET (1D), SCAPS (1D)

[TCAD : Silvaco TCAD, Cogenda TCAD](#)

Traps states Spectroscopy

- ✓ [Photocurrent \(AC, DC, transient\)](#)
- ✓ Capacitance (AC, transient)

....

Introduction : Objectifs de la formation

A la fin de la formation vous devriez être capable d'utiliser SCAPS :

- Pour **construire un modèle simplifié** d'une **cellule PV**
- Pour simuler les **caractéristiques électriques** d'une **cellule PV**
 - **Quelque soit la technologie**: matériau (Silicium, III-V...) ou filière (couches minces, cristallin)
 - **Quelque soit le type de jonction active** :
 - Homo-jonction,
 - hétérojonction
 - PIN
 -
- Pour décrire le fonctionnement interne d'une cellule PV
 - Interpréter, expliquer les résultats de la simulation

Introduction : Organisation

Formation par la pratique

→ Session 1 (1 h 20) :

- rappels

- découverte de SCAPS

- début projets

→ Session 2 (1h 20) : Suite projets

SESSION 1 : INTRODUCTION À SCAPS

A. DARGA

Session 1: SCAPS

SCAPS → Solar Cell Capacitance Simulator



→ Créateurs

Prof. Marc Burgelman,

Alex Niemegeers, Koen Decock, Johan Verschraegen, Stefaan Degrave

→ Gratuit avec support!

→ Pour obtenir → envoyer un message de demande au Prof. Marc Burgelman

→ Adresse et informations disponible ici : <http://scaps.elis.ugent.be/>

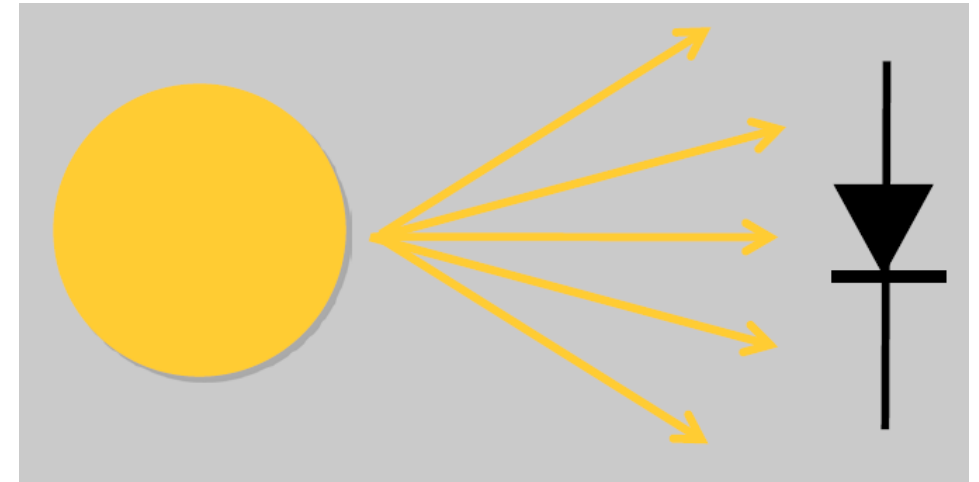
Session 1: SCAPS

- Qu'est-ce qu'une cellule photovoltaïque?

Diode

- Jonction PN :
 - Homojonction
 - Hétérojonction
- Jonction PIN
- Jonction Schottky ou Metal/Semiconducteur
- Jonction Métal/Semiconducteur/Métal

Diode éclairée

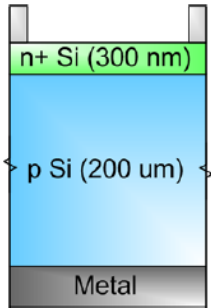


- Pour comprendre comment une cellule PV fonctionne il faut
 - Comprendre comment fonctionne la DIODE : **Caractéristiques à l'obscurité**
 - Comprendre comment la **lumière est absorbée dans un semiconducteur** : sans la diode
 - Comprendre ce qui se passe quand on met les **2 ensemble**

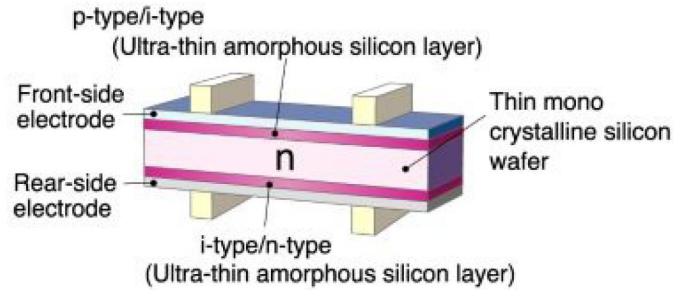
Session 1 : Rappels

■ Qu'est-ce qu'une cellule photovoltaïque?

Homojonction PN



Hétérojonction PN



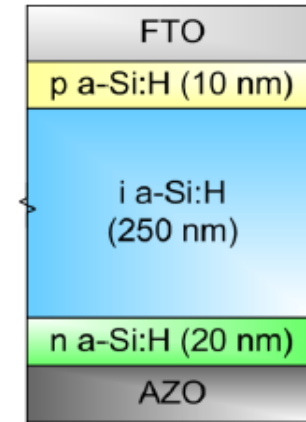
Silicium cristallin

Hétérojonction PN

| |
|---|
| ZnO-Al (n^+): 0,5 μm |
| ZnO-i (intrinsèque) : 0,1 μm |
| CdS (n type) : 0,02-0,07 μm |
| $\text{Cu}(\text{In}_{1-x}\text{Ga}_x)(\text{Se}_{1-y}\text{S}_y)_2$ (p type): 1-2,3 μm |
| MoSe_2 ou MoS_2 : 0,4-0,7 μm |
| Mo: 0,2-0,5 μm |
| Glass : 1-6 mm |

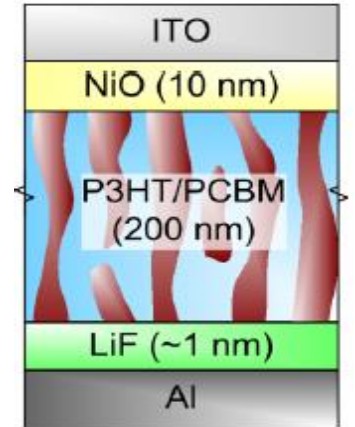
Couches minces
CIGSe, CdTe

PIN



Couches minces
a-Si, Perovskites

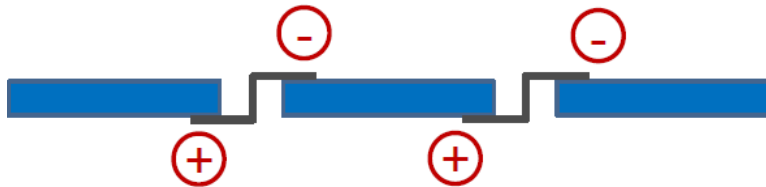
MIM



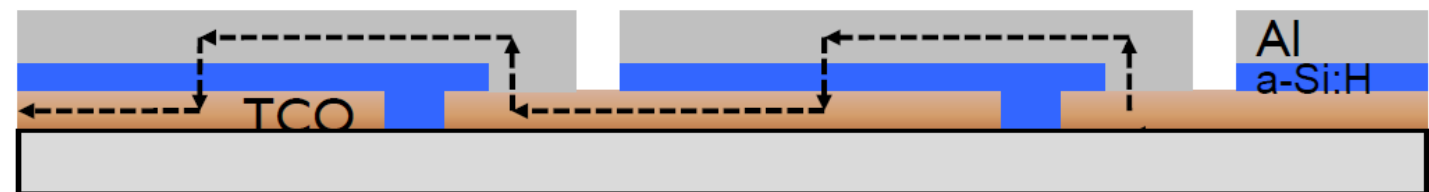
Couches minces
organique

Connection

Silicium cristallin



Connection Couches minces



Session 1 : SCAPS

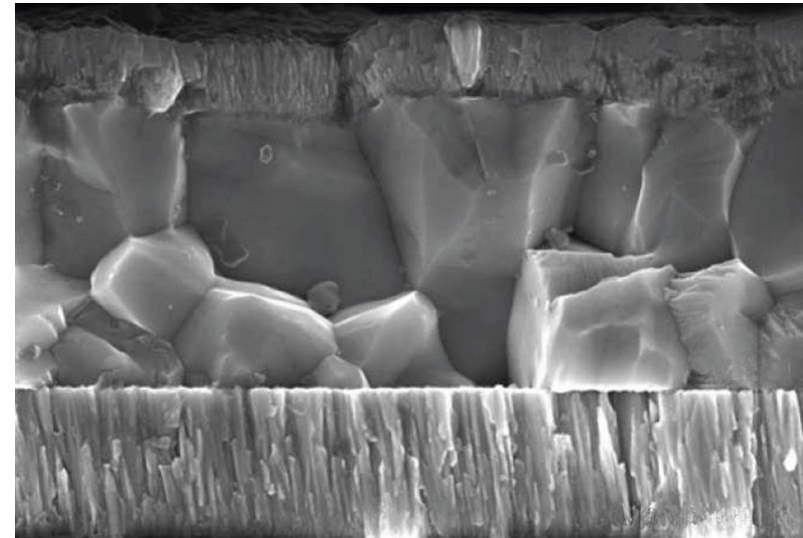
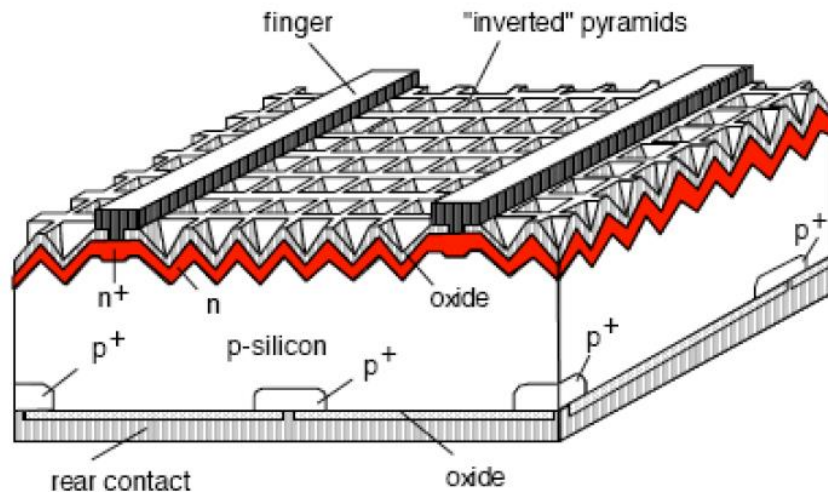
SCAPS → Solar Cell Capacitance Simulator

SCAPS ?

Logiciel de simulation 1D de cellule PV.

Ne traite pas les effets 2D comme

- Conduction latérale : Joint de grain, Taille des contacts...
- Texturation avancées: (possibilité de rentrer les données!)



Session 1: SCAPS

Entrées (interface Graphique):

- Structure de la cellule PV
 - Composition, dimensions, contacts, dopage
- Propriétés des couches:
 - constante diélectrique, paramètres des bandes(band interdite, affinité électronique...) mobilité des porteurs libres, paramètres de recombinaison, coefficient d'absorption, etc...
- Conditions de fonctionnement:
 - température, tension de polarisation, spectre de l'éclairement...

Méthode des differences Finies :

Résolution des équations de Poisson, continuité et transport

Sous diverses conditions:

Équilibre, DC, AC, éclairement

Recombinaisons : Radiative, Auger, Shockley-Read-Hall

....

Caractéristiques locales interne de la cellule : diagramme des bandes, taux de génération, taux de recombinaison, concentrations et densité de courant des porteurs libres...

