PHYSIQUE DES COMPOSANTS SEMI-CONDUCTEURS

VIII) Cellules solaires

P.A. Besse

EPFL

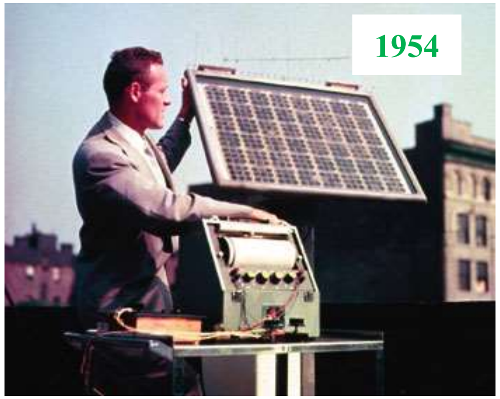
8.1 Premières cellules solaires p/n en silicium

1883: Ch. Fritts, première cellule solaire au sélénium, η_{el}=1%

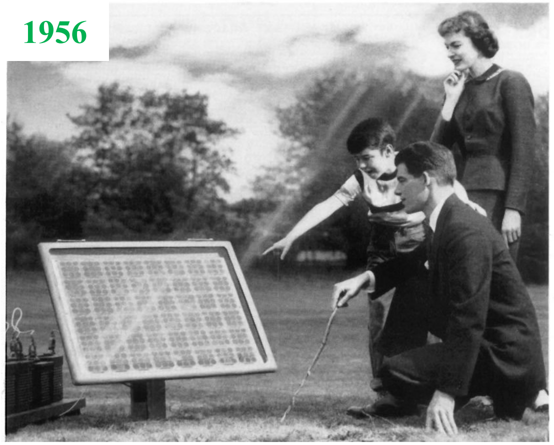
https://theinvisibleagent.wordpress.com/tag/1955/

Chapin,Fuller, Pearson
1954
η_{el}=5%

(50W/m^2)

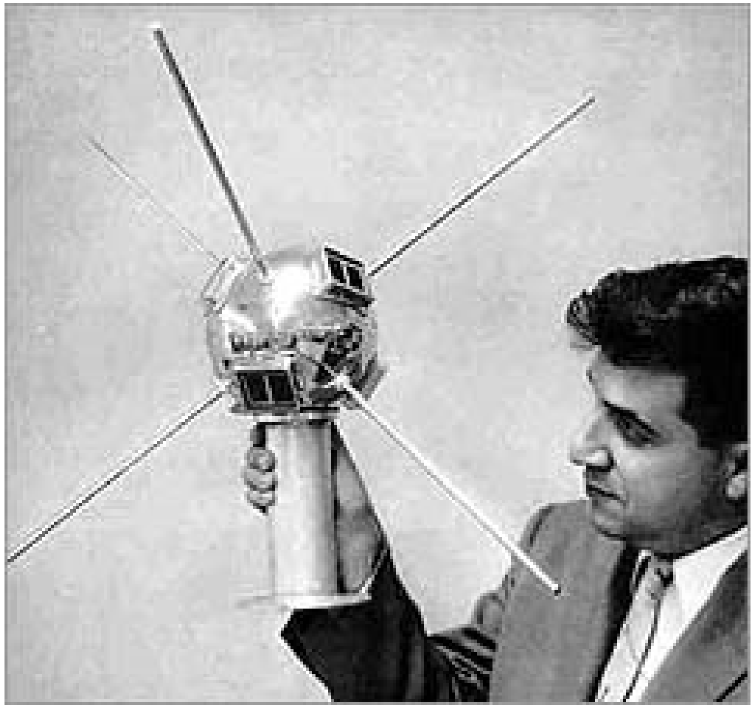


Sun-powered radio



Vanguard I (1958-1964)
First satellite solar electric powered

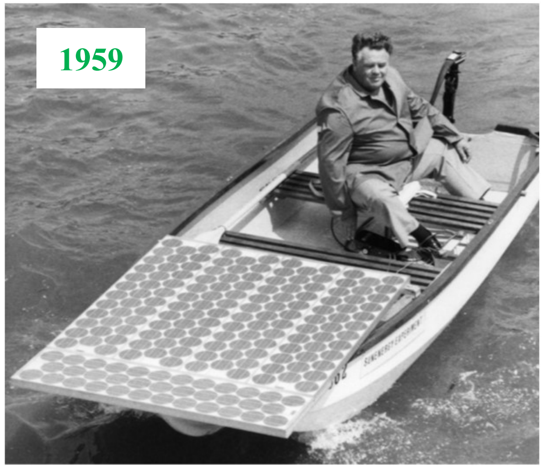
http://thepoormouth.blogspot.com/2008/03/oldest-satellite-in-orbit.html



https://www.gizmodo.com.au/2014/04/60-years-ago-today-bell-labs-unveiled-the-solar-cell/

Cellules solaires: historique (2)

Sun-powered car (1960)
(Baker Electric car 1912
72V battery system)



https://www.gizmodo.com.au/2014/04/60-years-ago-today-bell-labs-unveiled-the-solar-cell/

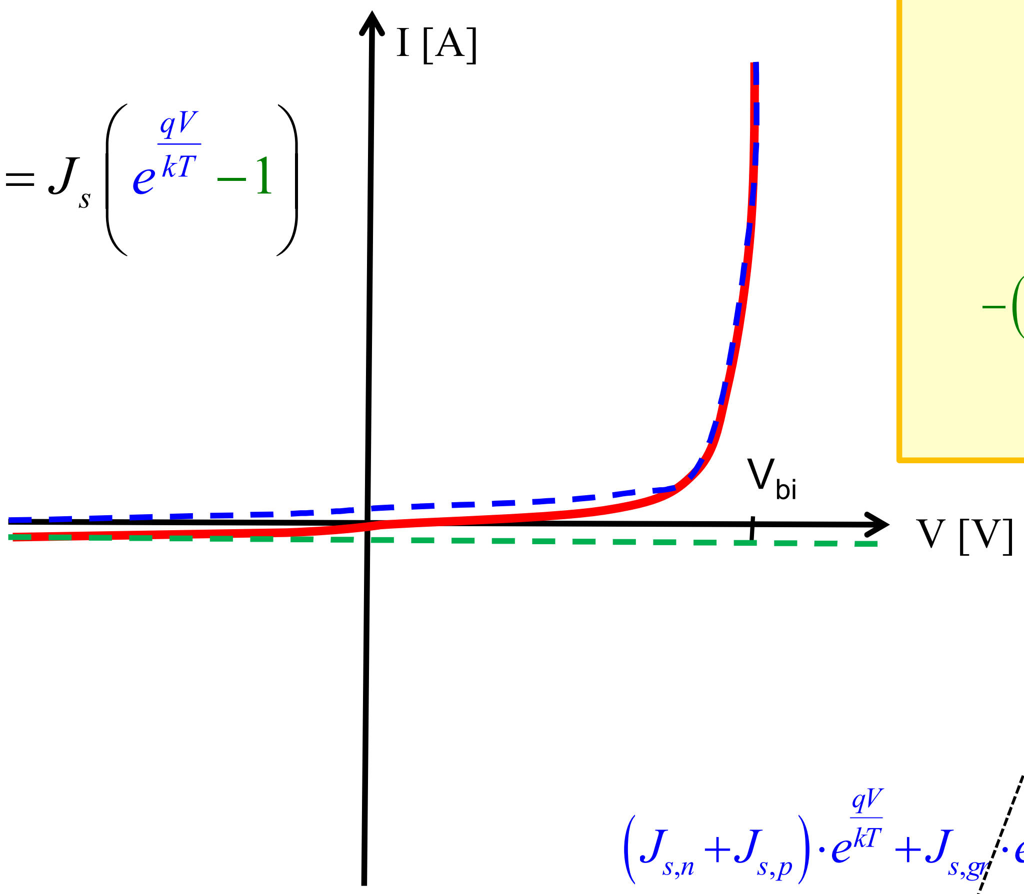
JO Lake Placid

https://www.thehenryford.org/collections-and-research/digital-collections

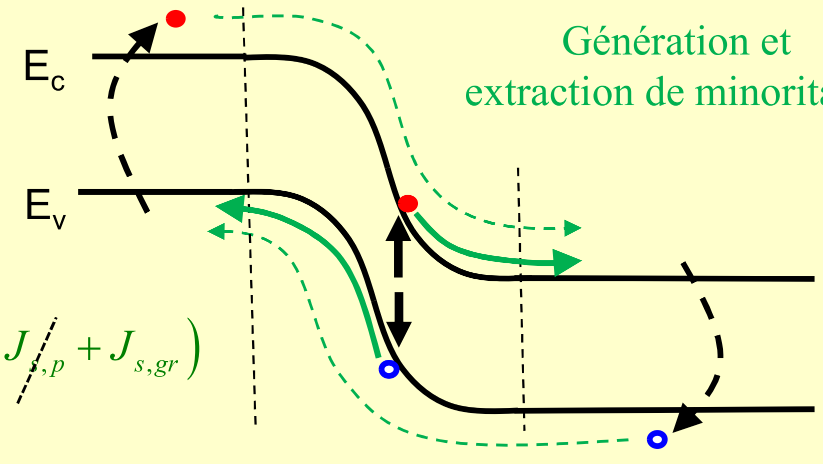
«Phoenix»: Trans-american Solar Auto Run (TSAR)

8.2: Courant dans une diode

$$J_D = J_s\left(e^{\frac{qV}{kT}} - 1\right)$$

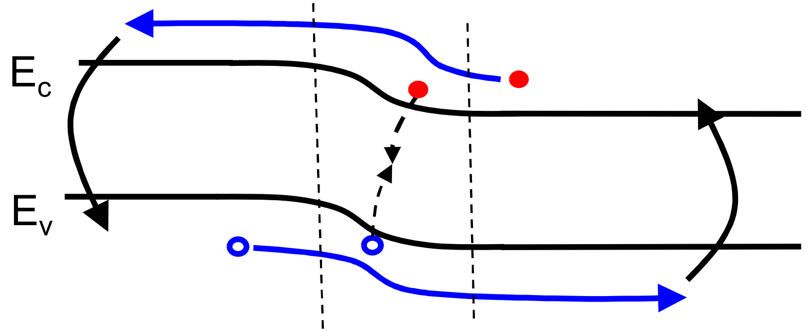


Génération et extraction de minoritaires



$$-\left(\cancel{J_{s,n}} + \cancel{J_{s,p}} + J_{s,gr}\right)$$

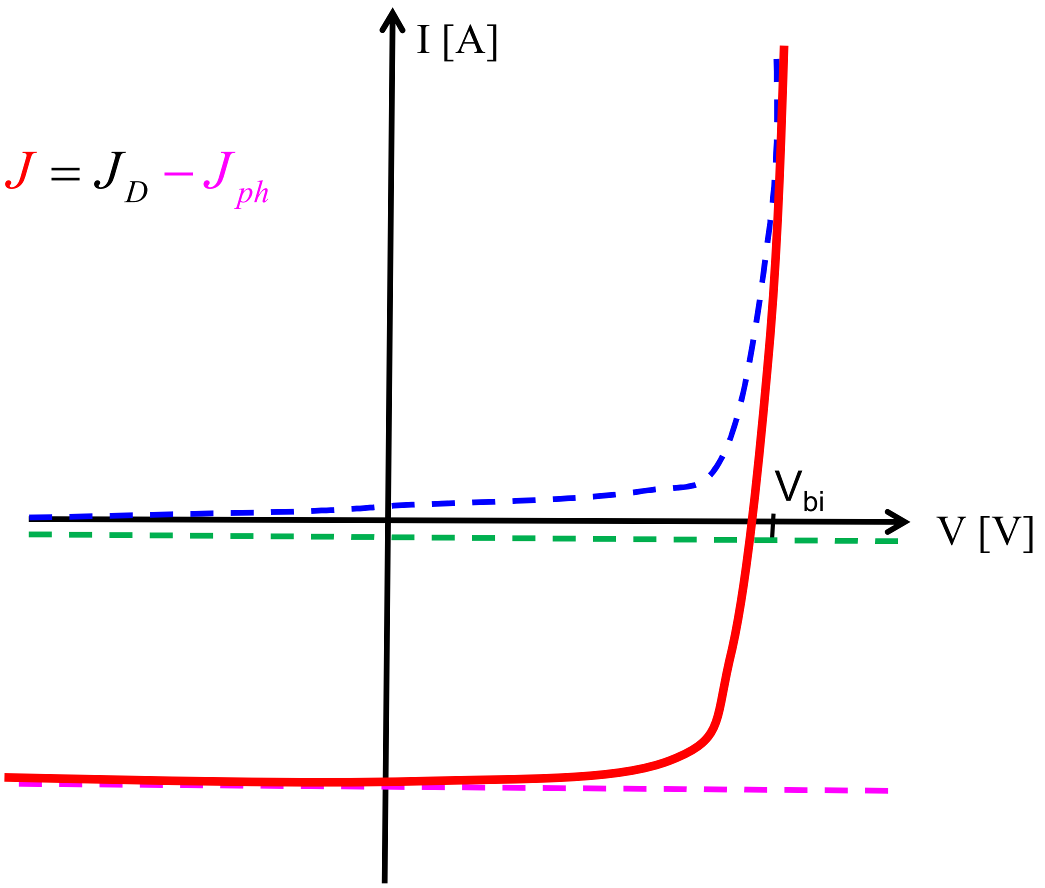
Injection et recombinaison de minoritaires



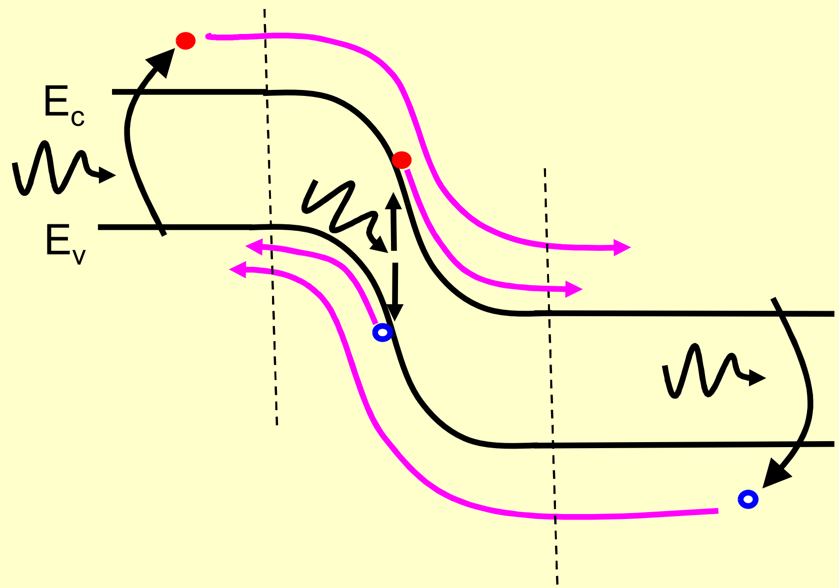
$$\left(J_{s,n} + J_{s,p}\right)\cdot e^{\frac{qV}{kT}} + \cancel{J_{s,gr}}\cdot e^{\frac{qV}{2kT}}$$

Courant dans une photodiode

$$J = J_D - J_{ph}$$



Génération et
extraction des photocharges

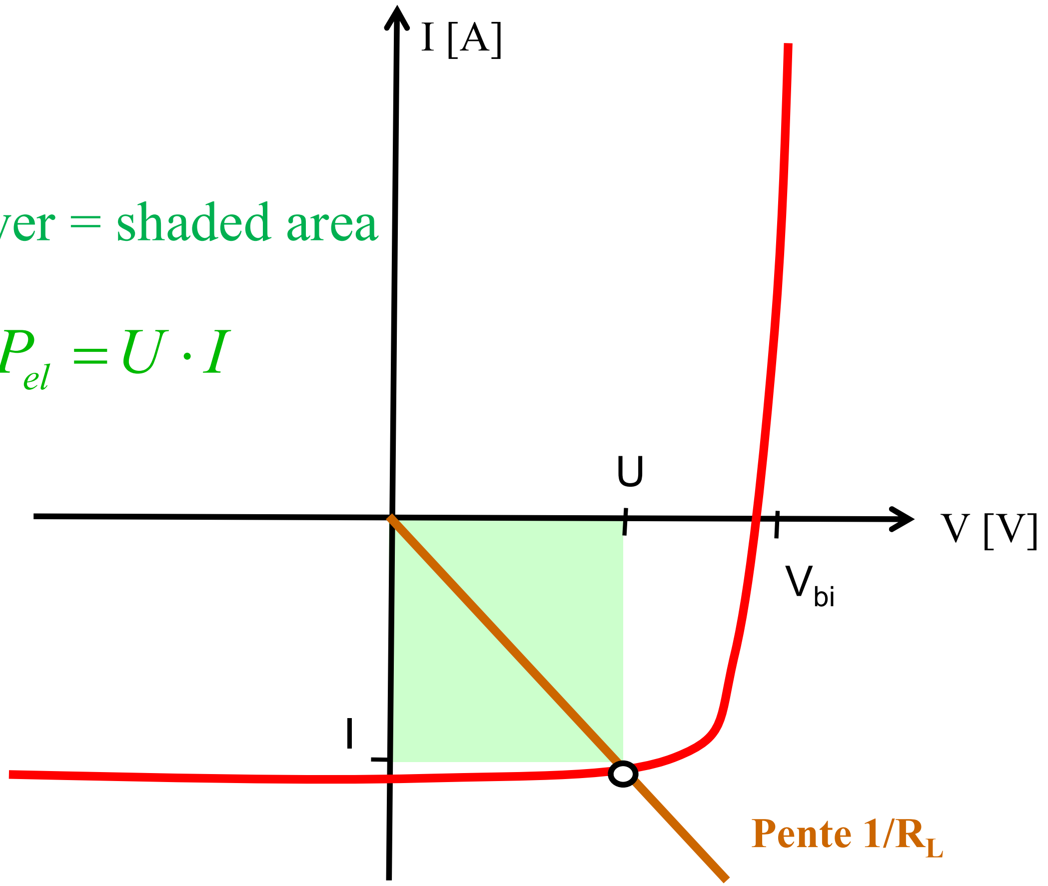


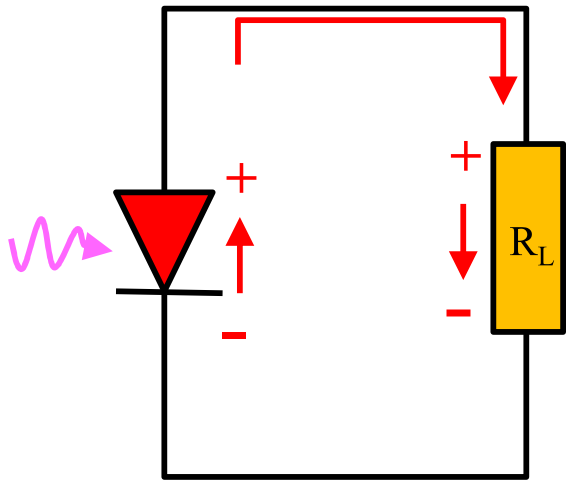
$$-J_{ph} = -\left(\frac{q}{h\nu}\right)(\eta_I + \eta_{II} + \eta_{III}) \cdot P_{opt}$$