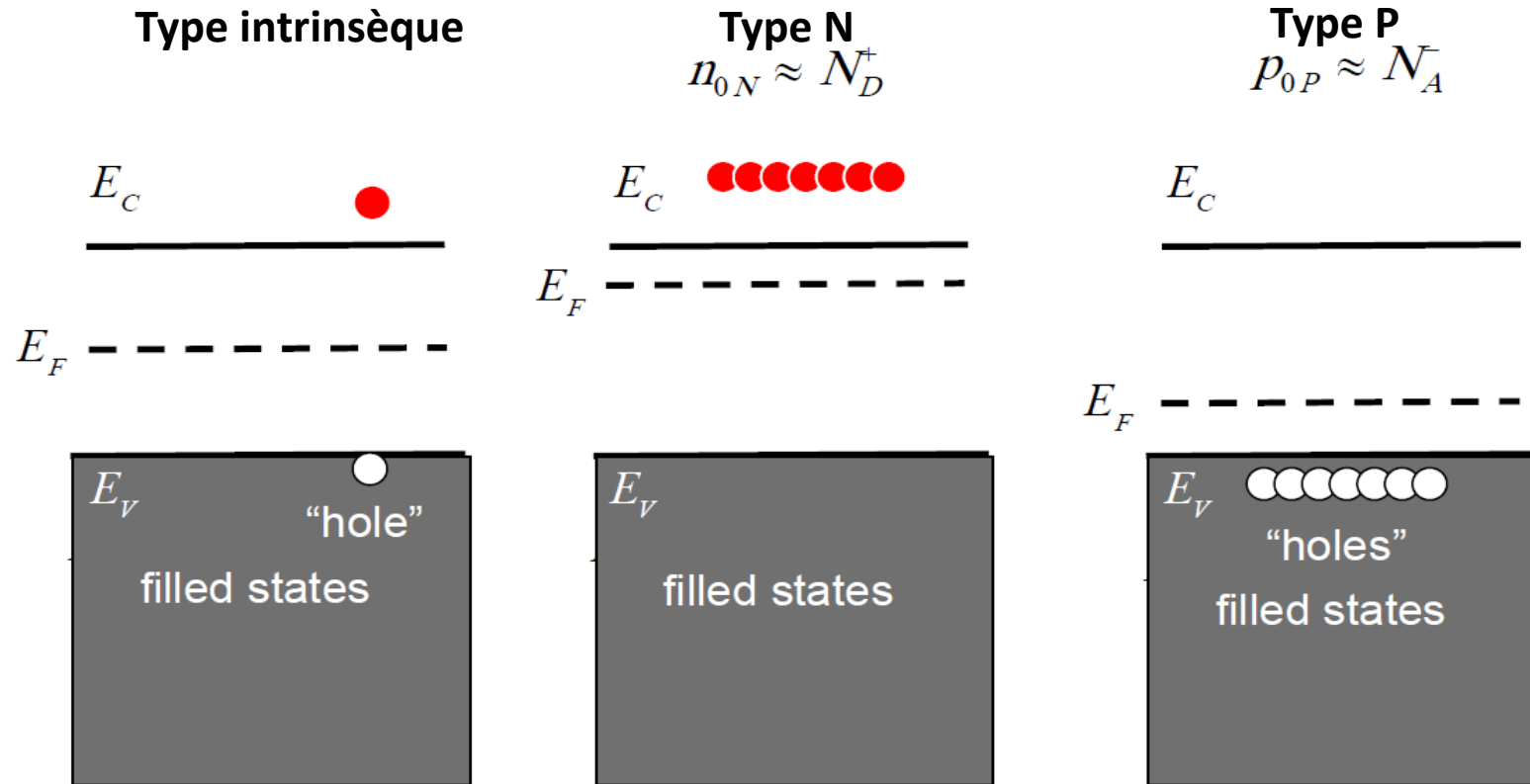
Simulation d'expérience: $I(V,T, \text{flux})$, $C-G(F,V,T)$, réponse-spectrale...

| layer 1 | |
|--|--------------------------------------|
| thickness (μm) | 2.000 |
| uniform pure A (y=0) | |
| The layer is pure A: y = 0, uniform | |
| Semiconductor Property P of the pure material | |
| pure A (y = 0) | |
| bandgap (eV) | 1.200 |
| electron affinity (eV) | 4.500 |
| dielectric permittivity (relative) | 10.000 |
| CB effective density of states (1/cm³) | 1.000E+19 |
| VB effective density of states (1/cm³) | 1.000E+19 |
| electron thermal velocity (cm/s) | 1.000E+7 |
| hole thermal velocity (cm/s) | 1.000E+7 |
| electron mobility (cm²/Vs) | 5.000E+1 |
| hole mobility (cm²/Vs) | 5.000E+1 |
| <input type="checkbox"/> Allow Tunneling | effective mass of electron: 1.000E+0 |
| | effective mass of holes: 1.000E+0 |
| no ND grading (uniform) | |
| shallow uniform donor density ND (1/cm³) | 1.000E+15 |
| no NA grading (uniform) | |
| shallow uniform acceptor density NA (1/cm³) | 1.000E+15 |
| Absorption model | |
| alpha (y=0) | |
| <input type="checkbox"/> from model <input type="checkbox"/> from file | |
| absorption constant A (1/cm eV^(1/2)) | 1.000E+5 |
| absorption constant B (eV^(1/2)/cm) | 0.000E+0 |
| show | save |
| absorption file for y = 0 | |

Session 1 : SCAPS et Niveau de Fermi

■ Semiconducteurs: Dopage

→ Dans SCAPS les dopants sont complètement ionisés : quelque soit la température

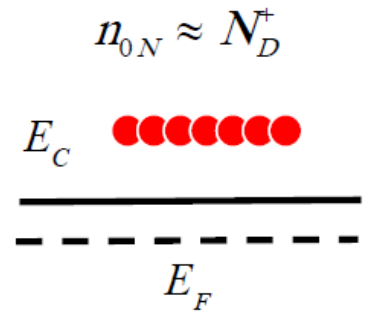


The screenshot shows the SCAPS 3.3.01 Layer Properties Panel for Layer 1. The panel is divided into several sections:

- General:** thickness (μm) is 2.000. The layer is pure A: y = 0, uniform. Semiconductor Property P of the pure material is pure A (y = 0).
- Physical Properties:** bandgap (eV) is 1.200, electron affinity (eV) is 4.500, dielectric permittivity (relative) is 10.000, CB effective density of states (1/cm³) is 1.000E+19, VB effective density of states (1/cm³) is 1.000E+19, electron thermal velocity (cm/s) is 1.000E+7, hole thermal velocity (cm/s) is 1.000E+7, electron mobility (cm²/Vs) is 5.000E+1, and hole mobility (cm²/Vs) is 5.000E+1.
- Grading:** no ND grading (uniform) and no NA grading (uniform) are selected. The shallow uniform donor density ND (1/cm³) is 1.000E+15 and the shallow uniform acceptor density NA (1/cm³) is 1.000E+15.
- Absorption model:** alpha (y=0) is set to "from model". The absorption constant A (1/cm eV^{1/2}) is 1.000E+5 and the absorption constant B (eV^{1/2}/cm) is 0.000E+0.

Session 1 : SCAPS et Niveau de Fermi

- Dans SCAPS → Maxwell-Boltzman
- Ne gère pas les semiconducteurs dégénérés

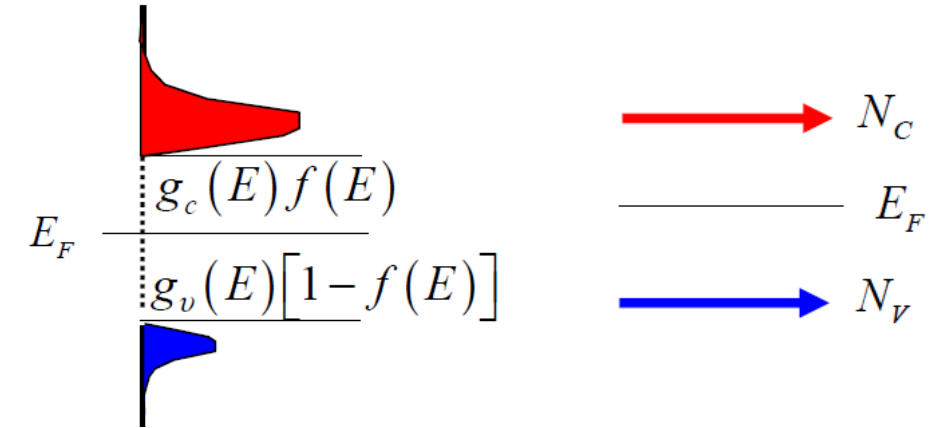
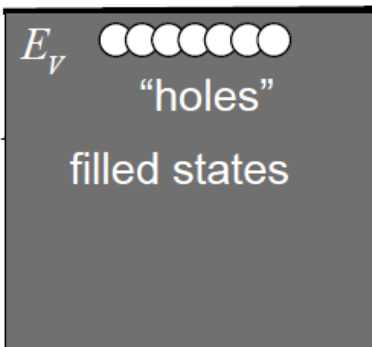
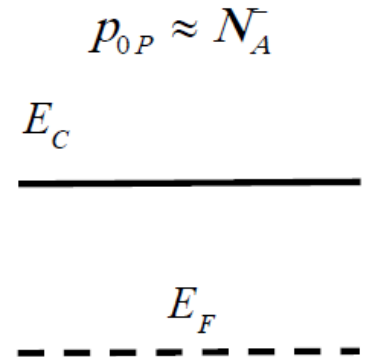
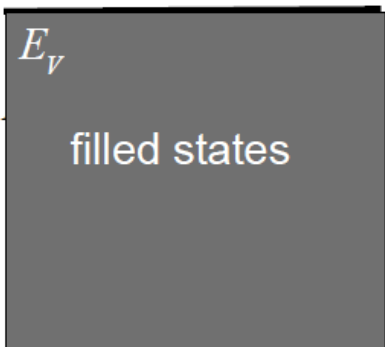


$$f_0(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

$$E = E_F \rightarrow f_0(E) = \frac{1}{2}$$

$$E \ll E_F \rightarrow f_0(E) = 1$$

$$E \gg E_F \rightarrow f_0(E) = 0$$



$$f(E) = \frac{1}{1 + \exp[(E-E_F)/kT]} \cong \begin{cases} \text{Fermi-Dirac} \\ \text{Maxwell-Boltzmann} \end{cases}$$

$$n = N_C \exp\left[-\frac{E_C - E_F}{kT}\right] \text{ with } N_C = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \text{ (cm}^{-3}\text{)}$$

$$p = N_V \exp\left[-\frac{E_F - E_V}{kT}\right] \text{ with } N_V = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \text{ (cm}^{-3}\text{)}$$

Session 1 : SCAPS et propriétés de transport électronique

Le transport des charges dans un semi-conducteur est, habituellement, caractérisé par deux paramètres, la mobilité $\mu_n(\mu_p)$ et la durée de vie $\tau_n(\tau_p)$ des électrons (trous) : **Longueur de diffusion**

$$L_n = \sqrt{D_n \tau_n} = \left(\frac{k_B T}{q} \right)^{\frac{1}{2}} (\mu_n \tau_n)^{\frac{1}{2}}$$

$$D_n = \left(\frac{k_B T}{q} \right) \mu_n$$

Durée de vie $\tau_n(\tau_p)$ des électrons (trous) \rightarrow centres de recombinaisons ou défauts

Session 1 : SCAPS et propriétés de transport électronique

- 3 types de mécanismes de recombinaisons
 - Radiative
 - Auger
 - Indirect via défaut ou centre recombinant

Recombination model

| Band to band recombination | |
|--|----------|
| Radiative recombination coefficient (cm ³ /s) | 0.000E+0 |
| Auger electron capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Auger hole capture coefficient (cm ⁶ /s) | 0.000E+0 |

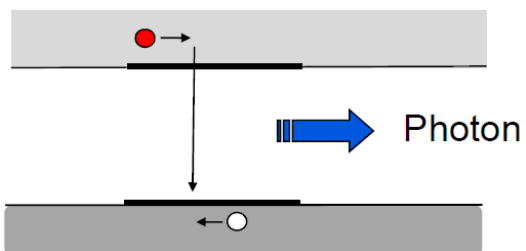
Recombination at defects: Summary

Add a Defect 1

Session 1 : SCAPS et propriétés de transport électronique

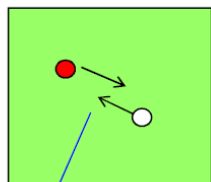
Recombinaison : Direct ou bande à bande

In energy space ...