Cellule solaire en circuit

Power = shaded area

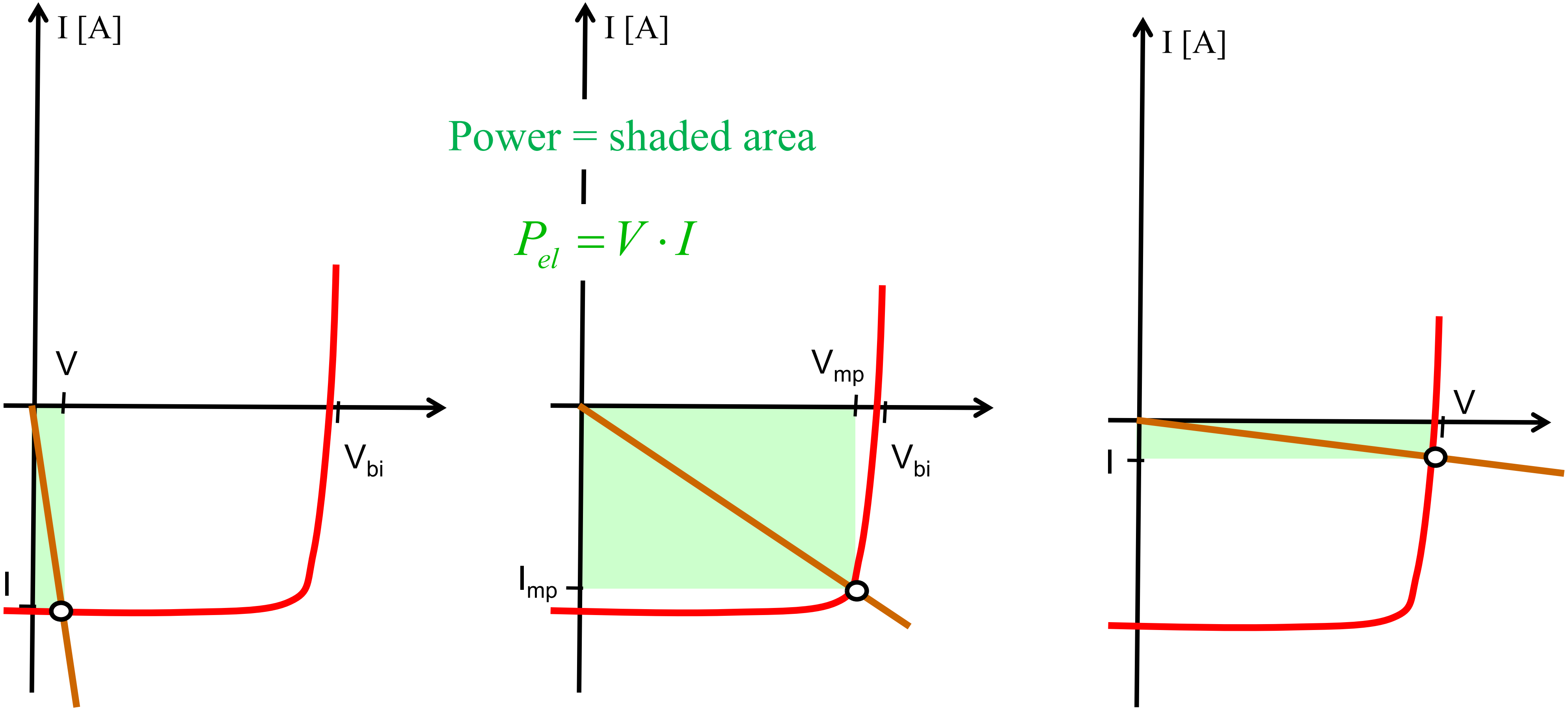
$$P_{el} = U \cdot I$$



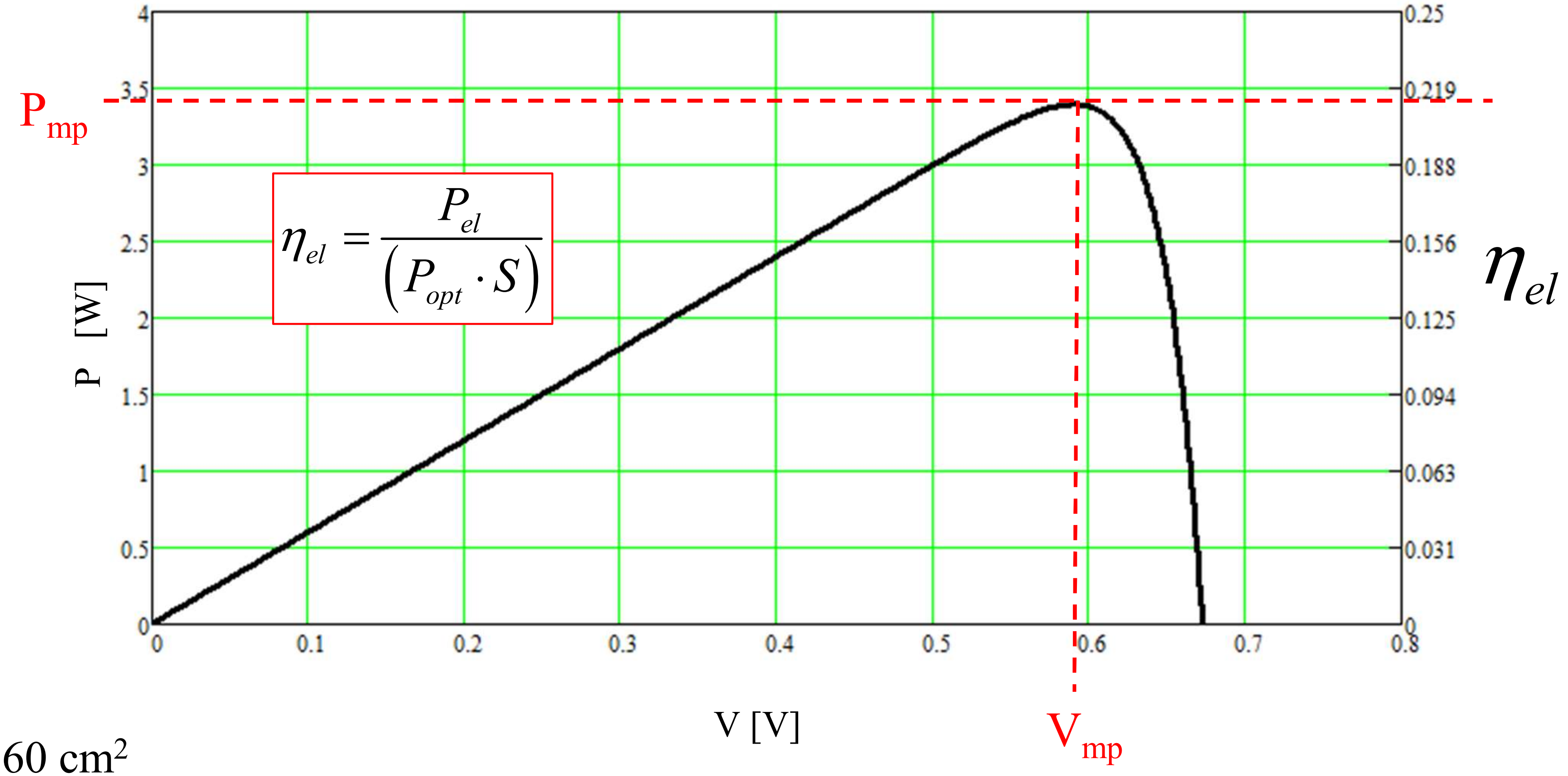


Cellule solaire et résistance de charge

R_L petit | R_L optimal | R_L grand

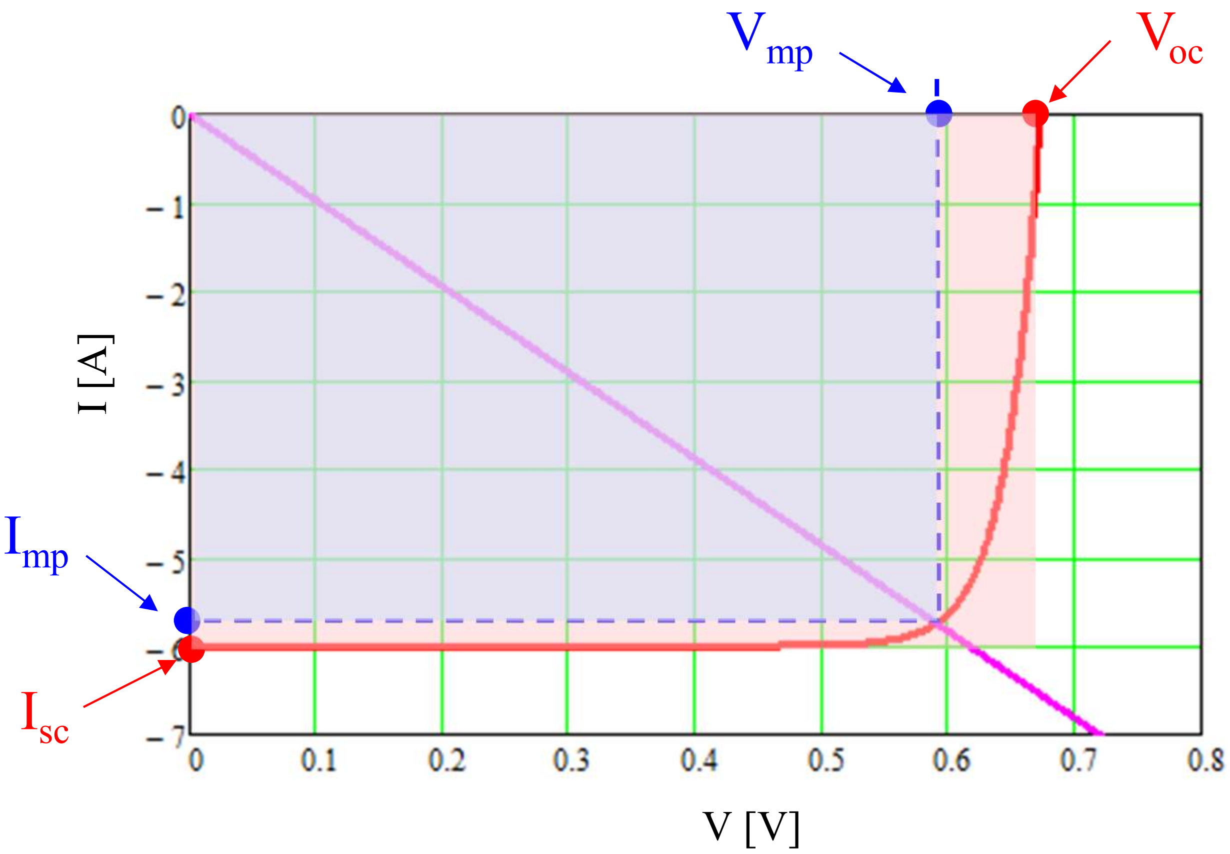


Power



$S = 160\ cm^2$
$P_{opt} = 1\ kW/m^2$

Définition: courants, tensions et fill-factor (FF)



Isc = short-circuit current (R_L=0)

Voc = open-circuit current (R_L=∞)

I_{mp} = maximal power current

V_{mp} = maximal power voltage

P_{mp} = maximal power = $V_{mp} \cdot I_{mp}$

FF = Fill-Factor = $(V_{mp} \cdot I_{mp})/(V_{oc} \cdot I_{sc})$

S=160 cm^2 = 25 pouces^2

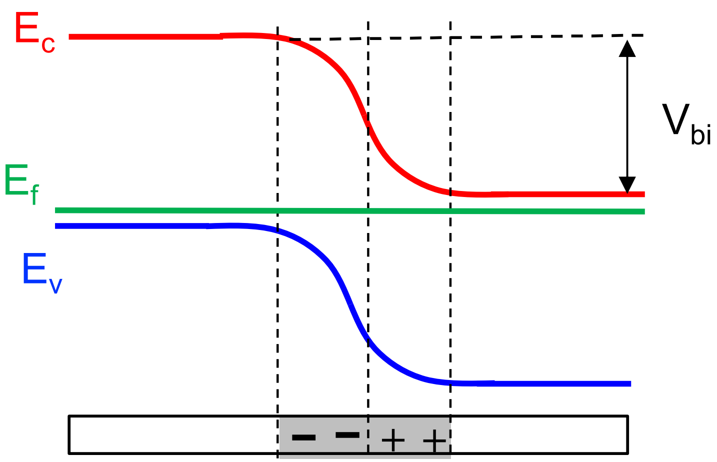
$\eta_{el} \cong 20\%$

P_{opt}=1 kW/m^2

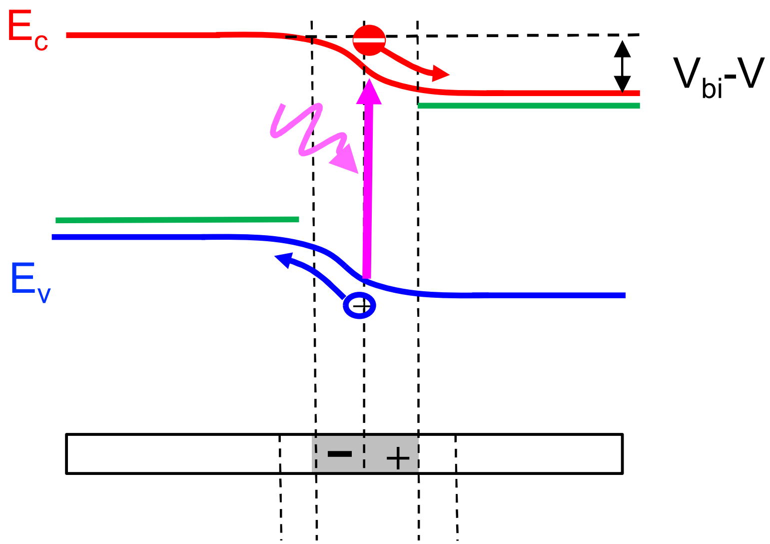
8.3: Solar cell: principe

Récupérer V_{bi} en réduisant la zone de déplétion

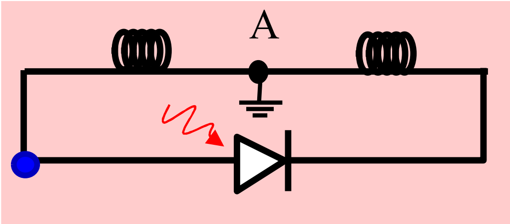
Solar cell: no illumination

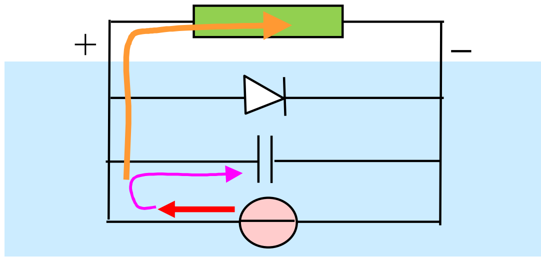


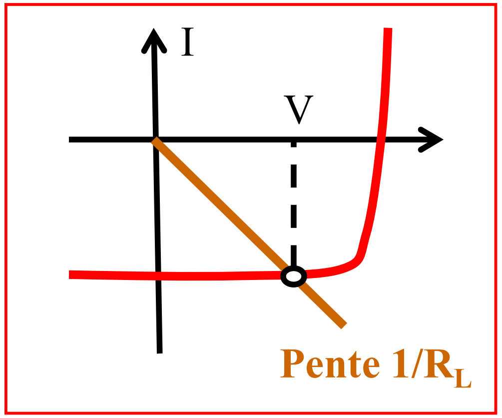
Solar cell: with illumination

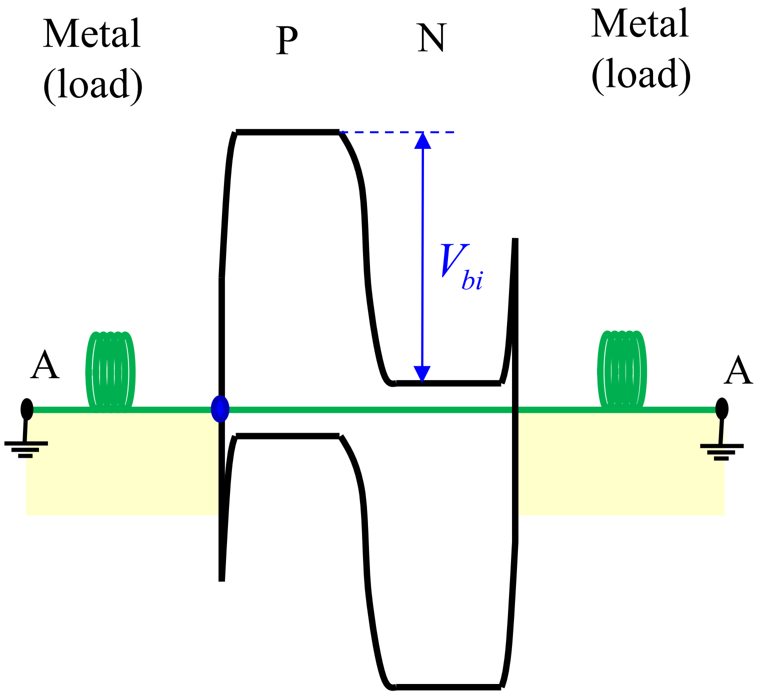


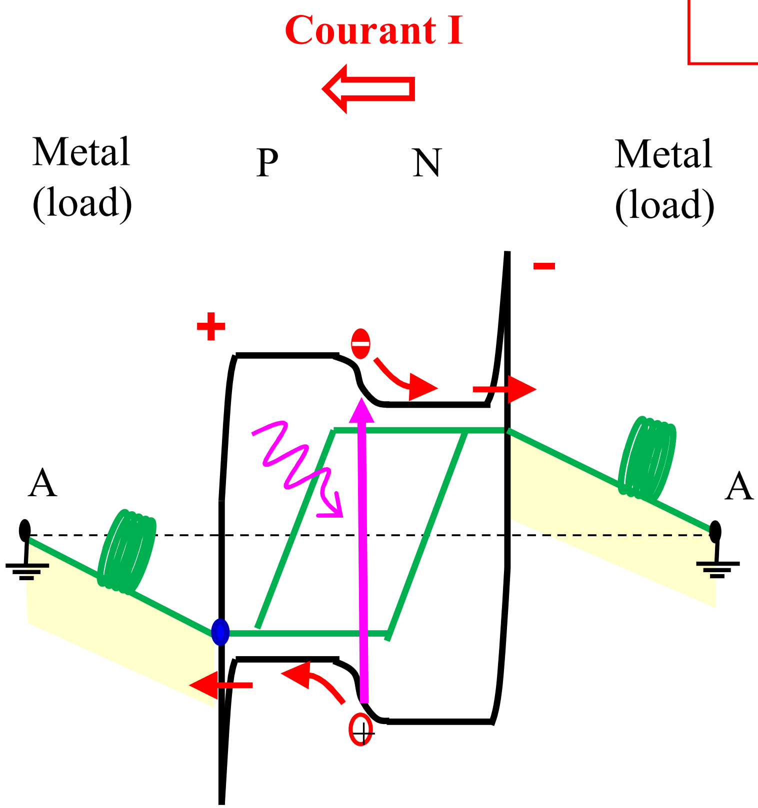
Solar cell: principe



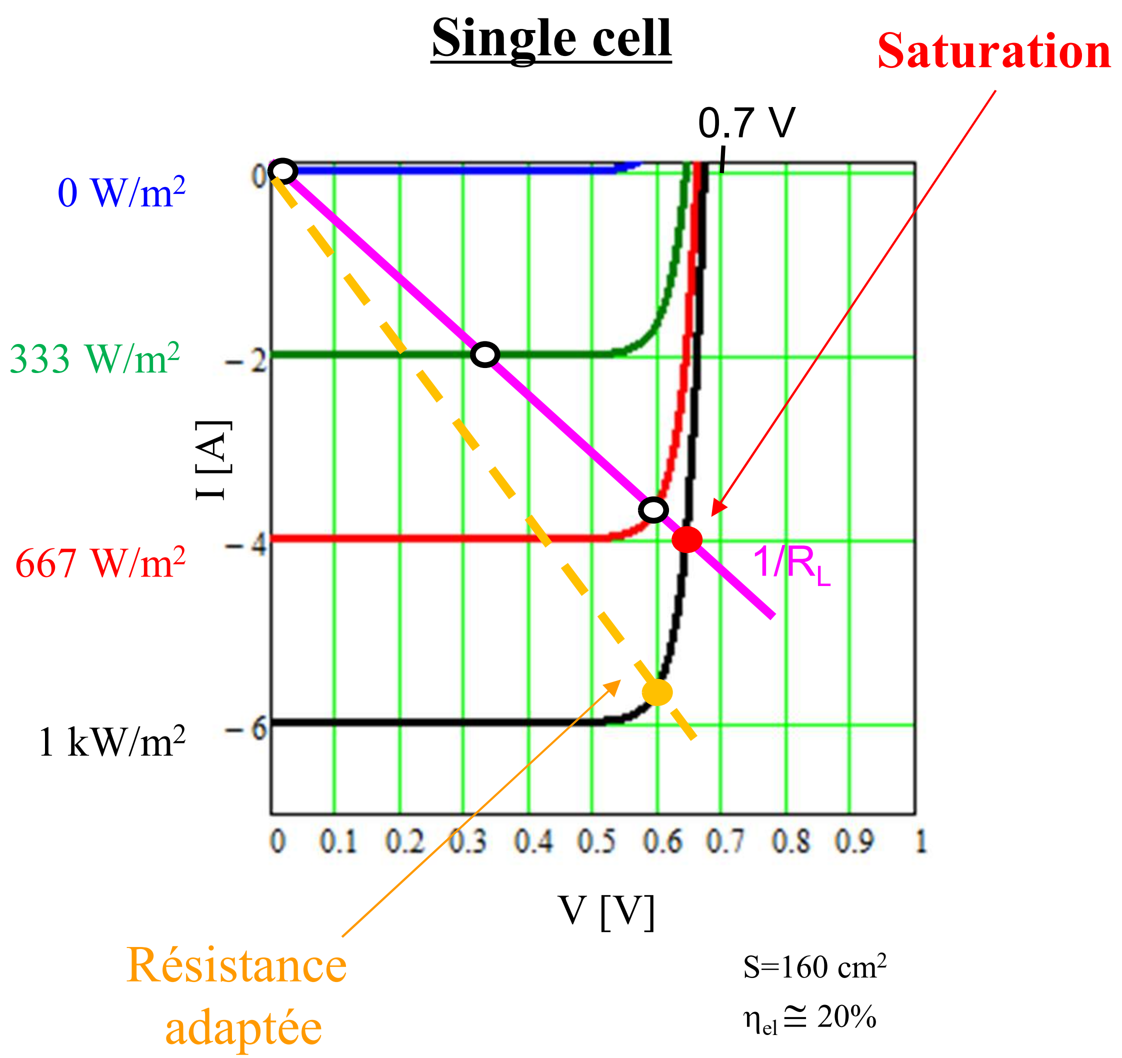


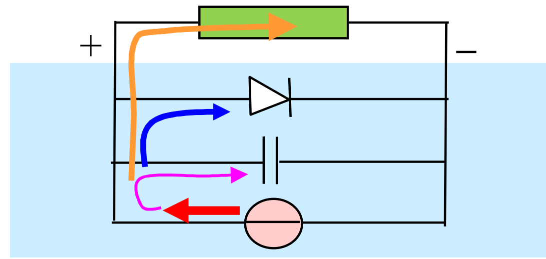


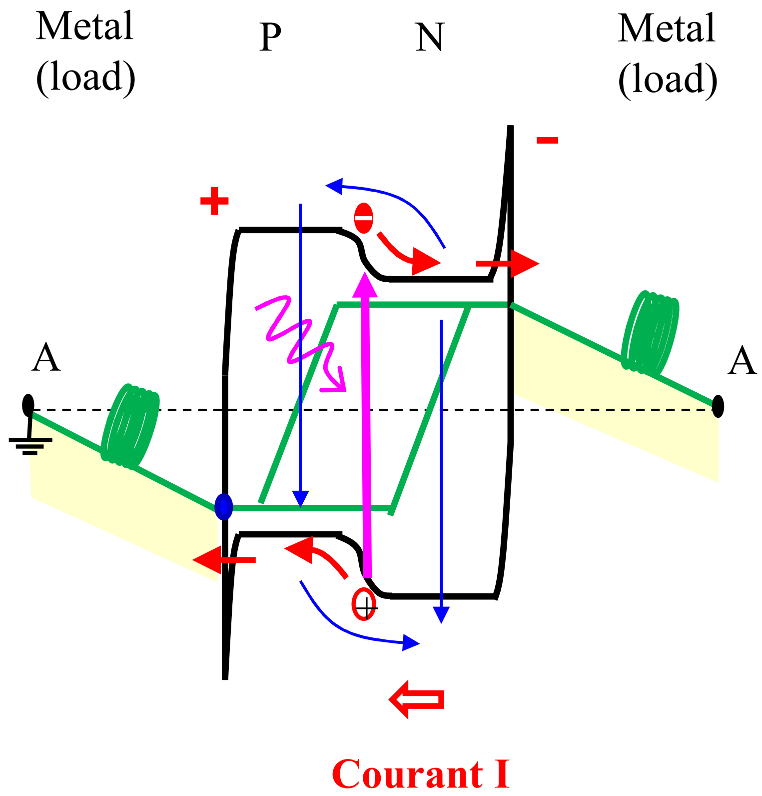




Solar cell: principe







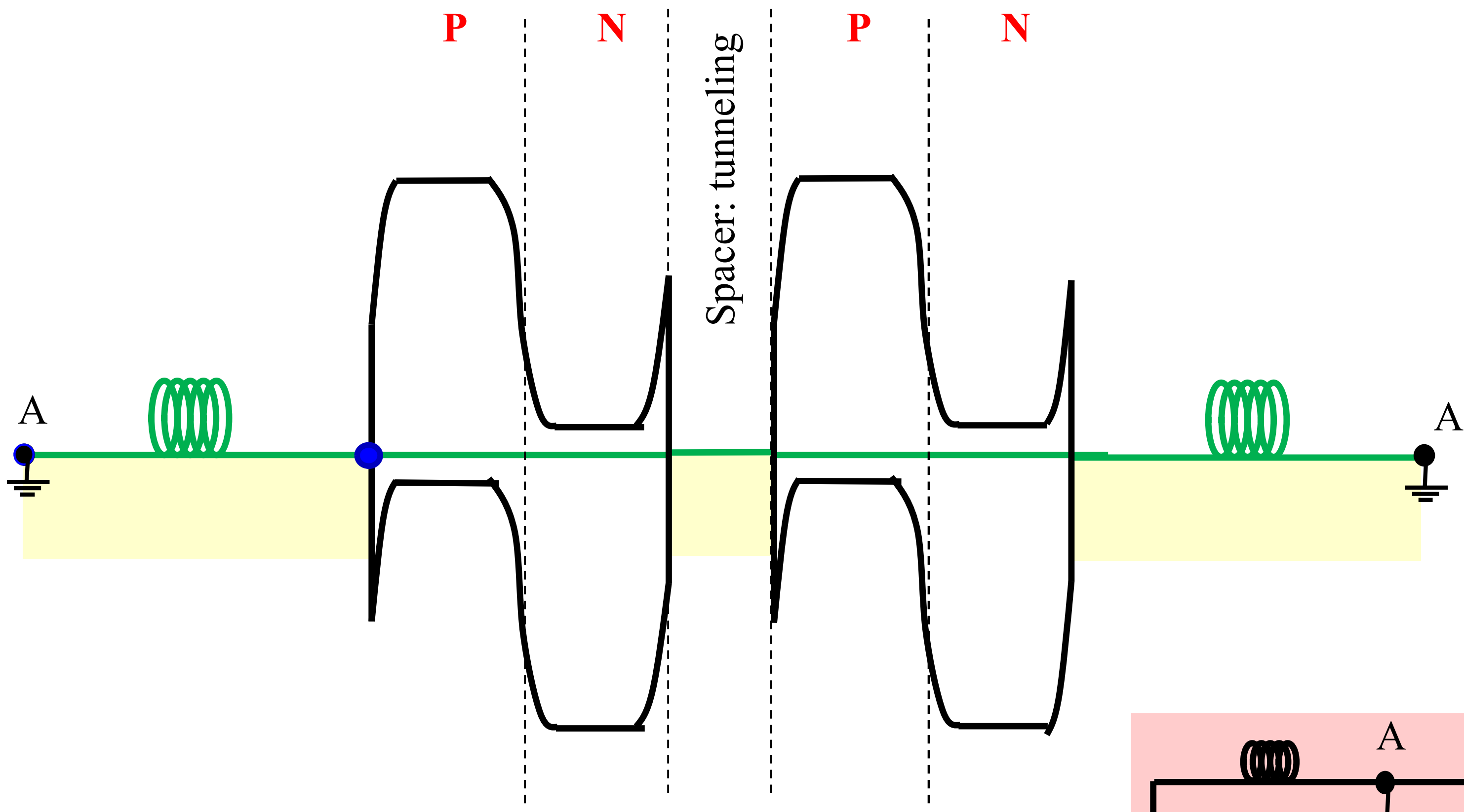
8.4: Exercice: Solar calculator

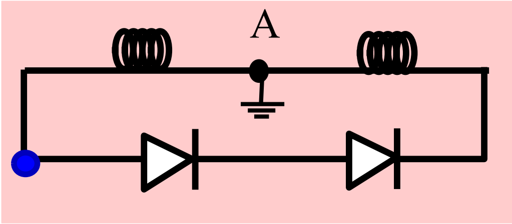
Why ?

4 cells

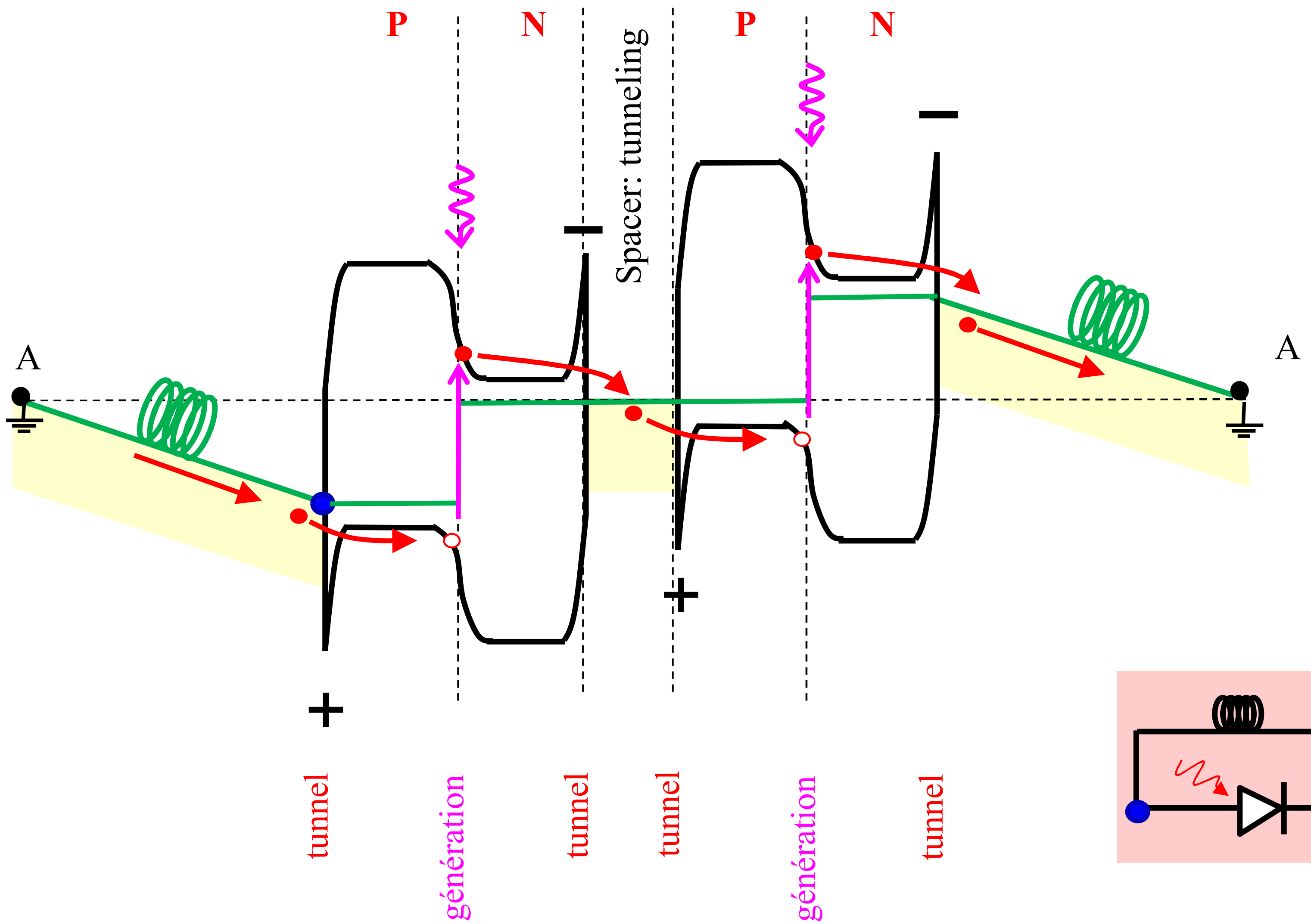
Vintage calculator
9 cells

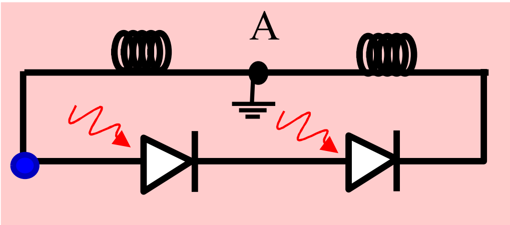
Two Solar Cells in Series (1): no illumination