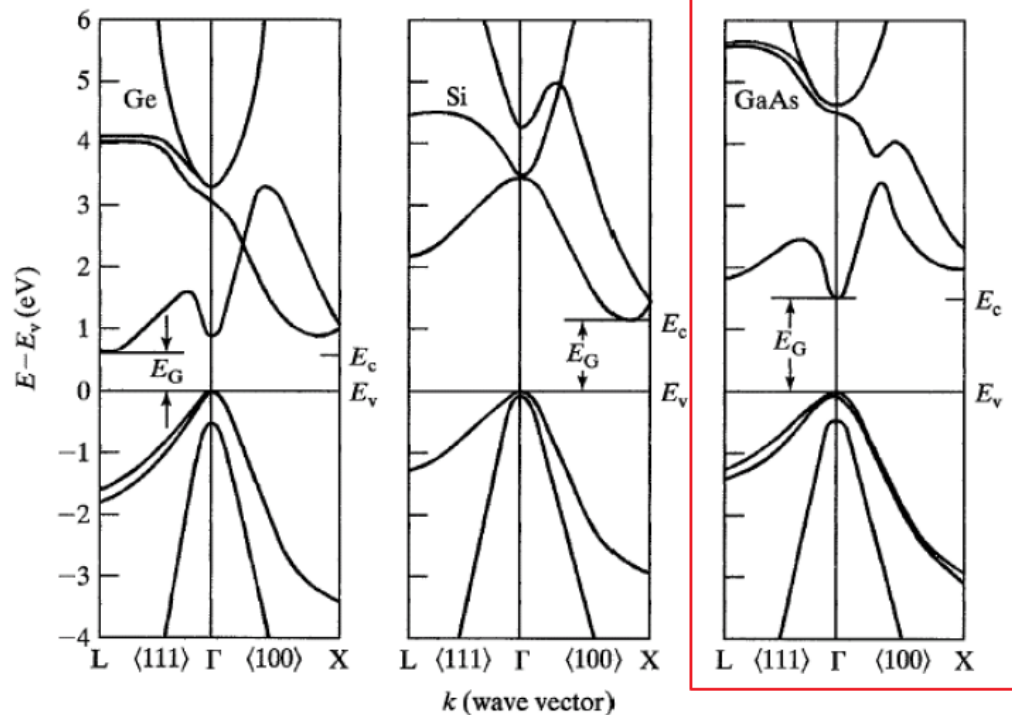


Direct transition –
direct gap material

In real space ...



e and h must
have same wavelength



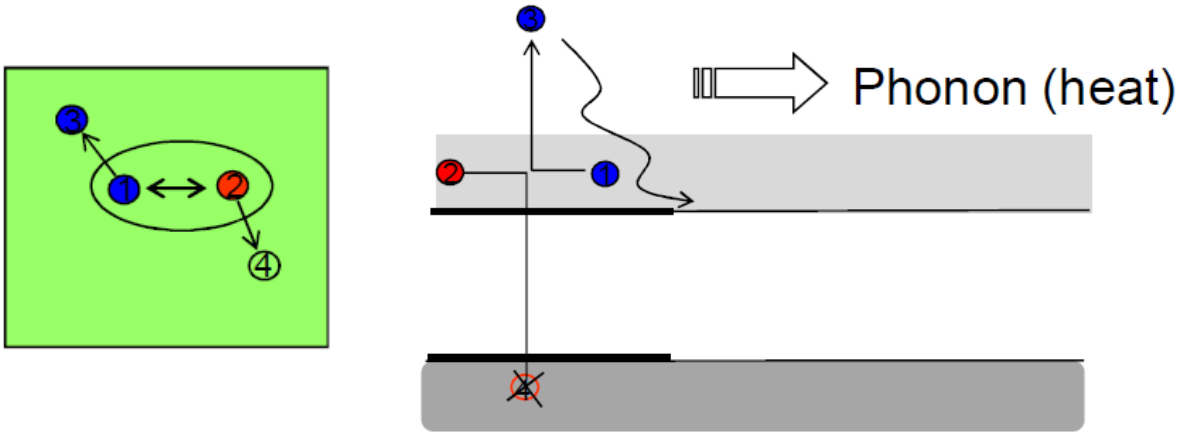
| Recombination model | |
|--|----------|
| Band to band recombination | |
| Radiative recombination coefficient (cm ³ /s) | 0.000E+0 |
| Auger electron capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Auger hole capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Recombination at defects: Summary | |

Très peu probable

Plus probable dans les matériau à gap direct

Session 1 : SCAPS et propriétés de transport électronique

Recombinaison : Auger



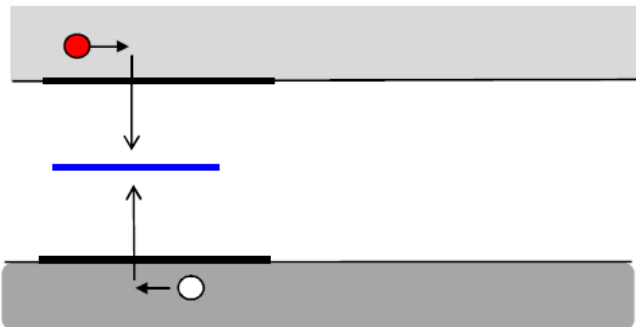
| Recombination model | |
|--|----------|
| Band to band recombination | |
| Radiative recombination coefficient (cm ³ /s) | 0.000E+0 |
| Auger electron capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Auger hole capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Recombination at defects: Summary | |

Il faut une grande quantité de porteurs libres :

- Éclairement intense
- Fort dopage

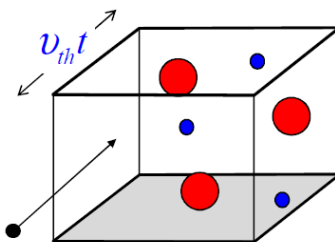
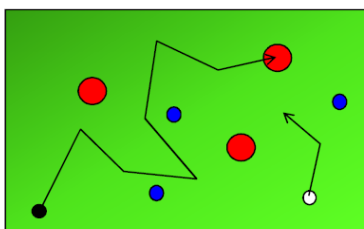
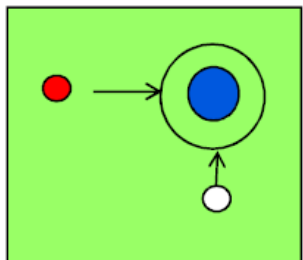
Session 1 : SCAPS et propriétés de transport électronique

Recombinaison indirect : défaut



$$R = \frac{np - n_i^2}{\left(\frac{1}{c_p N_T} \right) (n + n_1) + \left(\frac{1}{c_n N_T} \right) (p + p_1)}$$

$\tau_n \rightarrow \frac{1}{c_p N_T}$
 $\tau_p \rightarrow \frac{1}{c_n N_T}$



$$\frac{dn}{dt} = -n \times \left[\frac{\text{Volume} \times p_T \times \text{RelArea}}{\text{TotalArea} \times t} \right]$$

$$\frac{dn}{dt} = -n \times \left[\frac{A \times v_{th} \times p_T \times \sigma_n}{A \times t} \right]$$

$$\equiv -c_n p_T n \quad c_n \equiv \sigma_n v_{th}$$

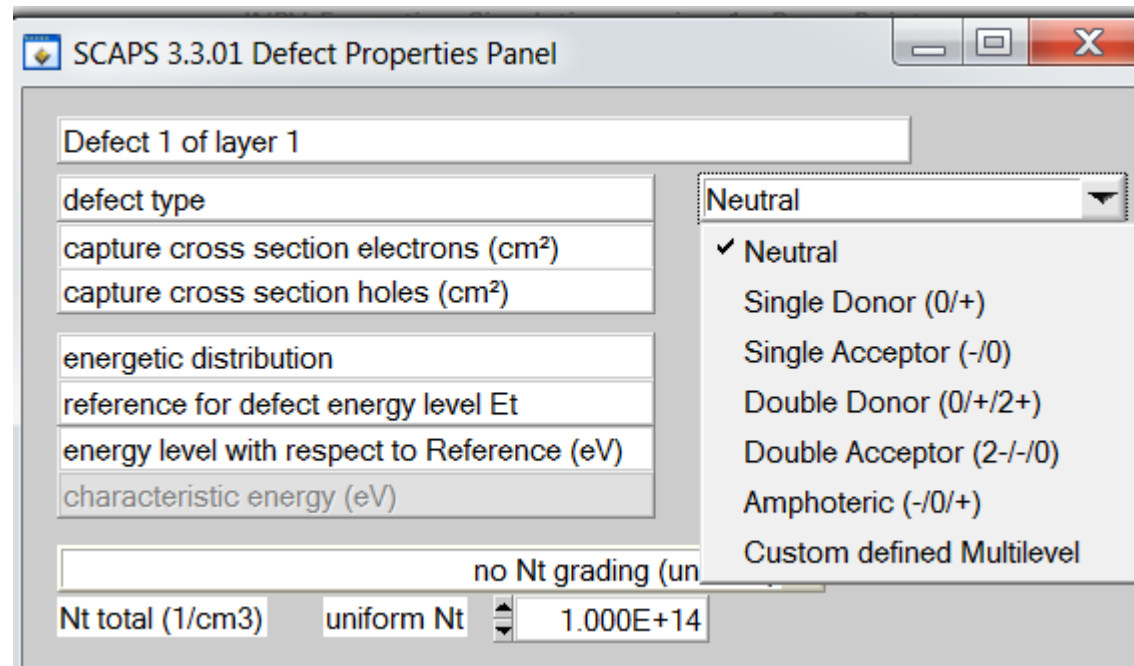
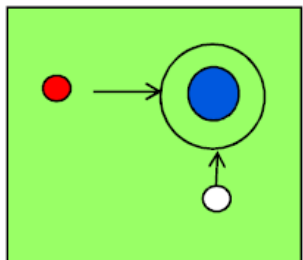
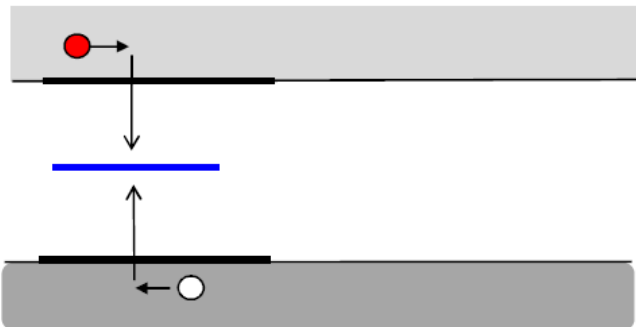
$$\frac{1}{2} m^* v_{th}^2 = \frac{3}{2} kT$$

$$v_{th} \approx 10^7 \frac{cm}{s}$$

| | |
|---|------------------------|
| Defect 1 of layer 1 | |
| defect type | Neutral |
| capture cross section electrons (cm²) | 1.000E-15 |
| capture cross section holes (cm²) | 1.000E-15 |
| energetic distribution | Single |
| reference for defect energy level Et | Above EV (SCAPS < 2.7) |
| energy level with respect to Reference (eV) | 0.600 |
| characteristic energy (eV) | 0.100 |
| no Nt grading (uniform) | |
| Nt total (1/cm3) | uniform Nt 1.000E+14 |

Session 1 : SCAPS et propriétés de transport électronique

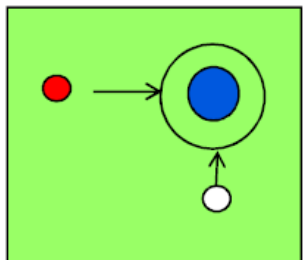
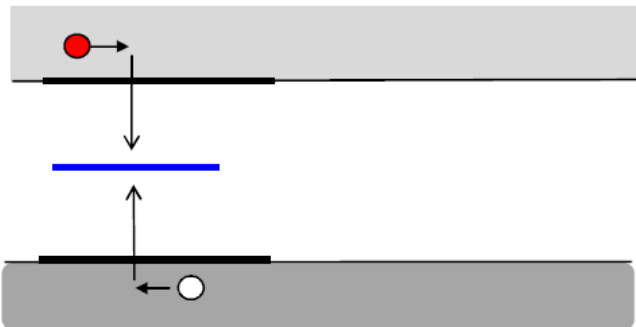
Recombinaison indirect : défaut



Neutre → lifetime killer : pas d'électrostatique

Session 1 : SCAPS et propriétés de transport électronique

Recombinaison indirect : défaut



| Defect 1 of layer 1 | |
|--|----------------------|
| defect type | Neutral |
| capture cross section electrons (cm ²) | 1.000E-15 |
| capture cross section holes (cm ²) | 1.000E-15 |
| energetic distribution | Single |
| reference for defect energy level Et | |
| energy level with respect to Reference (eV) | |
| characteristic energy (eV) | |
| no Nt grading (uniform Nt) | |
| Nt total (1/cm ³) | uniform Nt 1.000E+14 |

Single

✓ Single

Uniform

Gauß

CB tail

VB tail

Distributions

Session 1 : SCAPS et propriétés de transport électronique

■ Semiconducteur: Paramètres importants

$$n_i = \sqrt{N_C N_V} \exp\left(\frac{-E_G}{2kT}\right) \text{ cm}^{-3}$$

Effective density of states:

$$N_C = 2 \left[\frac{m_n^* kT}{2\pi\hbar^2} \right]^{\frac{3}{2}}, \quad N_V = 2 \left[\frac{m_p^* kT}{2\pi\hbar^2} \right]^{\frac{3}{2}} \text{ cm}^{-3}$$

Diffusivity

$$D_n = \left(\frac{kT}{q} \right) \mu_n, \quad D_p = \left(\frac{kT}{q} \right) \mu_p \text{ cm}^2/\text{s}$$

Minority carrier diffusion length:

$$L_n = \sqrt{D_n \tau_n}, \quad L_p = \sqrt{D_p \tau_p} \text{ (length units)}$$

Session1 : SCAPS et jonctions

- Diodes : homojonction : équilibre = résolution équation de Poisson

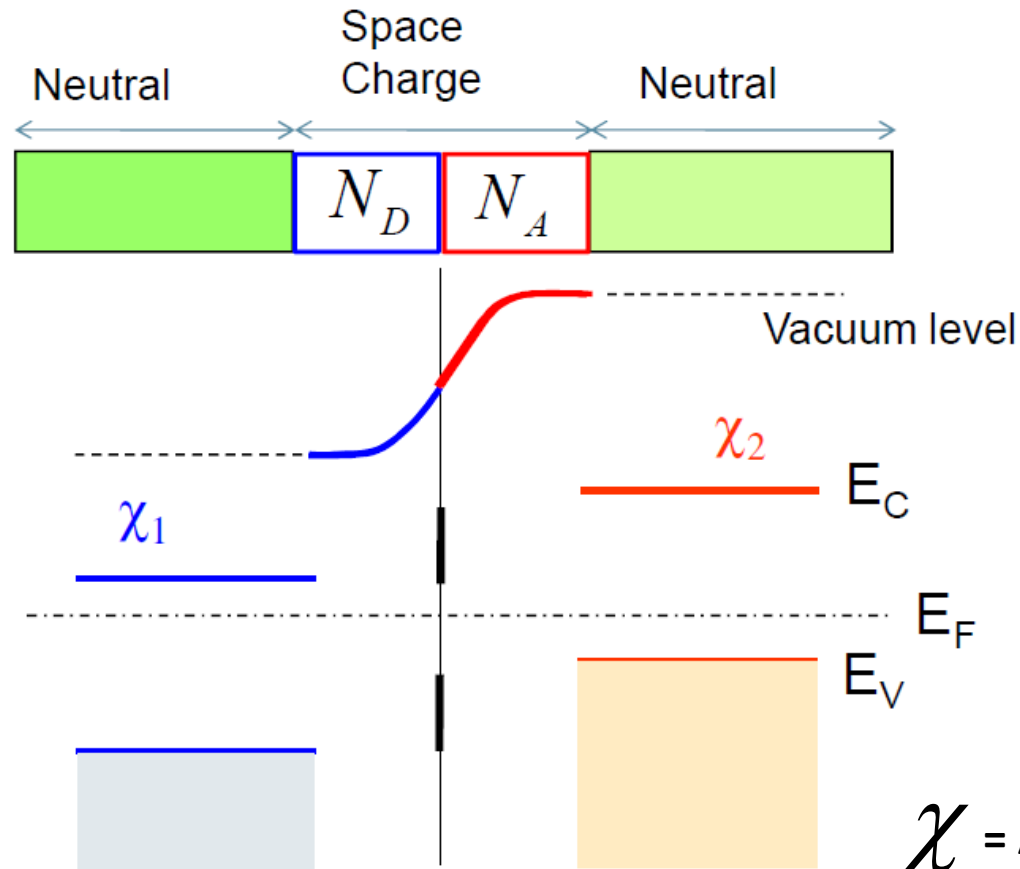
$$\nabla \cdot D = q(p - n + N_D^+ - N_A^-)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q} \nabla \cdot \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$



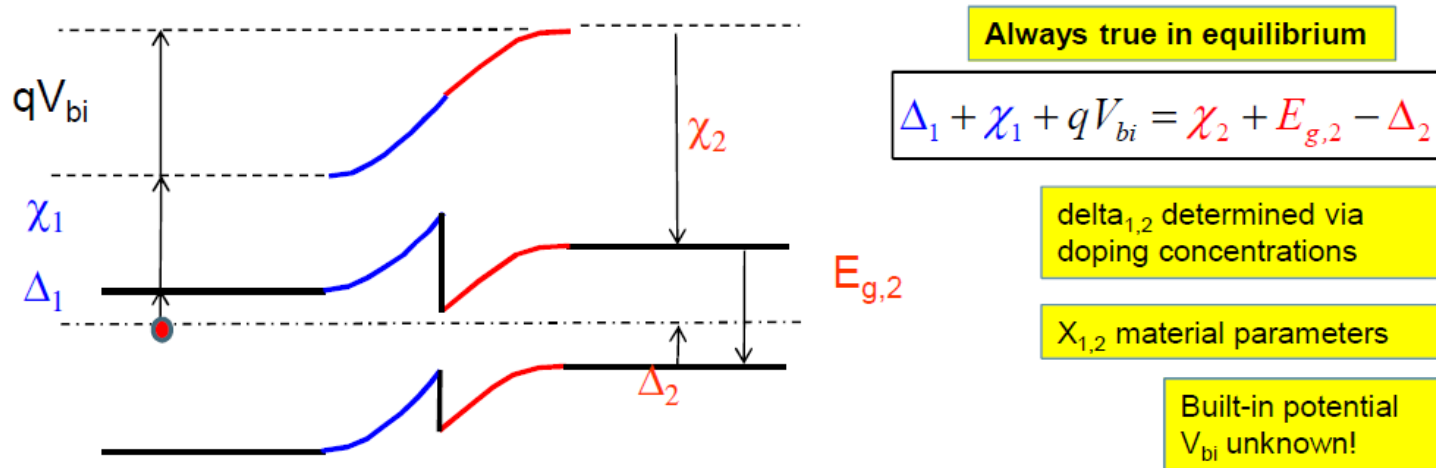
Drawing Recipe

- 1) Start with E_F
- 2) E_C/E_V in bulk n-side
- 3) E_C/E_V in bulk p-side
- 4) Vacuum level in N
- 5) Vacuum level in P
- 6) Join vacuum levels
- 7) "Transfer" vacuum slopes to join E_C/E_V

χ = Affinité électronique

Session1 : SCAPS et jonctions

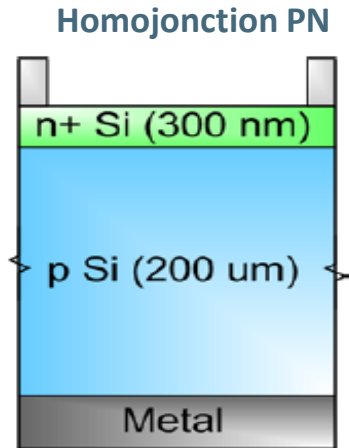
■ Diodes : Jonctions : équilibre = résolution équation de Poisson



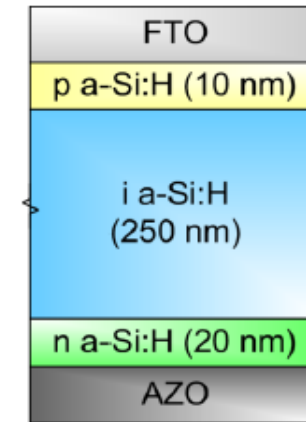
$$\begin{aligned}
 qV_{bi} &= E_{g,2} - \Delta_2 - \Delta_1 + \chi_2 - \chi_1 \\
 &= \left(E_{g,2} + k_B T \ln \frac{N_A}{N_{V,2}} \right) + k_B T \ln \frac{N_D}{N_{C,1}} + (\chi_2 - \chi_1) \\
 &= k_B T \ln \frac{N_A N_D}{N_{V,2} N_{C,1} e^{-E_{g,2}/k_B T}} + (\chi_2 - \chi_1)
 \end{aligned}$$

Session 1 : Travaux pratiques

■ Travaux pratiques 1: Homojonction PN vs Homojonction PIN



Homojonction PIN

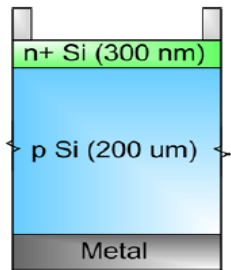


- caractéristiques à l'obscurité
 - Electrostatique :
 - Diagramme des bandes d'énergie
 - Tension de diffusion : V_{bi}
 - Champ électrique interne
 - Caractéristiques en régime continu (DC)
 - Courant de recombinaison
 - Courbe courant-tension

Session 1 : Travaux pratiques

■ Travaux pratiques 1: jonction PN vs jonction PIN

Homojonction PN



Layers

left contact (back)

couche p

couche n

add layer

right contact (front)

Interfaces

illuminated from : ☐ right ☐ left

apply voltage V to : ☐ left contact ☐ right contact

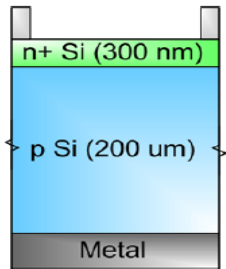
current reference as a : ☐ consumer ☐ generator

Info on graded parameters only available after a calculation

Session 1 : Travaux pratiques

■ Travaux pratiques 1: jonction PN vs jonction PIN

Homojonction PN



| LAYER 1 | | couche p | |
|---|--------------------------------------|----------------------|--|
| thickness (μm) | 2.000 | | |
| | | uniform pure A (y=0) | |
| The layer is pure A: y = 0, uniform | | 0.000 | |
| Semiconductor Property P of the pure material | | pure A (y = 0) | |
| bandgap (eV) | 1.200 | | |
| electron affinity (eV) | 4.500 | | |
| dielectric permittivity (relative) | 10.000 | | |
| CB effective density of states (1/cm ³) | 1.000E+19 | | |
| VB effective density of states (1/cm ³) | 1.000E+19 | | |
| electron thermal velocity (cm/s) | 1.000E+7 | | |
| hole thermal velocity (cm/s) | 1.000E+7 | | |
| electron mobility (cm ² /Vs) | 1.000E+3 | | |
| hole mobility (cm ² /Vs) | 5.000E+2 | | |
| <input type="checkbox"/> Allow Tunneling | effective mass of electron: 1.000E+0 | | |
| | effective mass of holes 1.000E+0 | | |
| no ND grading (uniform) | | | |
| shallow uniform donor density ND (1/cm ³) | | 0.000E+0 | |
| no NA grading (uniform) | | | |
| shallow uniform acceptor density NA (1/cm ³) | | 1.000E+15 | |
| Absorption model | | | |
| alpha (y=0) | | | |
| <input type="checkbox"/> from model <input checked="" type="checkbox"/> from file | | | |
| absorption constant A (1/cm eV ^(1/2)) | | 1.000E+5 | |
| absorption constant B (eV ^(1/2) /cm) | | 0.000E+0 | |

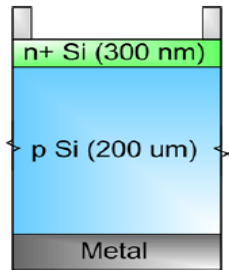
| Band to band recombination | |
|--|----------|
| Radiative recombination coefficient (cm ³ /s) | 0.000E+0 |
| Auger electron capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Auger hole capture coefficient (cm ⁶ /s) | 0.000E+0 |

| Recombination at defects: Summary | |
|---|--|
| Defect 1 | |
| Defect 1 | |
| charge type : neutral | |
| total density (1/cm ³): Uniform 1.000e+16 | |
| grading Nt(y): uniform | |
| energydistribution: single; Et = 0.60 eV above EV | |
| this defect only, if active: tau_n = 1.0e+01 ns, tau_p = 1.0e+01 ns | |
| this defect only, if active: Ln = 5.1e+00 μm, Lp = 3.6e+00 μm | |

Session 1 : Travaux pratiques

■ Travaux pratiques 1: jonction PN vs jonction PIN

Homojonction PN



| LAYER 2 | | couche n | |
|---|--------------------------------------|--------------------------|--|
| thickness (μm) | 0.050 | | |
| The layer is pure A: $y = 0$, uniform | | uniform pure A ($y=0$) | |
| Semiconductor Property P of the pure material | | pure A ($y = 0$) | |
| bandgap (eV) | 1.200 | | |
| electron affinity (eV) | 4.500 | | |
| dielectric permittivity (relative) | 10.000 | | |
| CB effective density of states ($1/\text{cm}^3$) | 1.000E+19 | | |
| VB effective density of states ($1/\text{cm}^3$) | 1.000E+19 | | |
| electron thermal velocity (cm/s) | 1.000E+7 | | |
| hole thermal velocity (cm/s) | 1.000E+7 | | |
| electron mobility (cm^2/Vs) | 1.000E+3 | | |
| hole mobility (cm^2/Vs) | 5.000E+2 | | |
| <input type="checkbox"/> Allow Tunneling | effective mass of electron: 1.000E+0 | | |
| | effective mass of holes: 1.000E+0 | | |
| no ND grading (uniform) | | | |
| shallow uniform donor density ND ($1/\text{cm}^3$) | | 1.000E+18 | |
| no NA grading (uniform) | | | |
| shallow uniform acceptor density NA ($1/\text{cm}^3$) | | 0.000E+0 | |
| Absorption model | | | |
| alpha ($y=0$) | | | |
| <input type="checkbox"/> from model <input checked="" type="checkbox"/> from file | | | |
| absorption constant A ($1/\text{cm eV}^{1/2}$) | | 1.000E+5 | |
| absorption constant B ($\text{eV}^{1/2}/\text{cm}$) | | 0.000E+0 | |

Recombination model

Band to band recombination

| | |
|--|----------|
| Radiative recombination coefficient (cm^3/s) | 0.000E+0 |
| Auger electron capture coefficient (cm^6/s) | 0.000E+0 |
| Auger hole capture coefficient (cm^6/s) | 0.000E+0 |