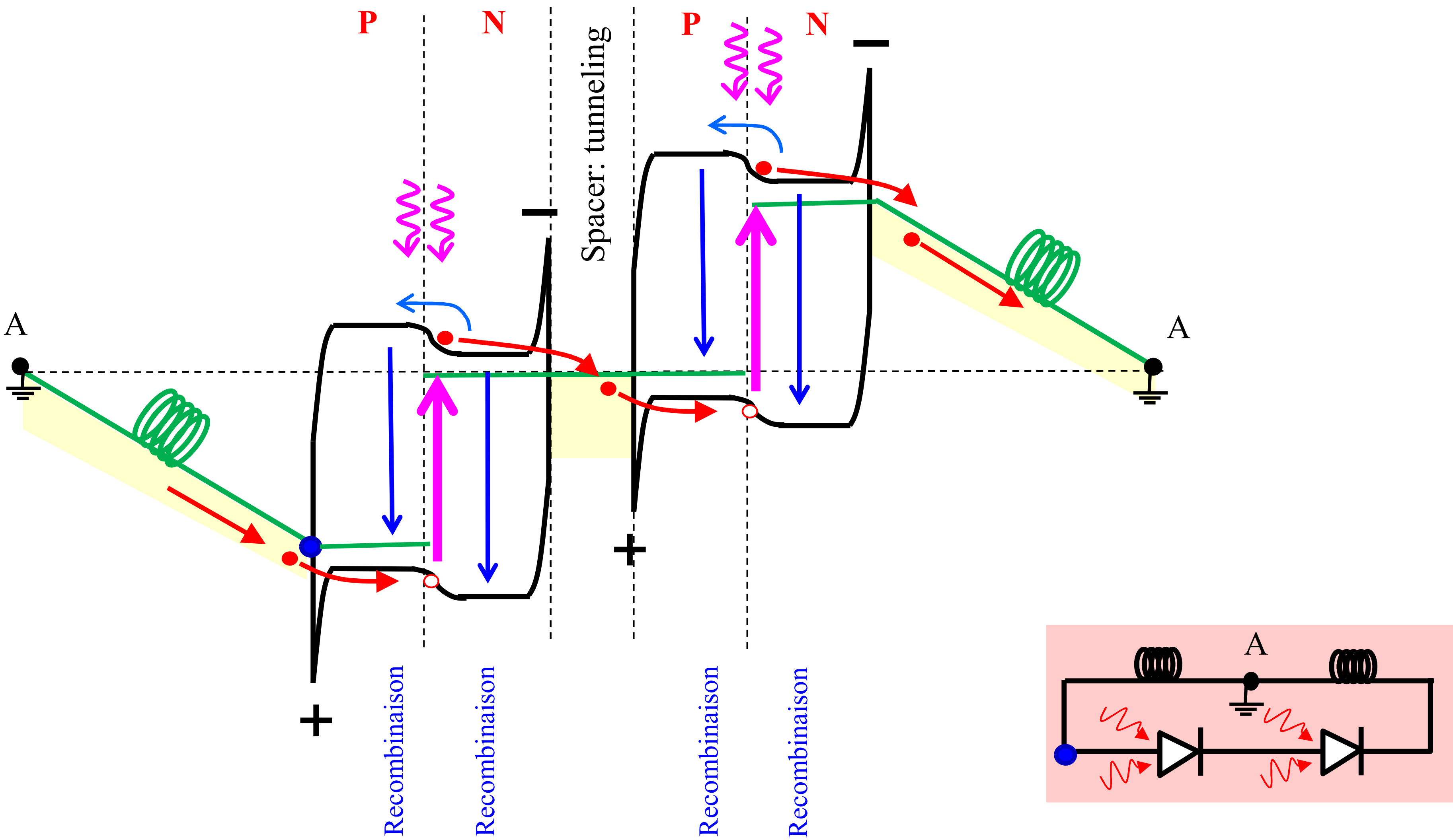


Two Solar Cells in Series (2): under illumination

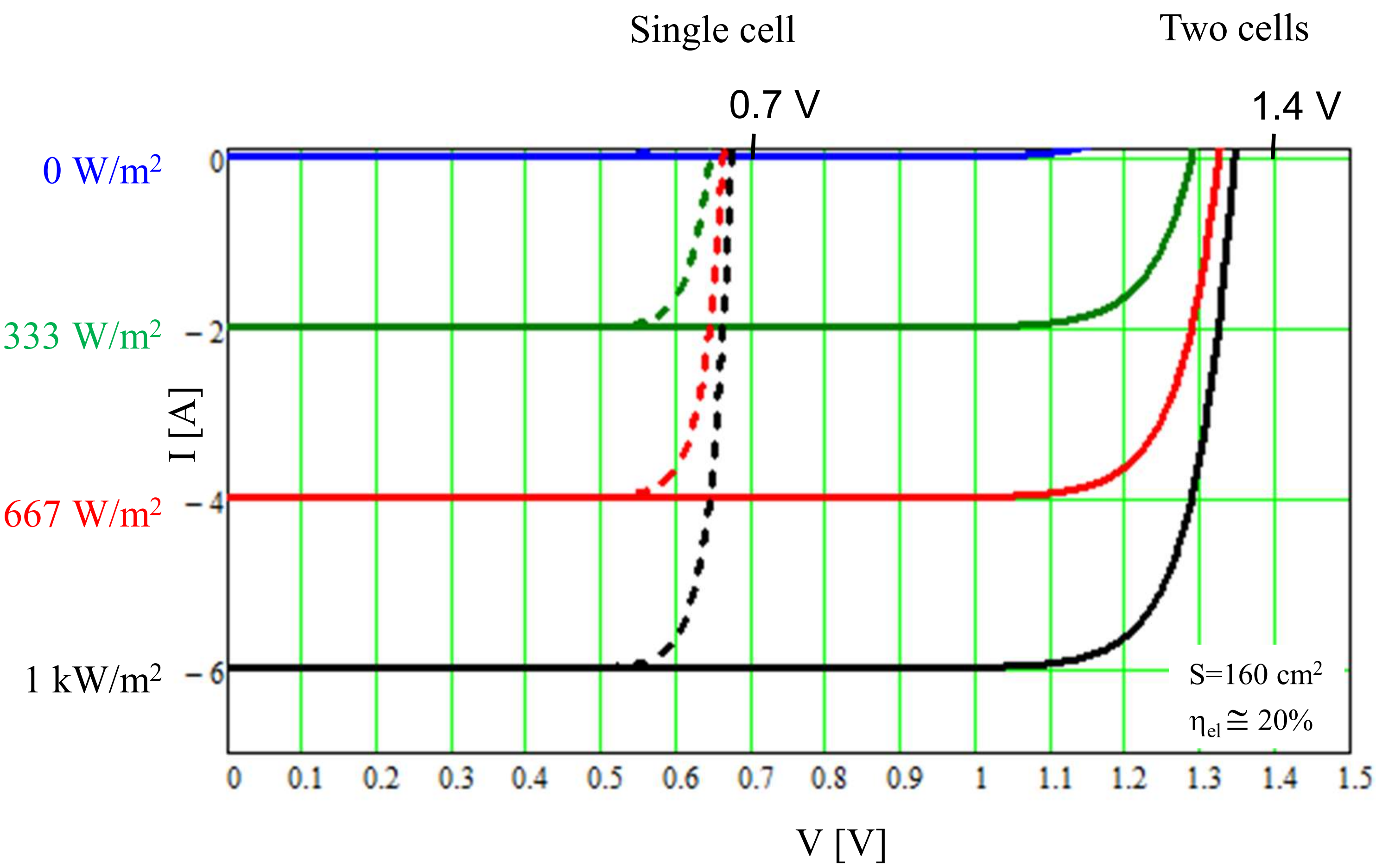




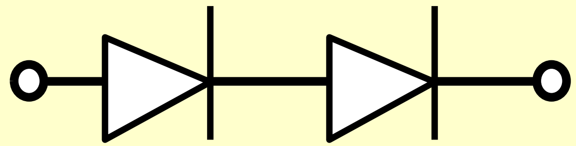
Two Solar Cells in Series (3): saturation



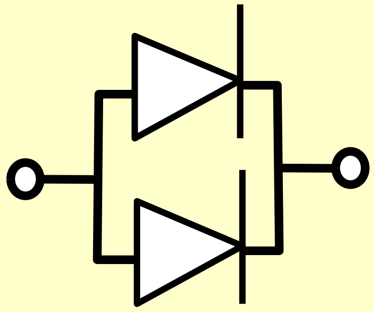
Two Solar Cells in Series (4)



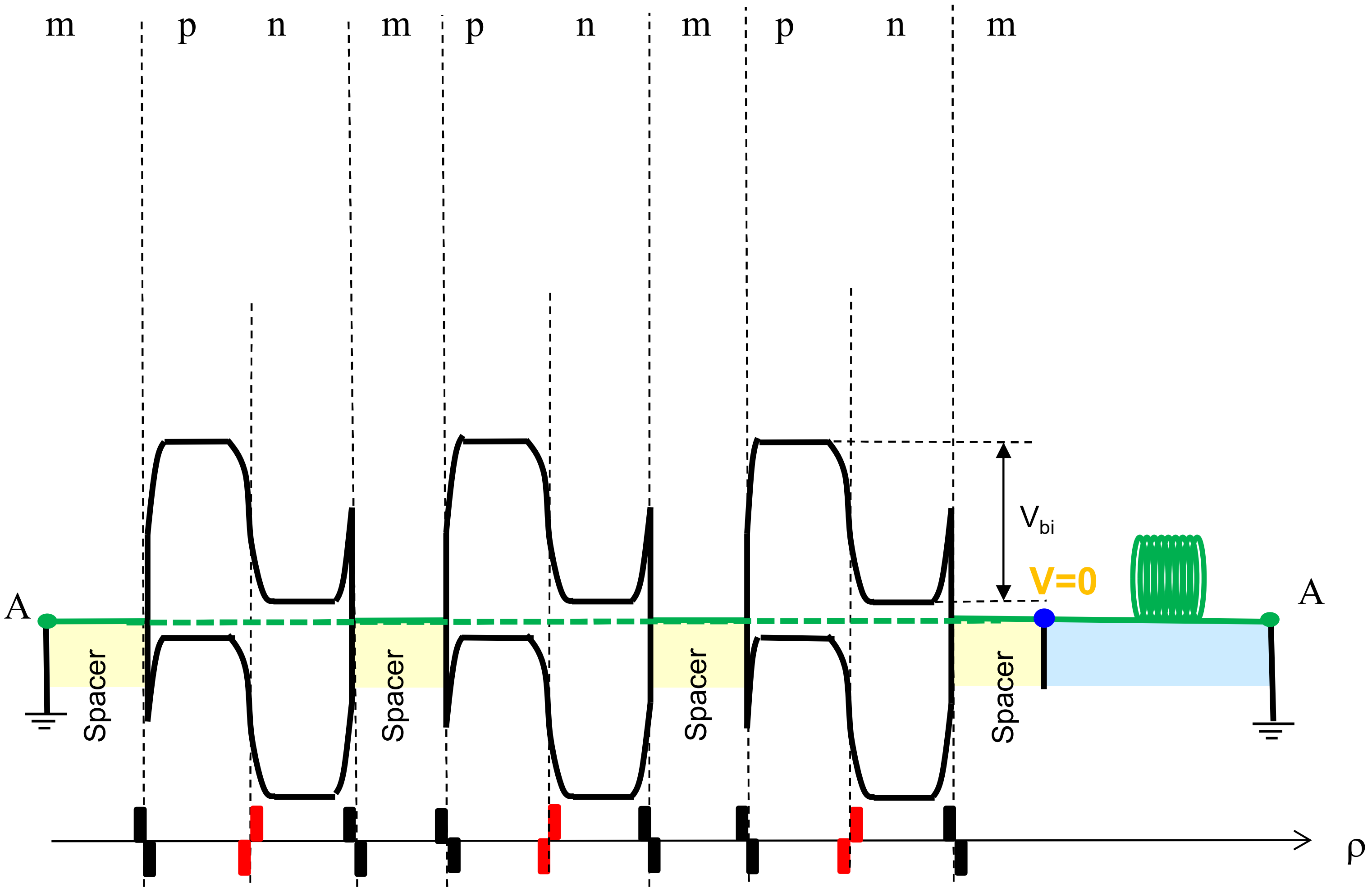
- n cells in series
  → same current
  at n times the voltage



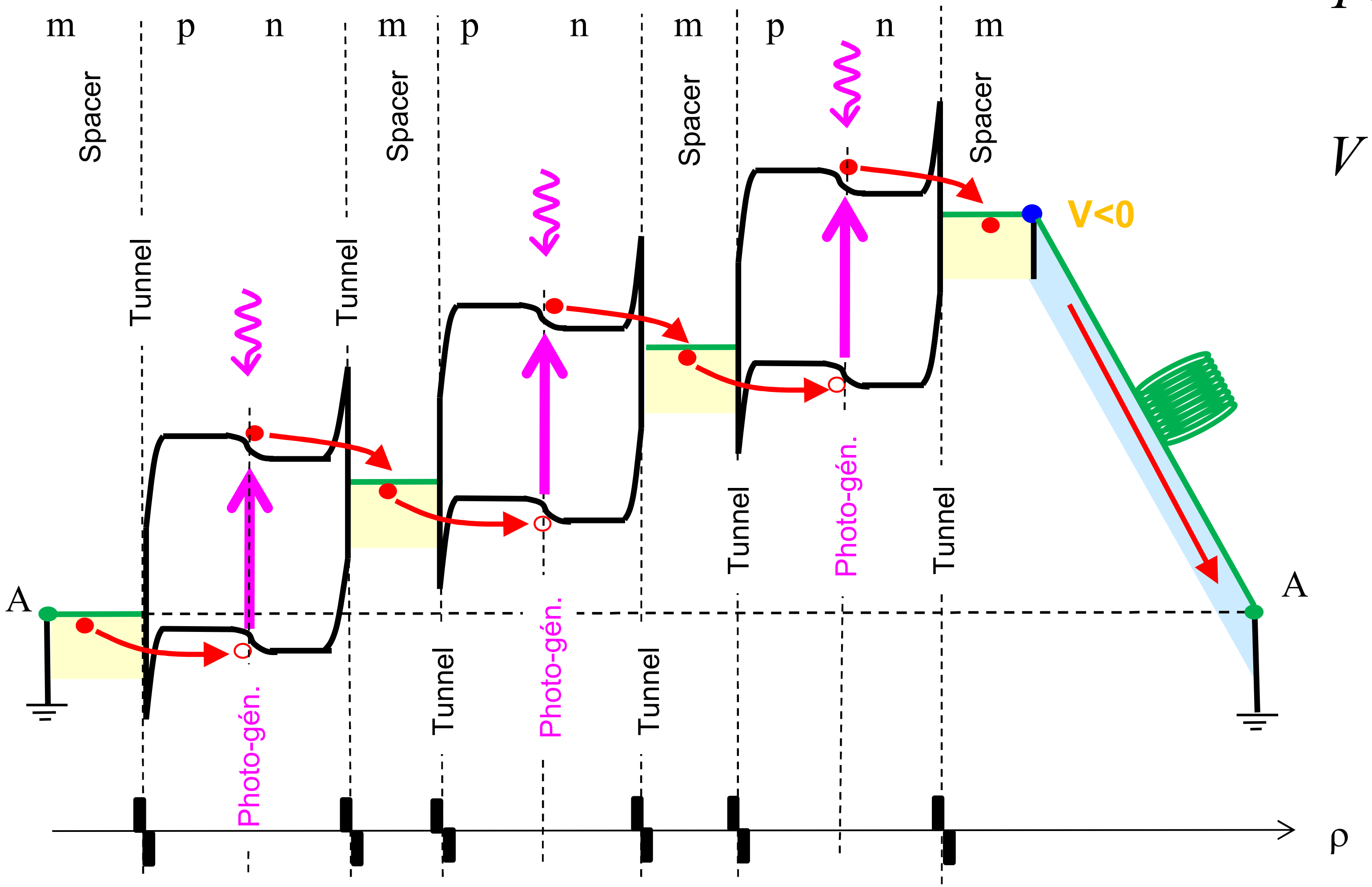
- n cells in parallel
  → n times the current
  at the same voltage