Recombination at defects: Summary

Defect 1

Defect 1

charge type : neutral

total density ($1/\text{cm}^3$): Uniform 1.000e+18

grading Nt(y): uniform

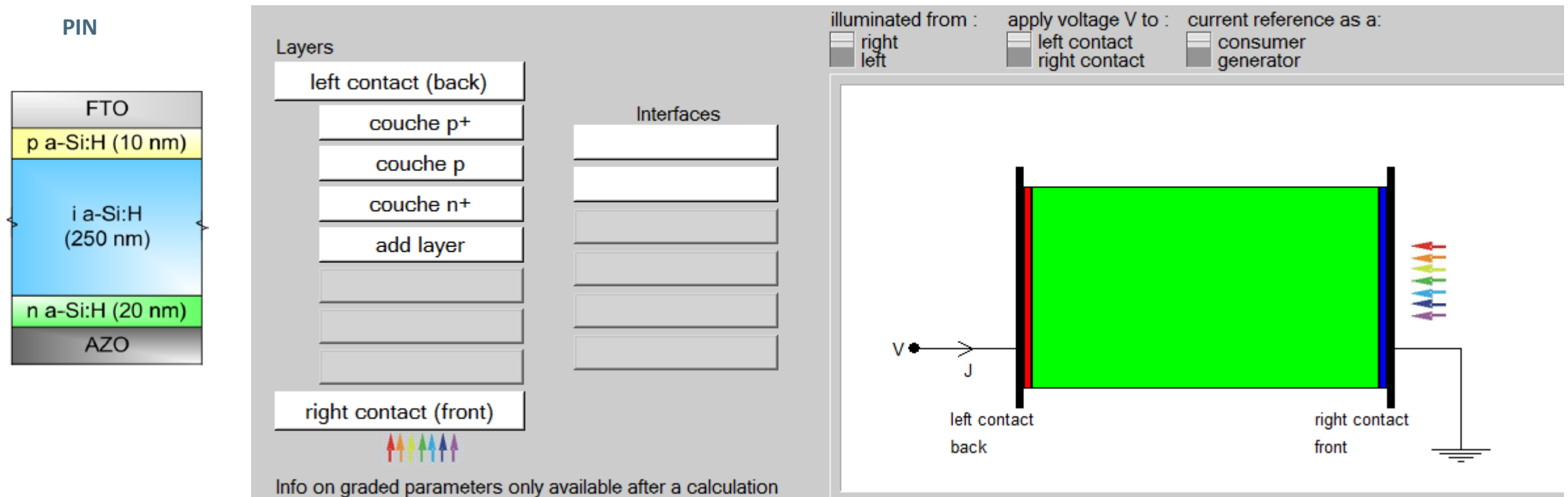
energydistribution: single; Et = 0.60 eV above EV

this defect only, if active: tau_n = 1.0e-01 ns, tau_p = 1.0e-01 ns

this defect only, if active: Ln = 5.1e-01 μm , Lp = 3.6e-01 μm

Session 1 : Travaux pratiques

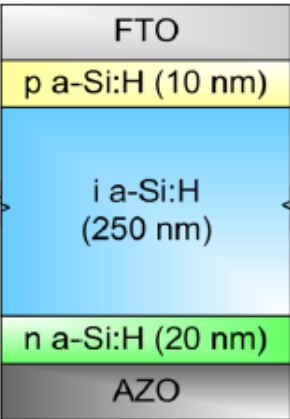
■ Travaux pratiques 1: jonction PN vs jonction PIN



Session 1 : Travaux pratiques

■ Travaux pratiques 1: jonction PN vs jonction PIN

PIN



LAYER 1

couche p+

thickness (μm) 0.050

uniform pure A (y=0)

The layer is pure A: y = 0, uniform 0.000

Semiconductor Property P of the pure material pure A (y = 0)

| | |
|---|--|
| bandgap (eV) | 1.200 |
| electron affinity (eV) | 4.500 |
| dielectric permittivity (relative) | 10.000 |
| CB effective density of states ($1/\text{cm}^3$) | $1.000\text{E}+19$ |
| VB effective density of states ($1/\text{cm}^3$) | $1.000\text{E}+19$ |
| electron thermal velocity (cm/s) | $1.000\text{E}+7$ |
| hole thermal velocity (cm/s) | $1.000\text{E}+7$ |
| electron mobility (cm^2/Vs) | $5.000\text{E}+1$ |
| hole mobility (cm^2/Vs) | $5.000\text{E}+1$ |
| <input type="checkbox"/> Allow Tunneling | effective mass of electron: $1.000\text{E}+0$ effective mass of holes $1.000\text{E}+0$ |
| no ND grading (uniform) | |
| shallow uniform donor density ND ($1/\text{cm}^3$) | $0.000\text{E}+0$ |
| no NA grading (uniform) | |
| shallow uniform acceptor density NA ($1/\text{cm}^3$) | $1.000\text{E}+18$ |

Absorption model

Recombination model

Band to band recombination

| | |
|--|-------------------|
| Radiative recombination coefficient (cm^3/s) | $0.000\text{E}+0$ |
| Auger electron capture coefficient (cm^6/s) | $0.000\text{E}+0$ |
| Auger hole capture coefficient (cm^6/s) | $0.000\text{E}+0$ |

Recombination at defects: Summary

Defect 1

Defect 1

charge type : neutral

total density ($1/\text{cm}^3$): Uniform $1.000\text{e}+18$

grading Nt(y): uniform

energydistribution: single; Et = 0.60 eV above EV

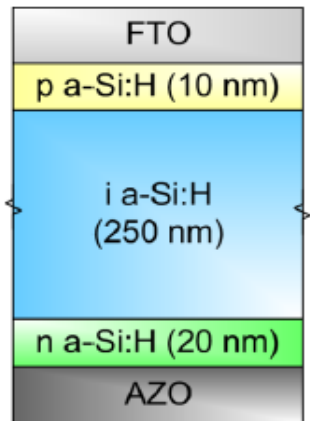
this defect only, if active: tau_n = $1.0\text{e}-01$ ns, tau_p = $1.0\text{e}-01$ ns

this defect only, if active: Ln = $5.1\text{e}-01$ μm , Lp = $3.6\text{e}-01$ μm

Session 1 : Travaux pratiques

■ Travaux pratiques 1: jonction PN vs jonction PIN

PIN



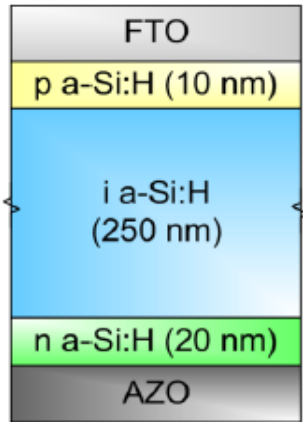
| | | | |
|--|--------------------------------------|--|--|
| LAYER 2 | | couche p | |
| thickness (μm) | 2.000 | | |
| | uniform pure A (y=0) | | |
| The layer is pure A: y = 0, uniform | | 0.000 | |
| Semiconductor Property P of the pure material | | pure A (y = 0) | |
| bandgap (eV) | 1.200 | | |
| electron affinity (eV) | 4.500 | | |
| dielectric permittivity (relative) | 10.000 | | |
| CB effective density of states (1/cm ³) | 1.000E+19 | | |
| VB effective density of states (1/cm ³) | 1.000E+19 | | |
| electron thermal velocity (cm/s) | 1.000E+7 | | |
| hole thermal velocity (cm/s) | 1.000E+7 | | |
| electron mobility (cm ² /Vs) | 1.000E-1 | | |
| hole mobility (cm ² /Vs) | 1.000E-1 | | |
| <input type="checkbox"/> Allow Tunneling | effective mass of electron: 1.000E+0 | | |
| | effective mass of holes: 1.000E+0 | | |
| no ND grading (uniform) | | | |
| shallow uniform donor density ND (1/cm ³) | 1.000E+10 | | |
| no NA grading (uniform) | | | |
| shallow uniform acceptor density NA (1/cm ³) | 1.000E+10 | | |
| Absorption model | | | |
| | | alpha (y=0) | |
| | | <input type="checkbox"/> from model <input checked="" type="checkbox"/> from file | |
| absorption constant A (1/cm eV ^(1/2)) | 1.000E+5 | | |
| absorption constant B (eV ^(1/2) /cm) | 0.000E+0 | | |

| | |
|---|----------|
| Band to band recombination | |
| Radiative recombination coefficient (cm ³ /s) | 0.000E+0 |
| Auger electron capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Auger hole capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Recombination at defects: Summary | |
| Defect 1 | |
| Defect 1 | |
| charge type : neutral | |
| total density (1/cm ³): Uniform 1.000e+16 | |
| grading Nt(y): uniform | |
| energydistribution: single; Et = 0.60 eV above EV | |
| this defect only, if active: tau_n = 1.0e+01 ns, tau_p = 1.0e+01 ns | |
| this defect only, if active: Ln = 5.1e+00 μm, Lp = 3.6e+00 μm | |

Session 1 : Travaux pratiques

■ Travaux pratiques 1: jonction PN vs jonction PIN

PIN



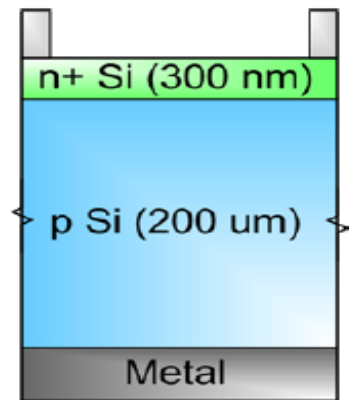
| LAYER 3 | | couche n+ | |
|--|-----------------------------|---|--|
| thickness (μm) | | 0.050 | |
| | | uniform pure A (y=0) | |
| The layer is pure A: y = 0, uniform | | 0.000 | |
| Semiconductor Property P of the pure material | | pure A (y = 0) | |
| bandgap (eV) | | 1.200 | |
| electron affinity (eV) | | 4.500 | |
| dielectric permittivity (relative) | | 10.000 | |
| CB effective density of states (1/cm ³) | | 1.000E+19 | |
| VB effective density of states (1/cm ³) | | 1.000E+19 | |
| electron thermal velocity (cm/s) | | 1.000E+7 | |
| hole thermal velocity (cm/s) | | 1.000E+7 | |
| electron mobility (cm ² /Vs) | | 5.000E+1 | |
| hole mobility (cm ² /Vs) | | 5.000E+1 | |
| <input type="checkbox"/> Allow Tunneling | effective mass of electron: | 1.000E+0 | |
| | effective mass of holes | 1.000E+0 | |
| no ND grading (uniform) | | | |
| shallow uniform donor density ND (1/cm ³) | | 1.000E+18 | |
| no NA grading (uniform) | | | |
| shallow uniform acceptor density NA (1/cm ³) | | 0.000E+0 | |
| Absorption model | | | |
| | | alpha (y=0) | |
| | | <input type="checkbox"/> from model | |
| | | <input checked="" type="checkbox"/> from file | |
| absorption constant A (1/cm eV ^(1/2)) | | 1.000E+5 | |
| absorption constant B (eV ^(1/2) /cm) | | 0.000E+0 | |

| Recombination model | |
|---|----------|
| Band to band recombination | |
| Radiative recombination coefficient (cm ³ /s) | 0.000E+0 |
| Auger electron capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Auger hole capture coefficient (cm ⁶ /s) | 0.000E+0 |
| Recombination at defects: Summary | |
| Defect 1 | |
| Defect 1 | |
| charge type : neutral | |
| total density (1/cm ³): Uniform 1.000e+18 | |
| grading Nt(y): uniform | |
| energydistribution: single; Et = 0.60 eV above EV | |
| this defect only, if active: tau_n = 1.0e-01 ns, tau_p = 1.0e-01 ns | |
| this defect only, if active: Ln = 5.1e-01 μm, Lp = 3.6e-01 μm | |

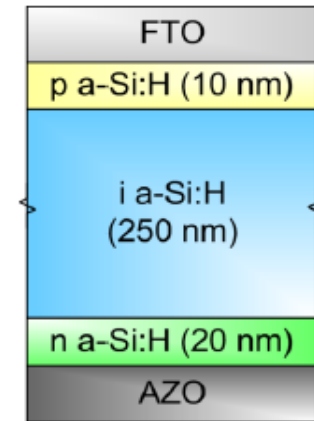
Session 1 : Travaux pratiques

- Travaux pratiques 1: jonction PN vs jonction PIN

Homojonction PN



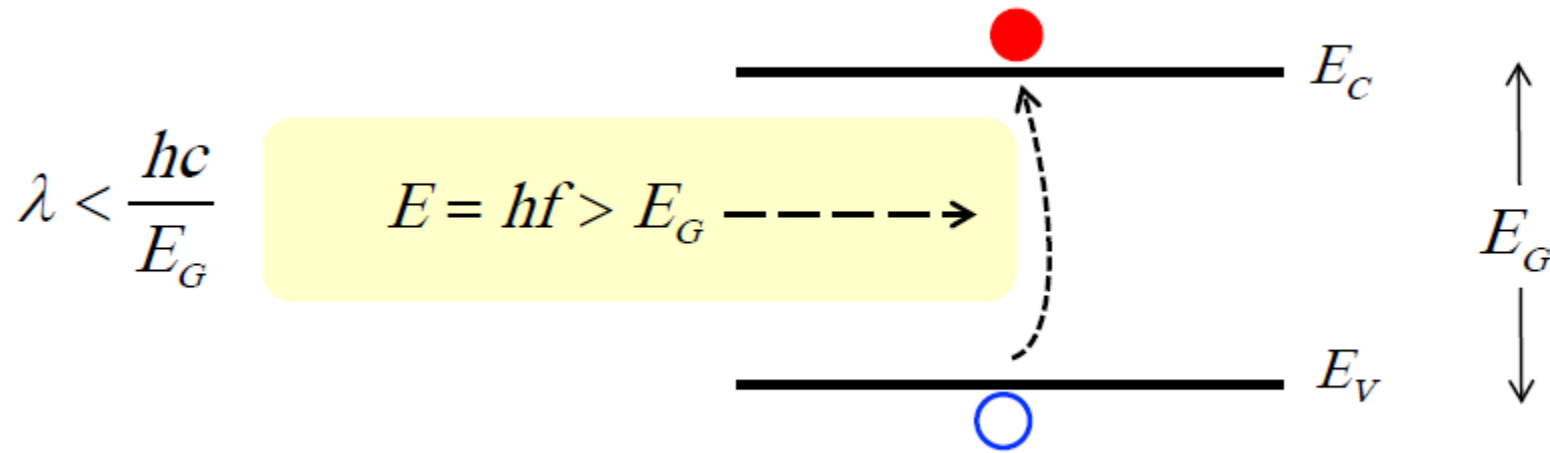
PIN



- Caractéristiques sous-éclairage
- Impacts de la qualité électronique du matériau

Session 1 : Travaux pratiques

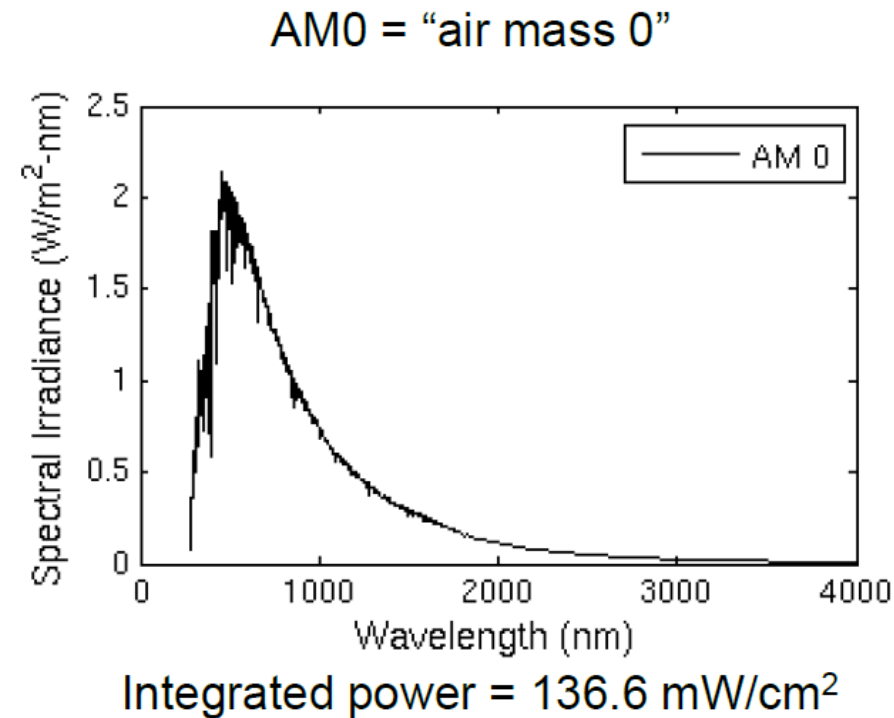
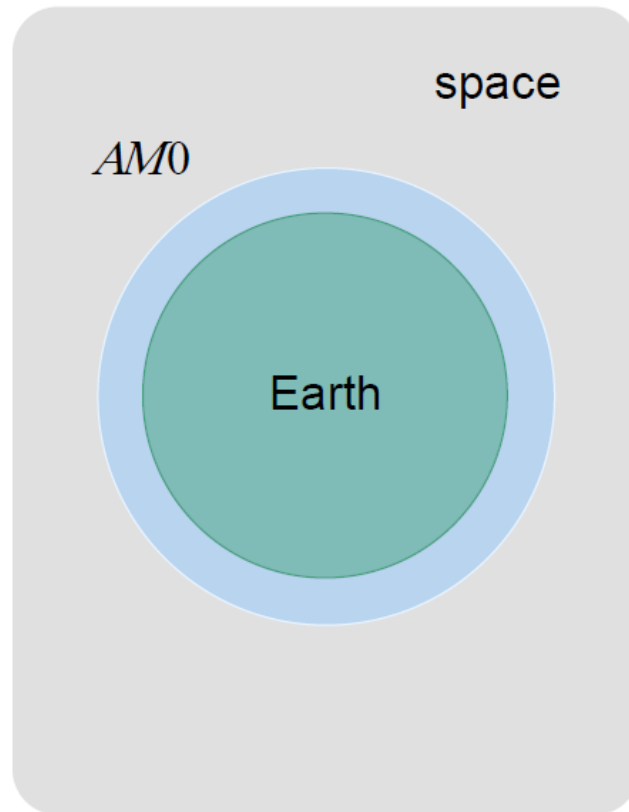
- Travaux pratiques 1: jonction PN vs jonction PIN
- Absorption de la lumière : Photo-courant



$$f\lambda = c \quad f = \frac{c}{\lambda} \quad E = hf = \frac{hc}{\lambda}$$

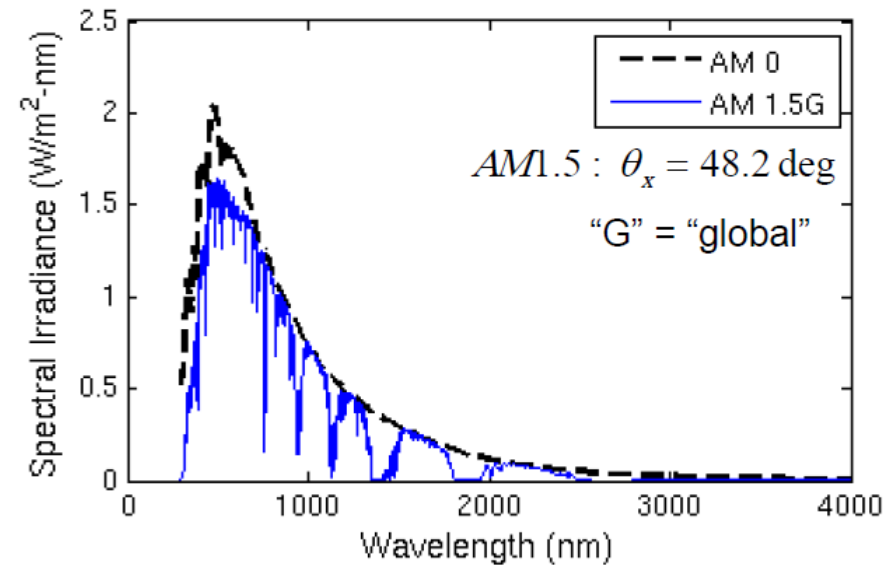
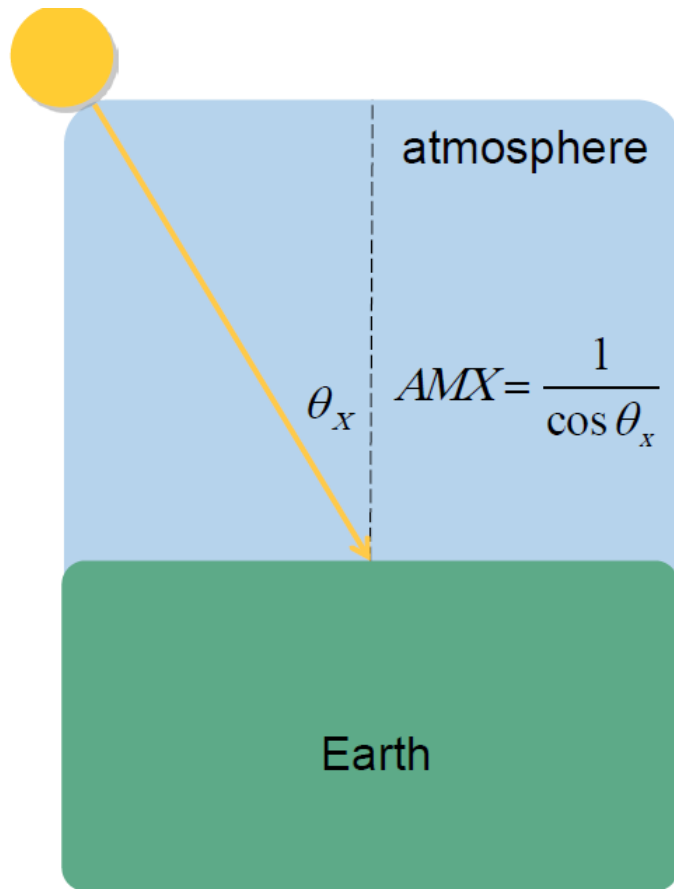
Session 1 : Travaux pratiques

- Travaux pratiques 1: jonction PN vs jonction PIN
- Absorption de la lumière : Photo-courant



Session 1 : Travaux pratiques

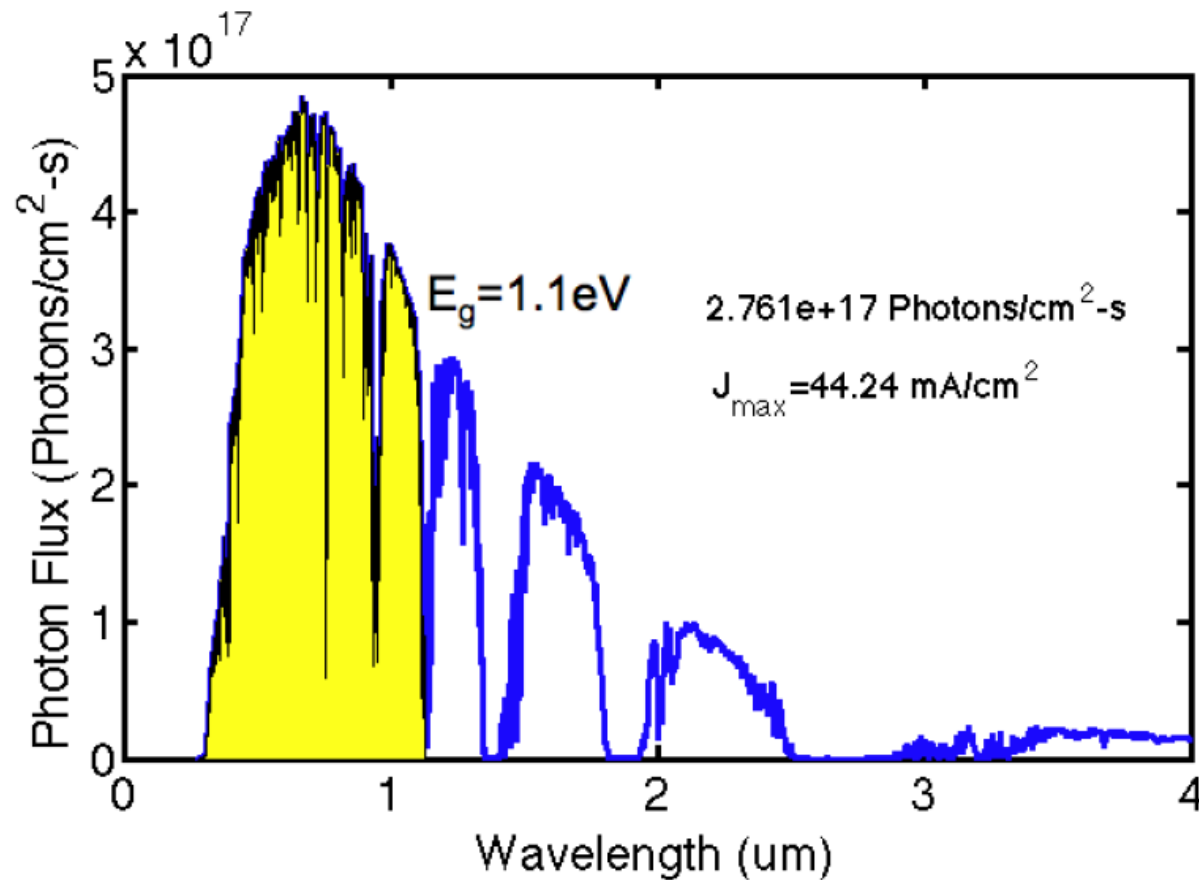
- Travaux pratiques 1: jonction PN vs jonction PIN
- Absorption de la lumière : Photo-courant



Integrated power = 100 mW/cm²)

Session 1 : Travaux pratiques

- Travaux pratiques 1: jonction PN vs jonction PIN
- Absorption de la lumière : Photo-courant



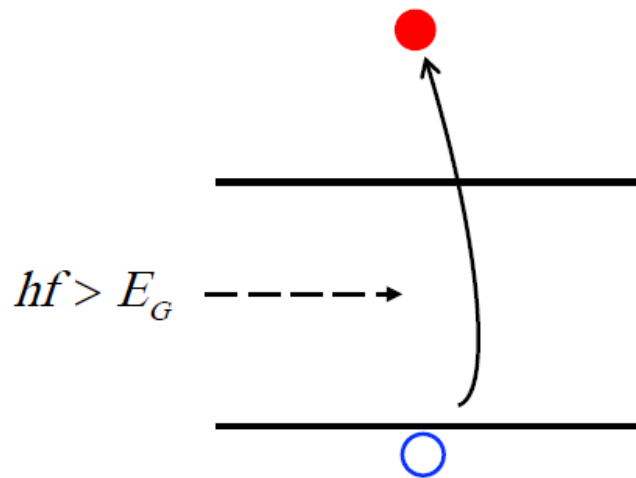
solar
spectrum
(AM1.5G)

Exemple : Si $E_g = 1.1\text{ eV}$
uniquement les photons avec $E < E_g$
qui seront absorbés

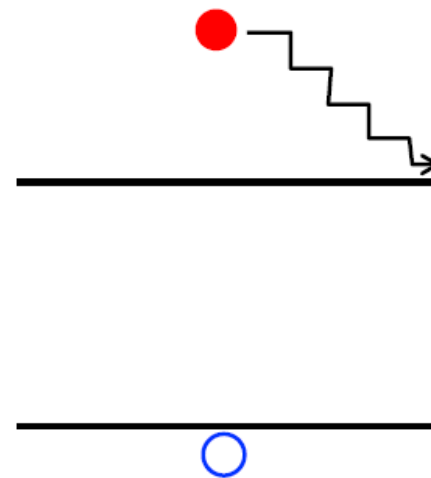
Session 1 : Travaux pratiques

- Travaux pratiques 1: jonction PN vs jonction PIN
- Absorption de la lumière : Photo-courant

Energy is lost for photons with energy greater than the bandgap.