Solar cells in series: no illumination



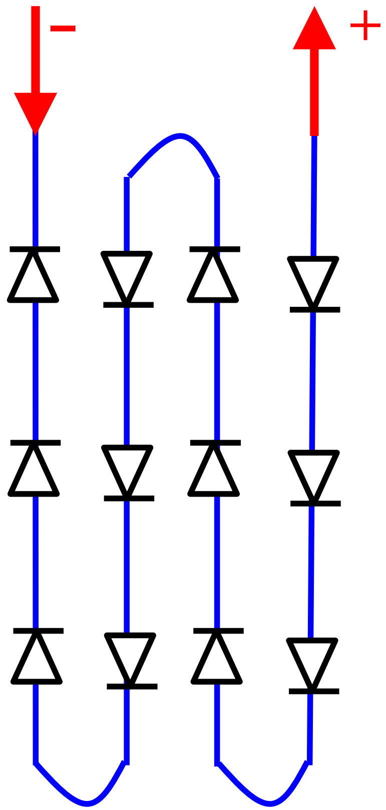
Solar cells in series: under illumination

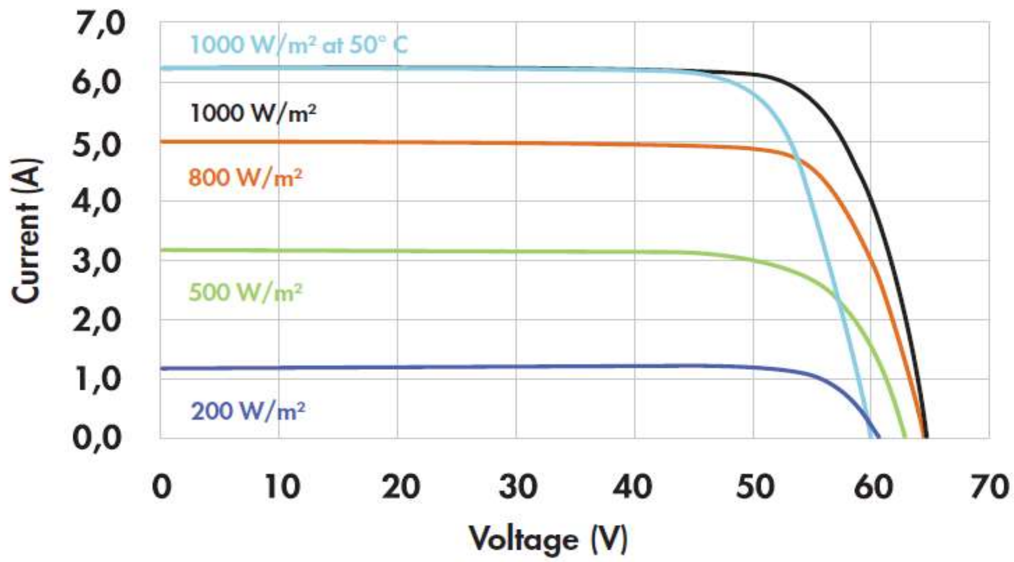


$$I = I_1 = I_2 = I_3 \ldots = I_n$$

$$V = \sum_n V_n$$

Example of a Panel: Sun Power 315





96 cells in series → 96xV_{oc}= env. 60V

Series of solar panels

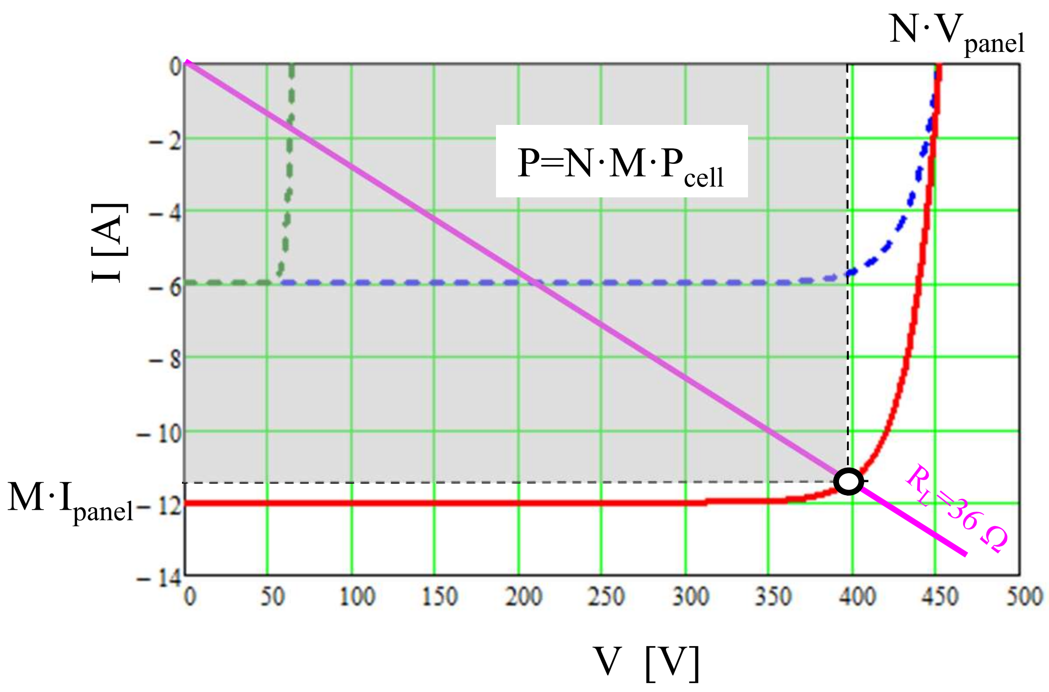
N panels in series: → same current, sum of all voltages

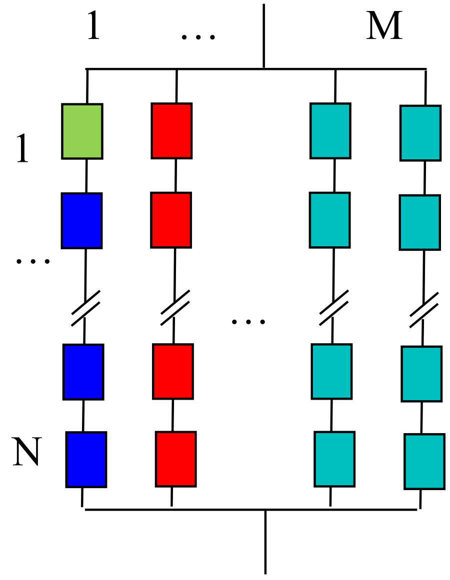
M panels in parallel: → sum of the currents same voltage

N=M=1

N=7, M=1

N=7, M=2



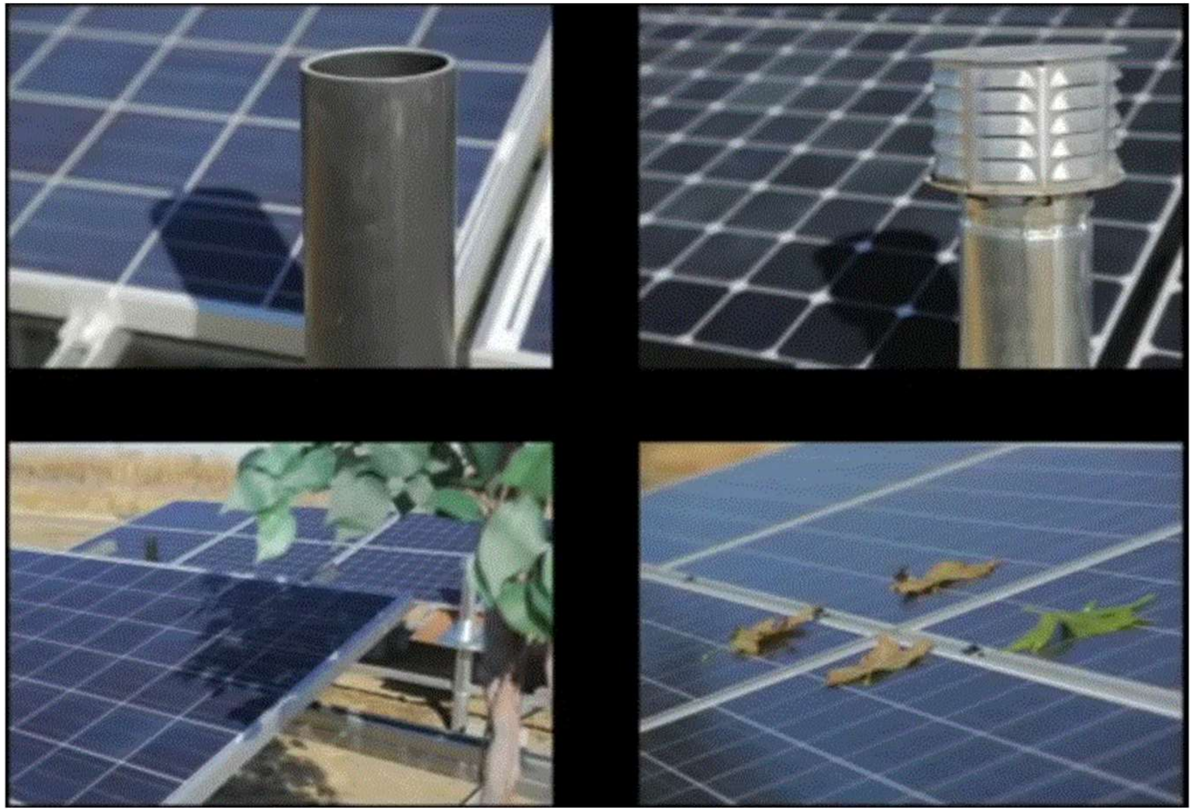


1 kW/m²
I_{panel}=6A
V_{panel}=64V

8.5: Solar Cell with a Defect

Ombres:

- Cheminée
- Arbres
- Feuilles
- …

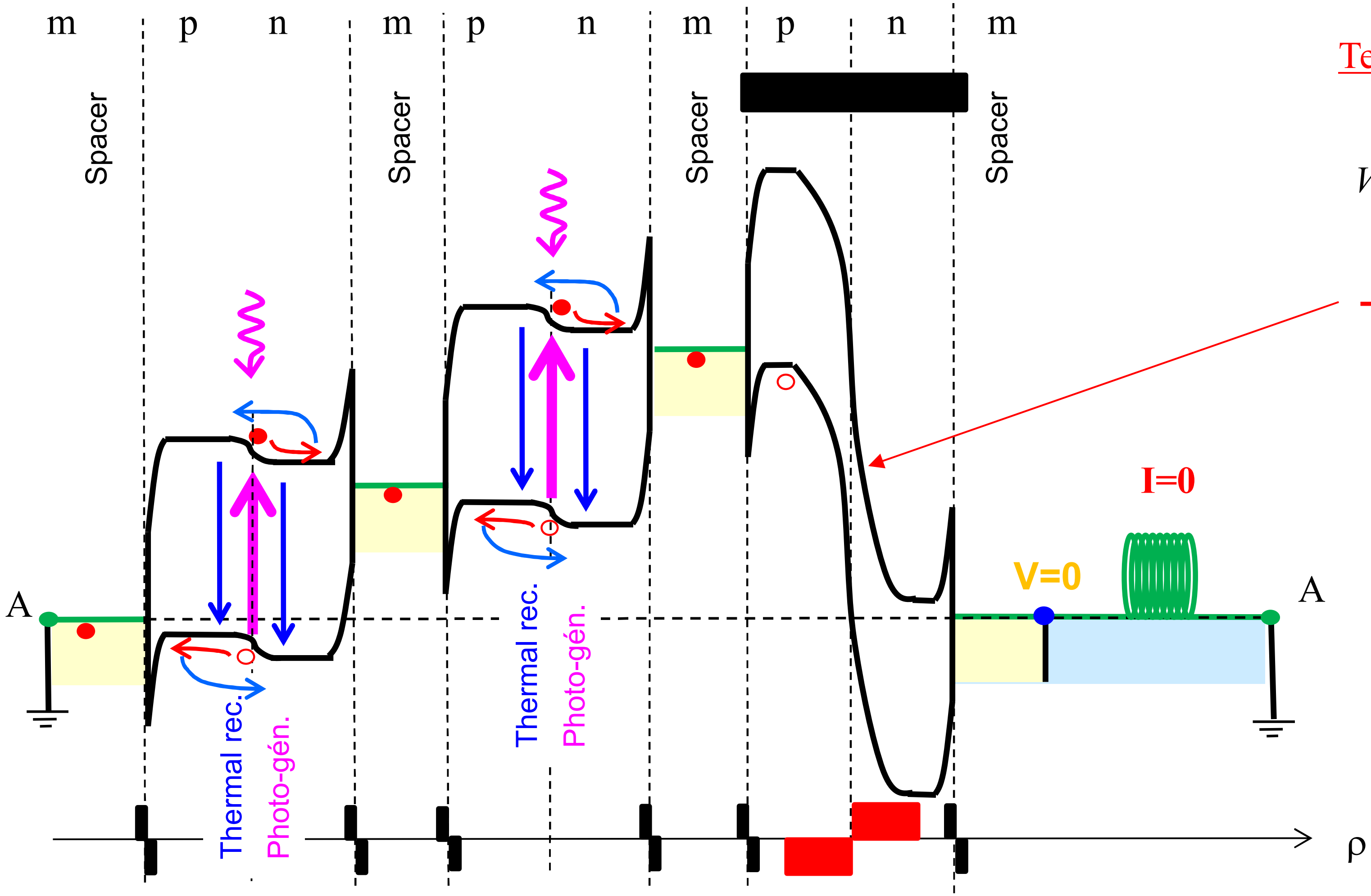


https://www.youtube.com/watch?v=sznZHSuZXrc

Question:

Quels effets ?