Electron is excited above the conduction band.



However, extra energy is lost due to thermalization as electron relaxes back to the band edge.

Session 1 : Travaux pratiques

- Travaux pratiques 1: jonction PN vs jonction PIN
- Absorption de la lumière : combien de photons absorbés pour une épaisseur finie

Incident flux: Φ_0

Flux at position, x : $\Phi(x) = \Phi_0 e^{-\alpha(\lambda)x}$

optical absorption coefficient:

$$\alpha(\lambda) > 0 \quad \text{for} \quad E > E_G \quad (\lambda < hc/E_G)$$

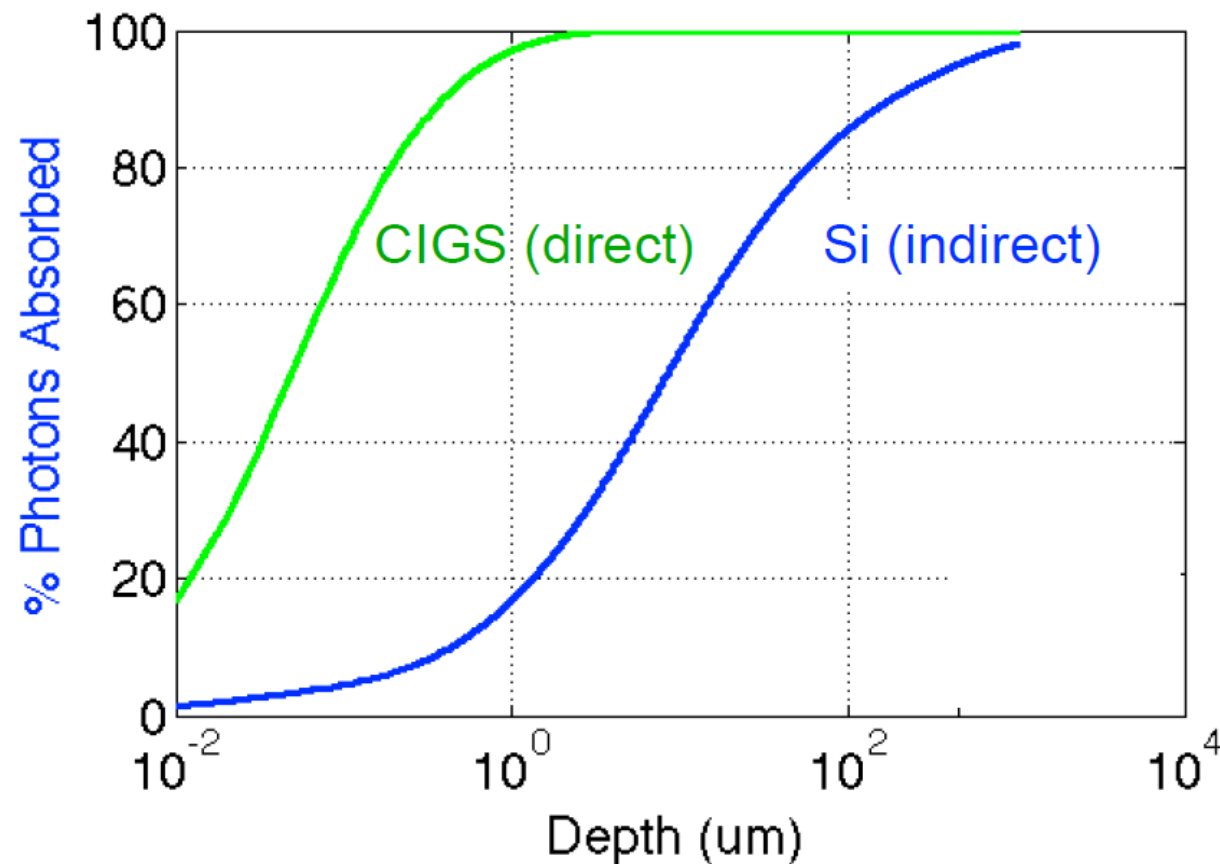
Generation rate at position, x :

$$G(x) = -\frac{d\Phi(x)}{dx} = \Phi_0 \alpha(\lambda) e^{-\alpha(\lambda)x}$$

$$G_{tot} = \int \left\{ \int_0^L G(x, \lambda) dx \right\} d\lambda$$

Session 1 : Travaux pratiques

- Travaux pratiques 1: jonction PN vs jonction PIN
 - Absorption de la lumière : combien de photons absorbés pour une épaisseur finie



SESSION 2 : PROJETS

A. DARGA

Session 2 : Projets

Projet 1 : : cellule PV à base de CIGSe : modèle simplifié

| | |
|---|--|
| Hétérojonction N+P ZnO/CdS/CIGSe/Mo | |
| ZnO-Al (n^+): 0,5 μm | |
| ZnO-i (intrinseque) : 0,1 μm | |
| CdS (n type) : 0,02-0,07 μm | |
| Cu(In _{1-x} Ga _x)(Se _{1-y} S _y) ₂ (p type): 1-2,3 μm | |
| MoSe ₂ ou MoS ₂ : | |
| 0,4-0,7 μm | |
| Mo: 0,2-0,5 μm | |
| Glass : 1-6 mm | |

Session 2 : Projets

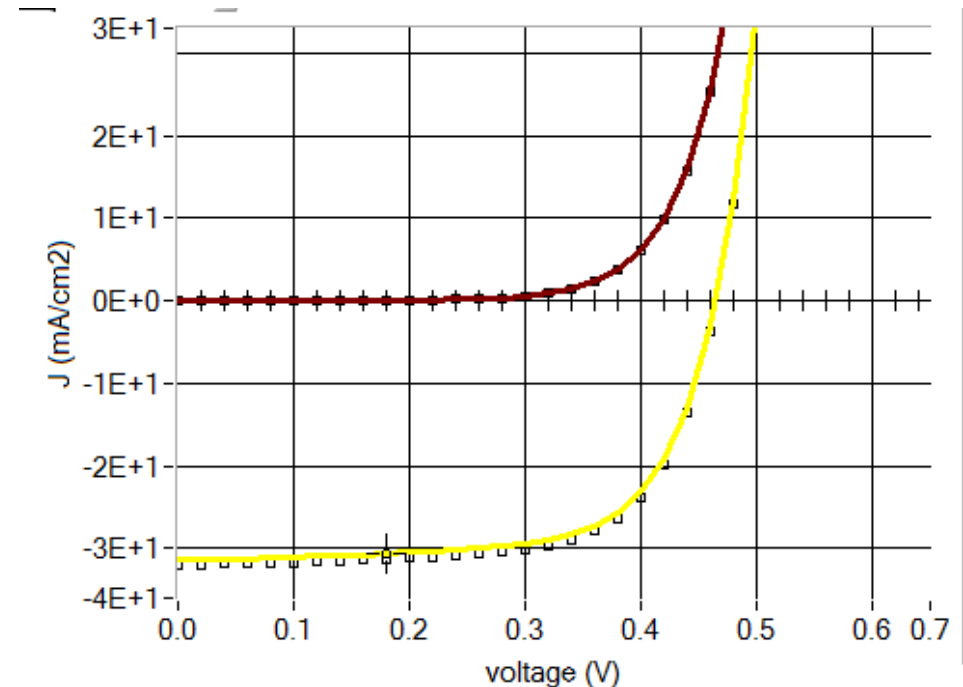
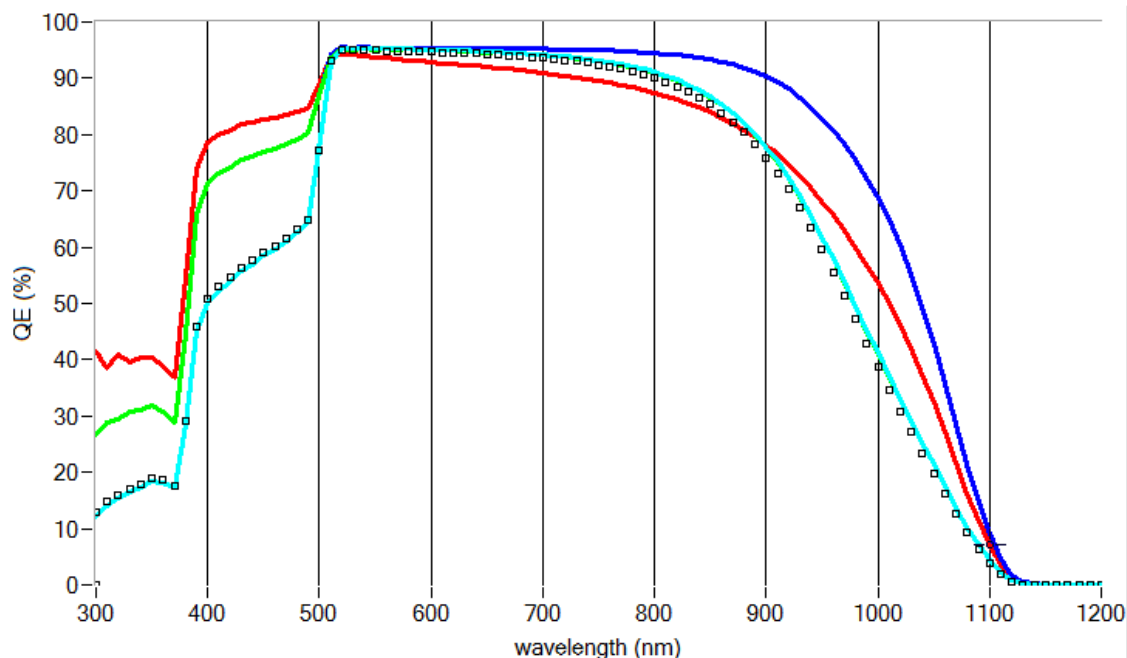
Projet 1 : cellule PV à base de CIGSe : modèle simplifié

On cherche à reproduire par simulation, les tracés (EQE et I-V) d'une cellule PV à base CIGSe.

À partir d'un modèle de base fourni.