Solar cells in series: one defect



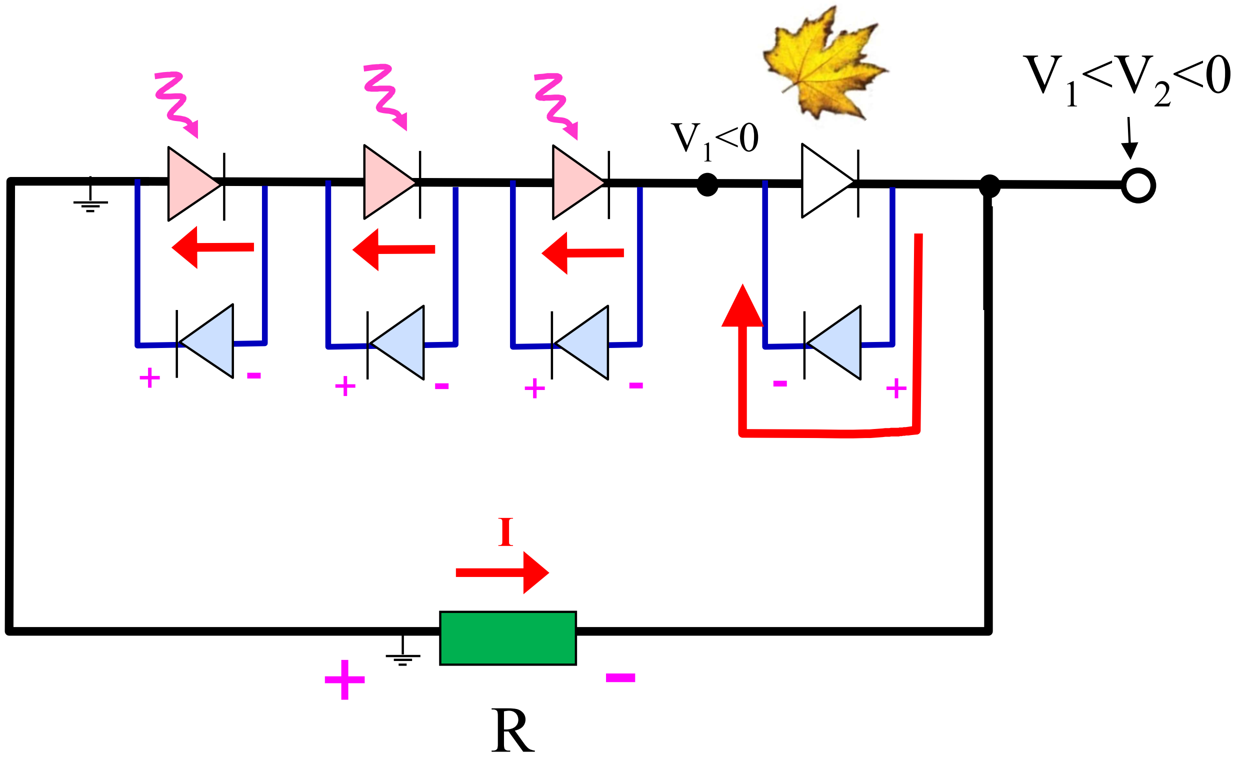
Tension sur la dernière cellule:

$$V_n = -\sum_{j=1}^{n-1} V_j \quad \ll 0$$

→ **Risque de claquage**

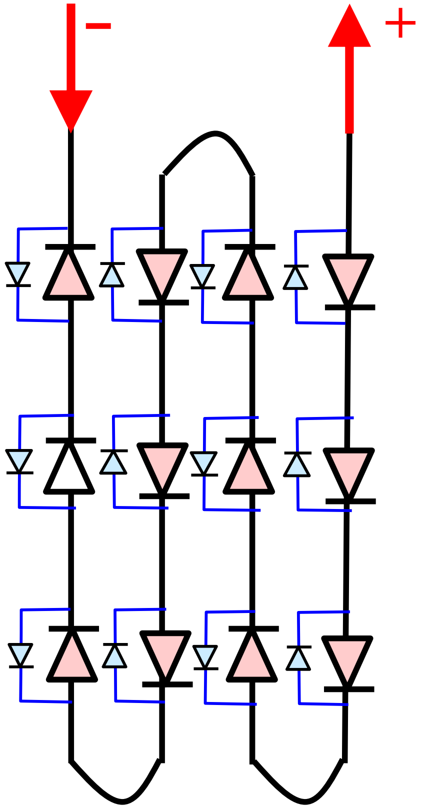
$$I = \min\left[I_1, I_2, I_3, \ldots I_n\right] = 0$$

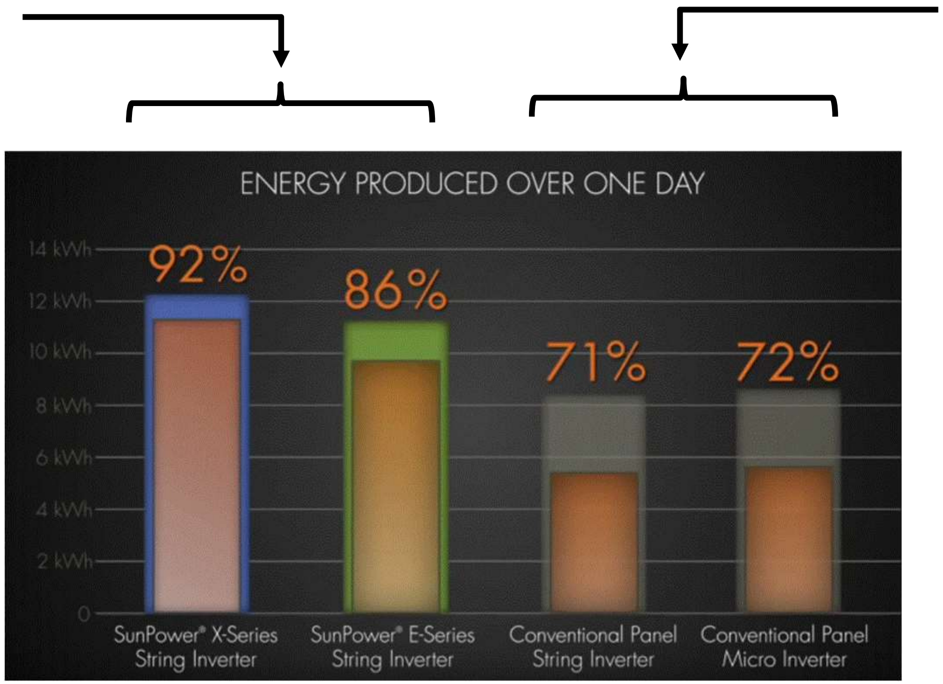
Solar Cell with protection

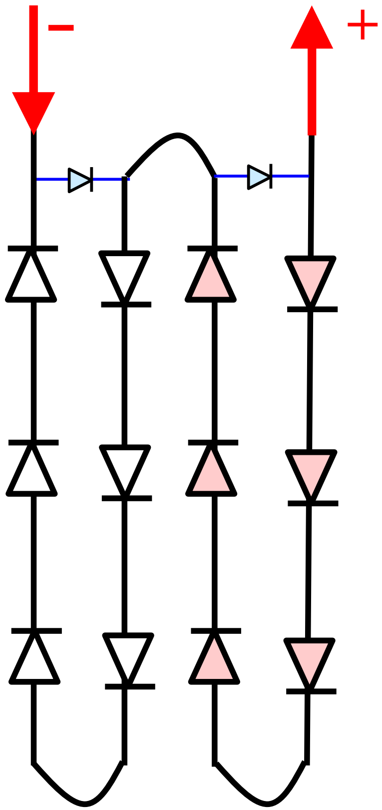


By-pass diodes

Panneaux solaires
avec diodes de by-pass

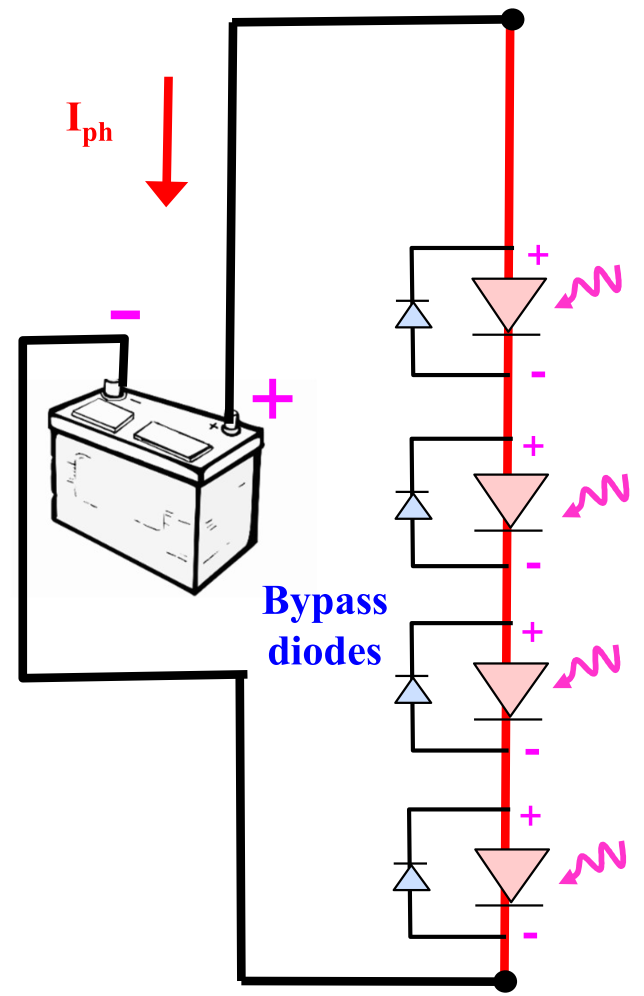


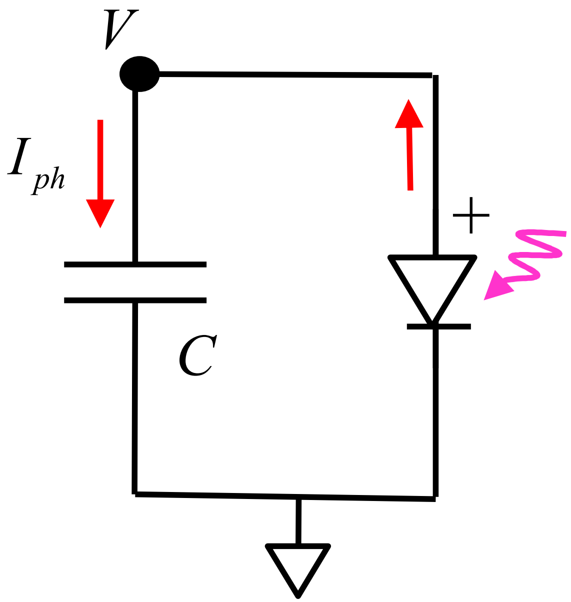


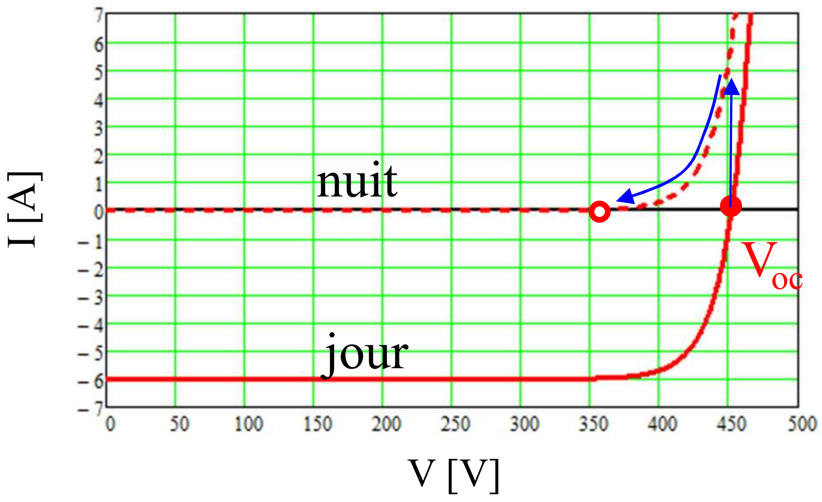


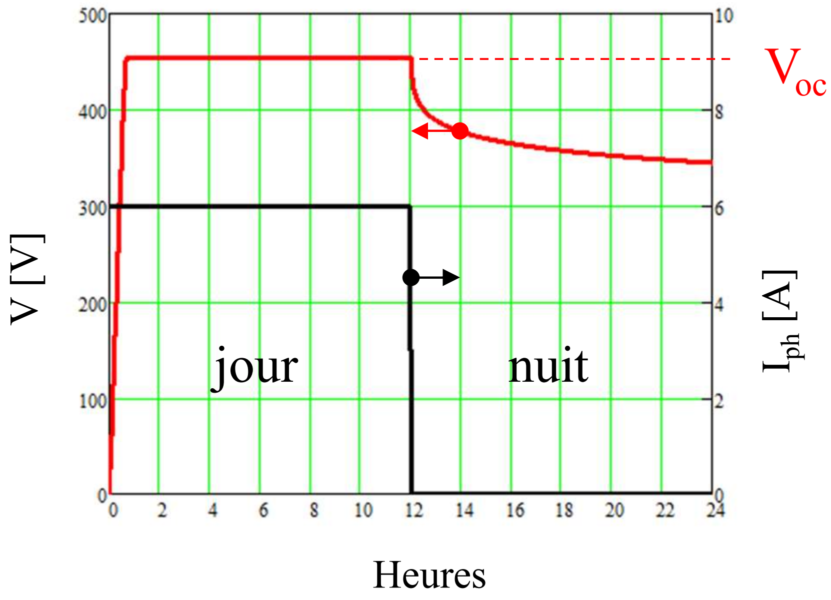
https://www.youtube.com/watch?v=sznZHSuZXrc