Les paramètres sont :

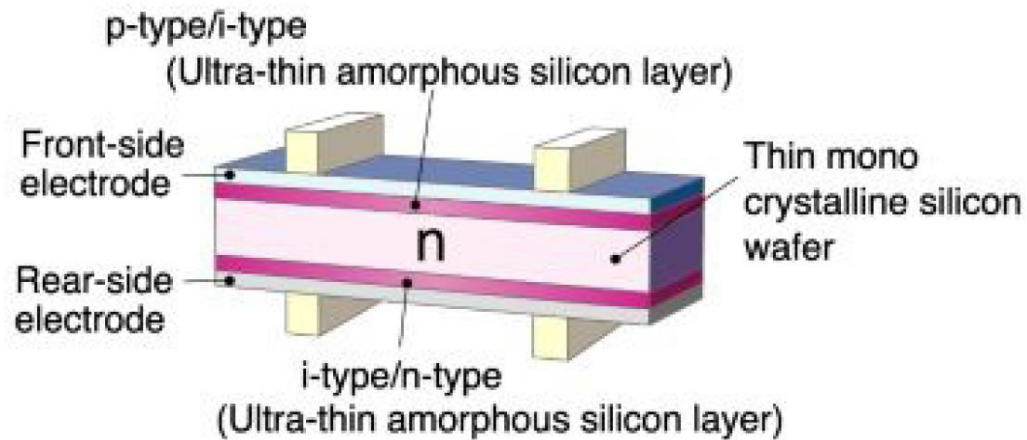
1. Épaisseur de la couche de CdS
2. Dopage de la couche de CIGSe
3. Taux de recombinaison dans la couche CIGSe



Session 2 : Projets

Projet 2 : Cellule PV HIT:

Hétérojonction P+N



Session 2 : Projets

Projet 2 : Cellule PV HIT : a-Si (P+)/c-Si (N)

On cherche a reproduire par simulation, les tracés (EQE et I-V) d'une cellule PV HIT

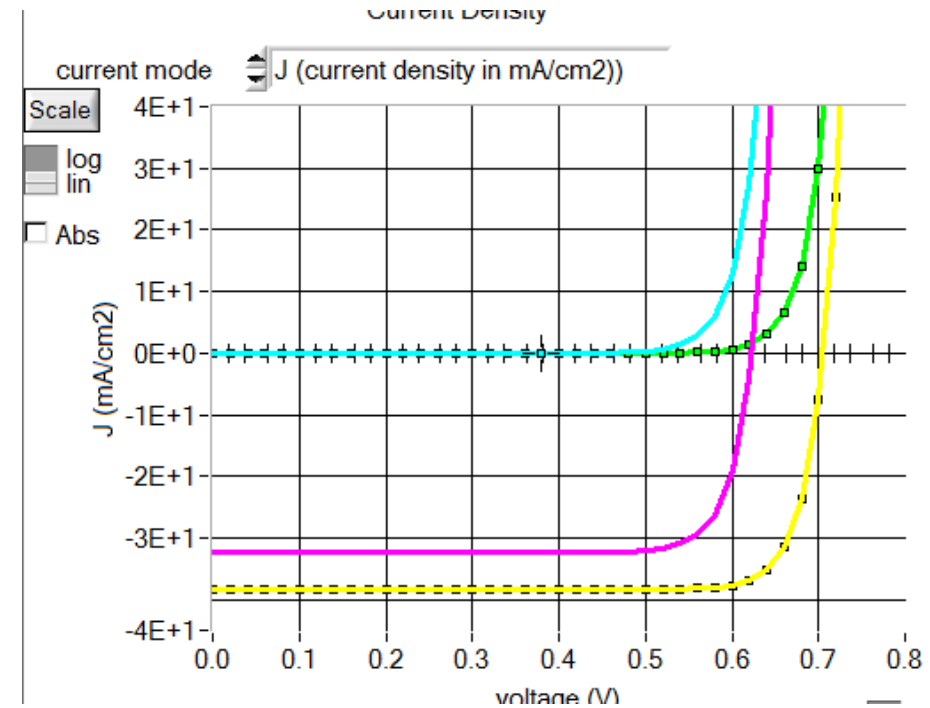
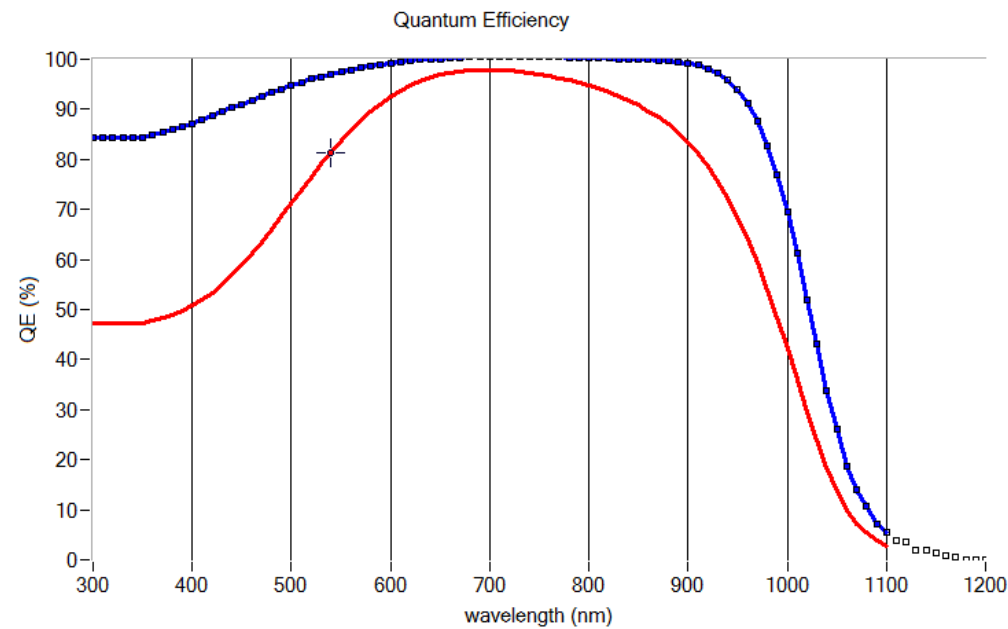
A partir d'un modèle de base fourni.

Les paramètres sont :

1. **Epaisseur de la couche a-Si (p+)**

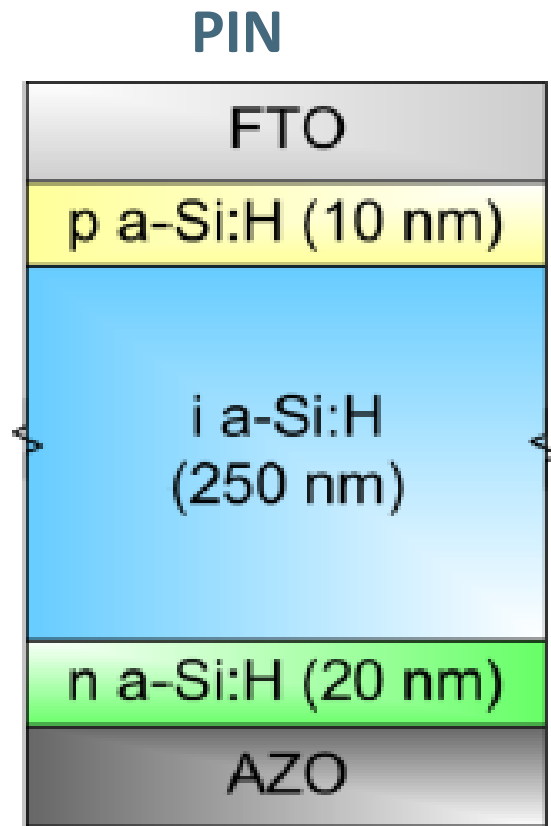
2. **Contact arrière c-Si(N)/Contact**

1. **Possibilité de rajouter une couche**



Session 2 : Projets

Projet 3 : Cellule PV PIN : a-Si (N+)/a-Si(i)/a-Si(P+)



Session 2 : Projets

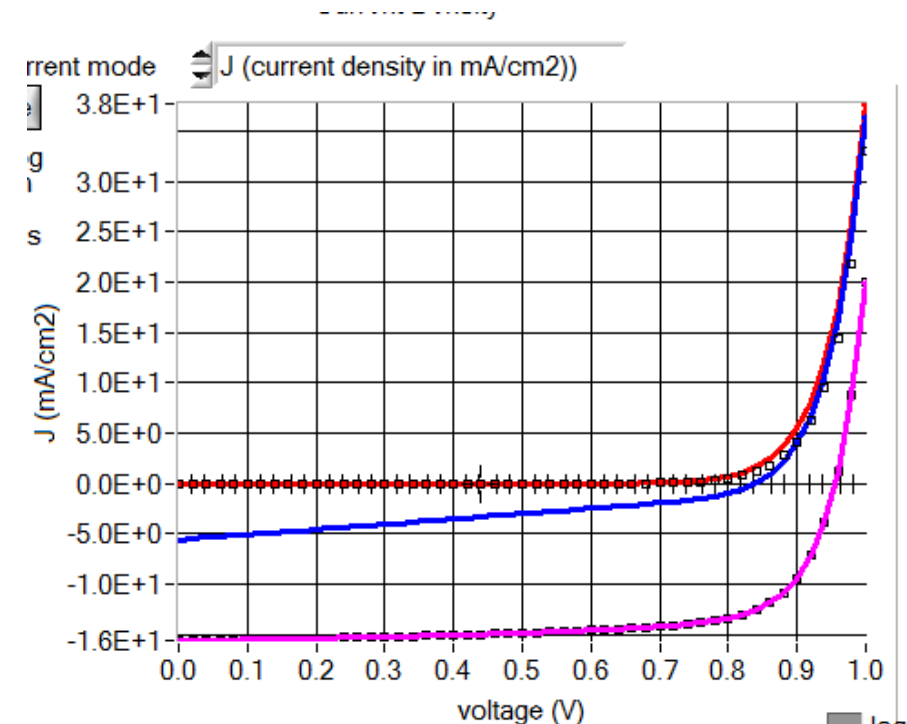
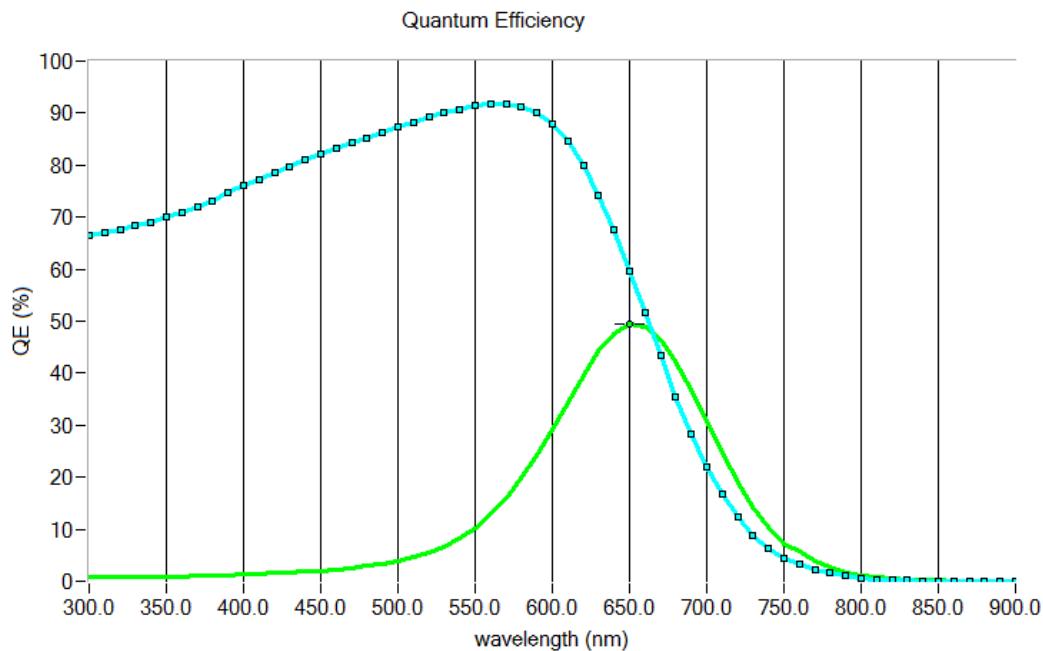
Projet 3 : Cellule PV PIN : a-Si (N+)/a-Si(i)/a-Si(P+)

On cherche à reproduire par simulation, les tracés (EQE et I-V) d'une cellule PIN

À partir d'un modèle de base fourni.

Les paramètres sont :

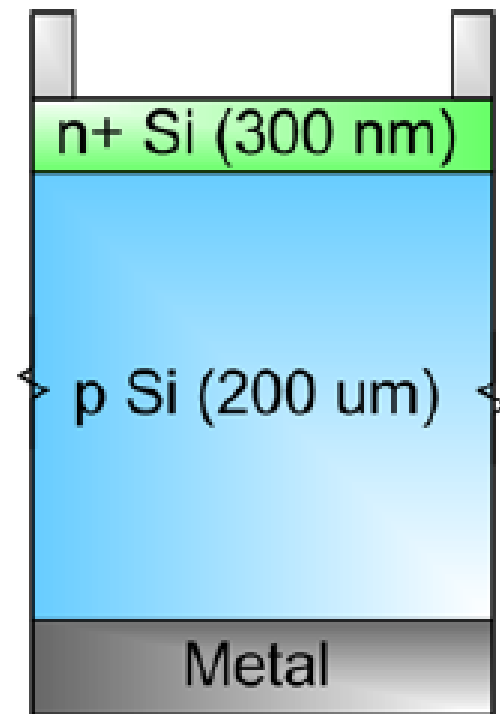
1. Épaisseur de la couche a-Si (intrinsèque)
2. Face éclairée
3. Dopage des couches P+ et N+



Session 2 : Projets

Projet 4 : Cellule Homojonction C-Si:

Homojonction PN



Session 2 : Projets

Projet 3 : Cellule Homojonction C-Si:

On cherche a reproduire par simulation, les tracés (EQE et I-V) d'une cellule à base d'homojonction C-Si

A partir d'un modèle de base fourni.

Les paramètres sont :

- 1. Epaisseur de la couche émettrice**
- 2. Le dopage de la couche émettrice**
- 3. Le contact arrière C-Si (p)/Contact : possibilité de rajouter une couche**

Références bibliographiques

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