Charge et décharge de la batterie







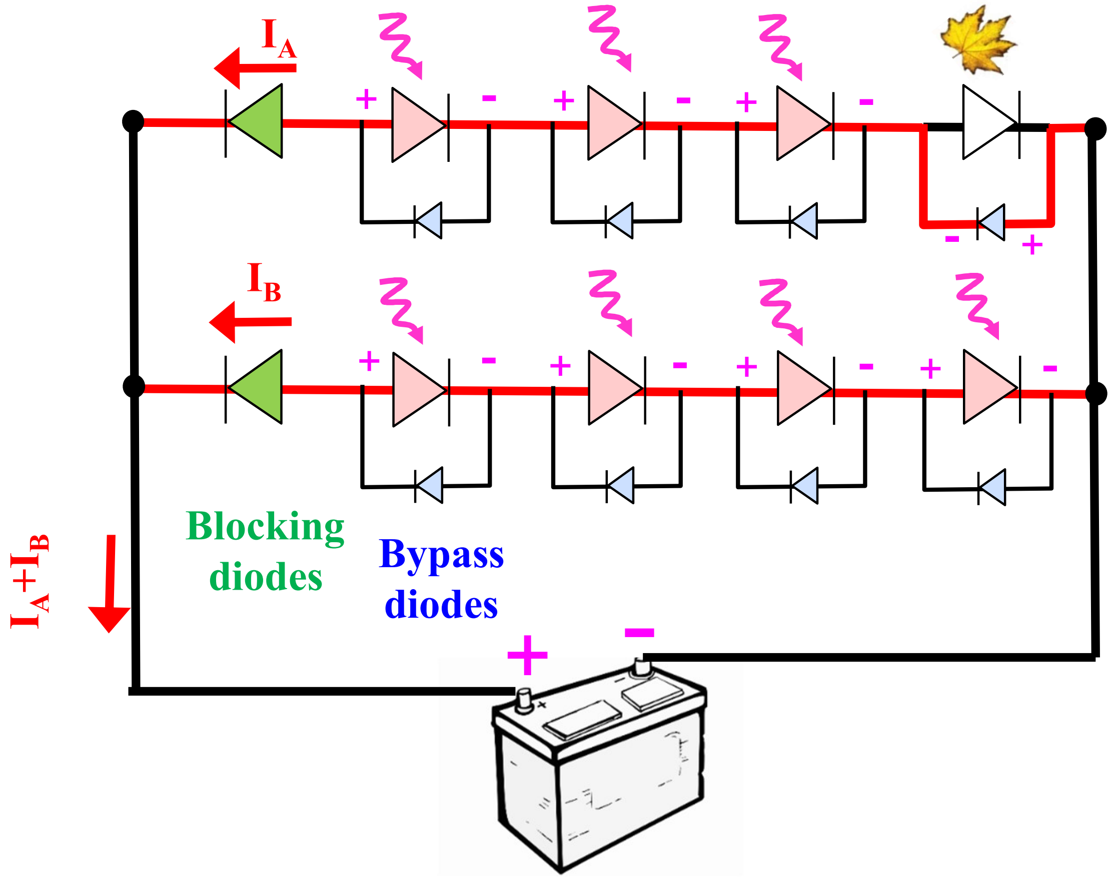


Blocking and bypass diodes

Blocking diodes:

→ Eviter:

- Décharge de nuit
- Courant inverse dans la branche faible



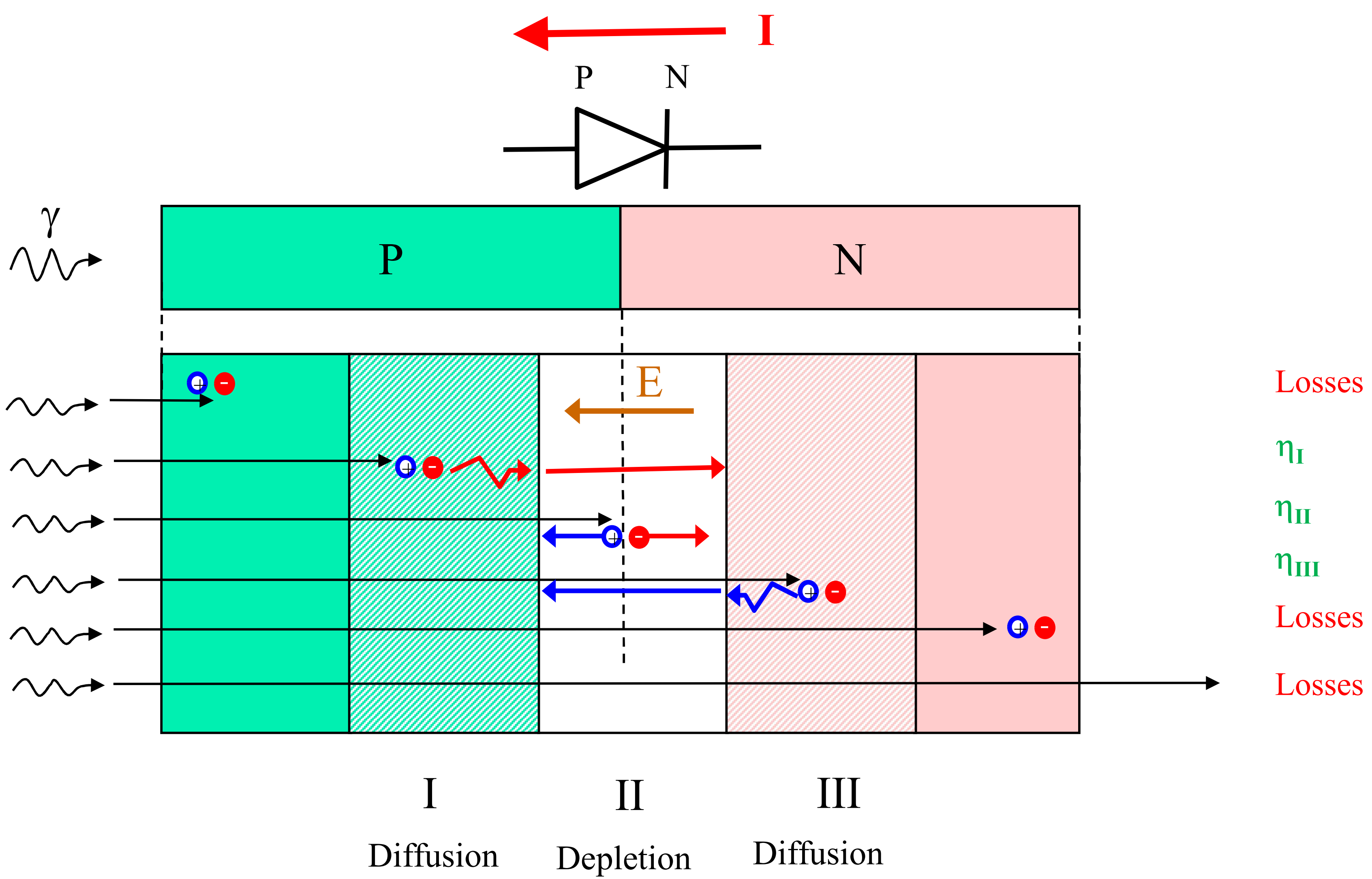
Low corner voltage
→ Schottky diodes as:

- bypass and

- blocking

PV lab, Prof.. Ballif et Dr. Haug

8.6: Schematic diagram of the working principle

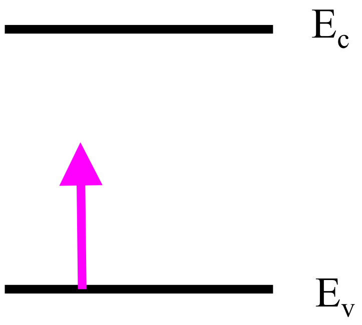


Pertes et efficience optimal d'une jonction unique

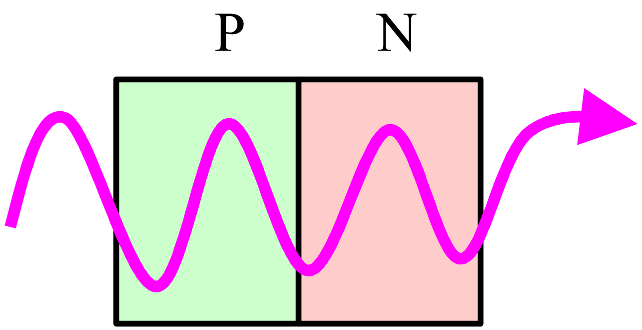
$$\underbrace{2/3}_{\text{Transparence} \quad \text{Thermalisation}} \qquad 1/3$$

Transparence **Thermalisation** **Optimal**

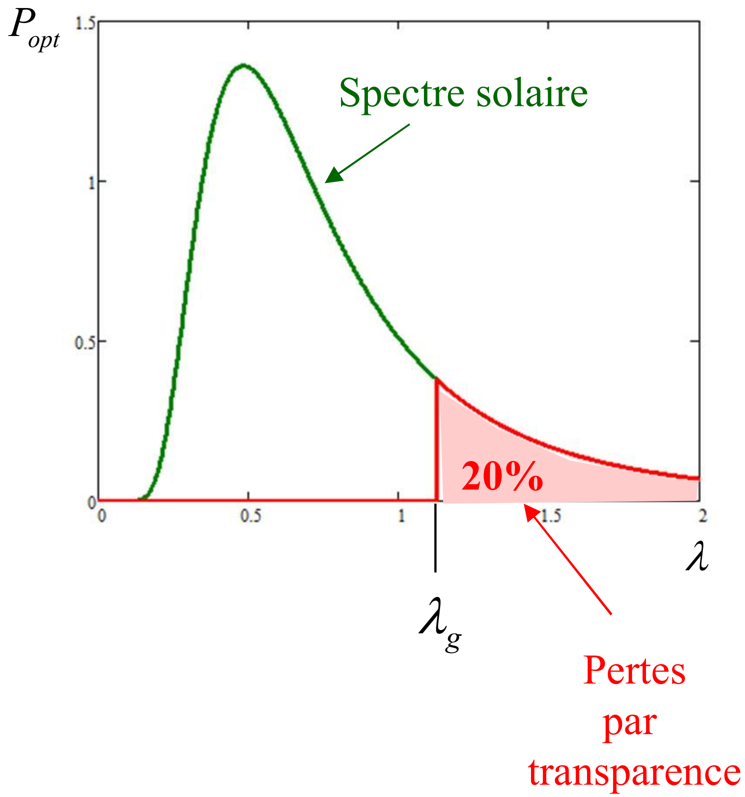
Pertes: (1) par transparence



$$h\frac{c}{\lambda} < E_g$$

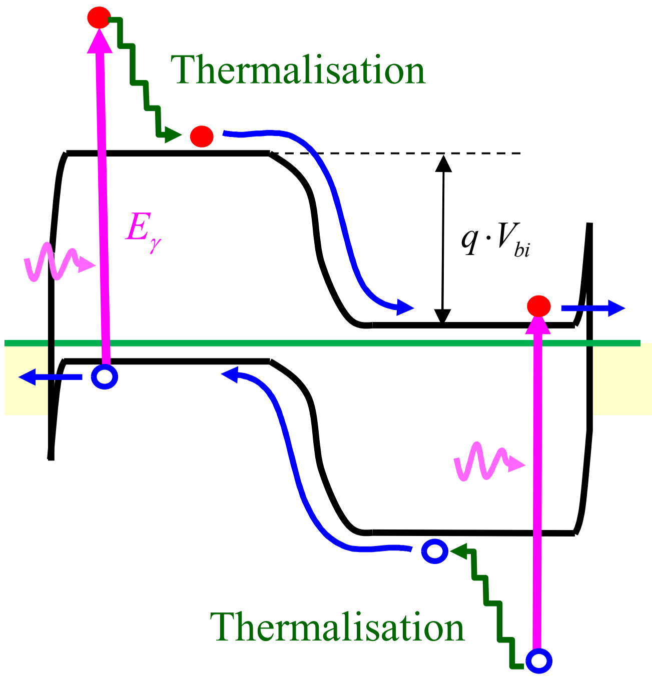


Silicium monocristallin

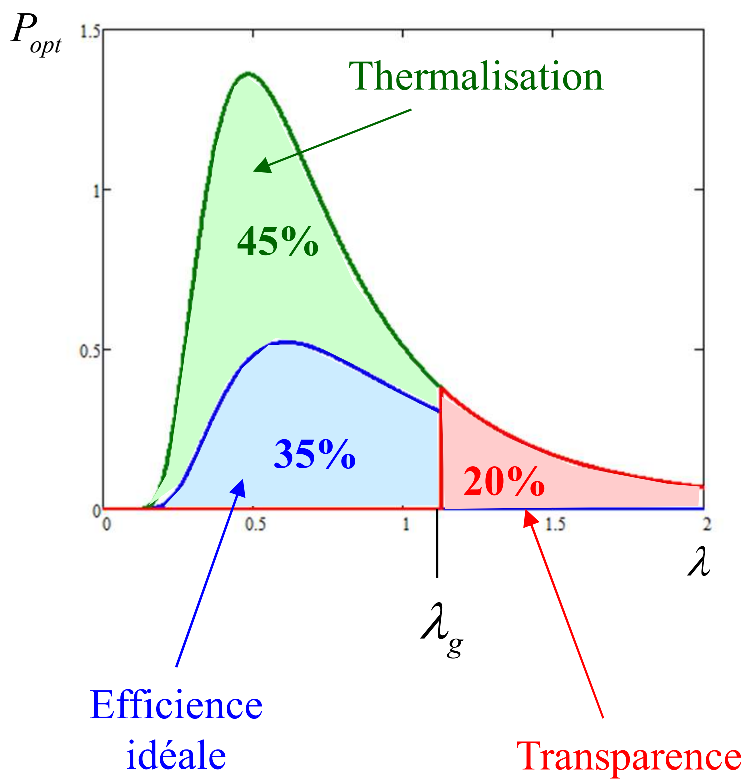


Le semiconducteur est transparent pour $\lambda > \lambda_g$

Pertes: (2) par thermalisation

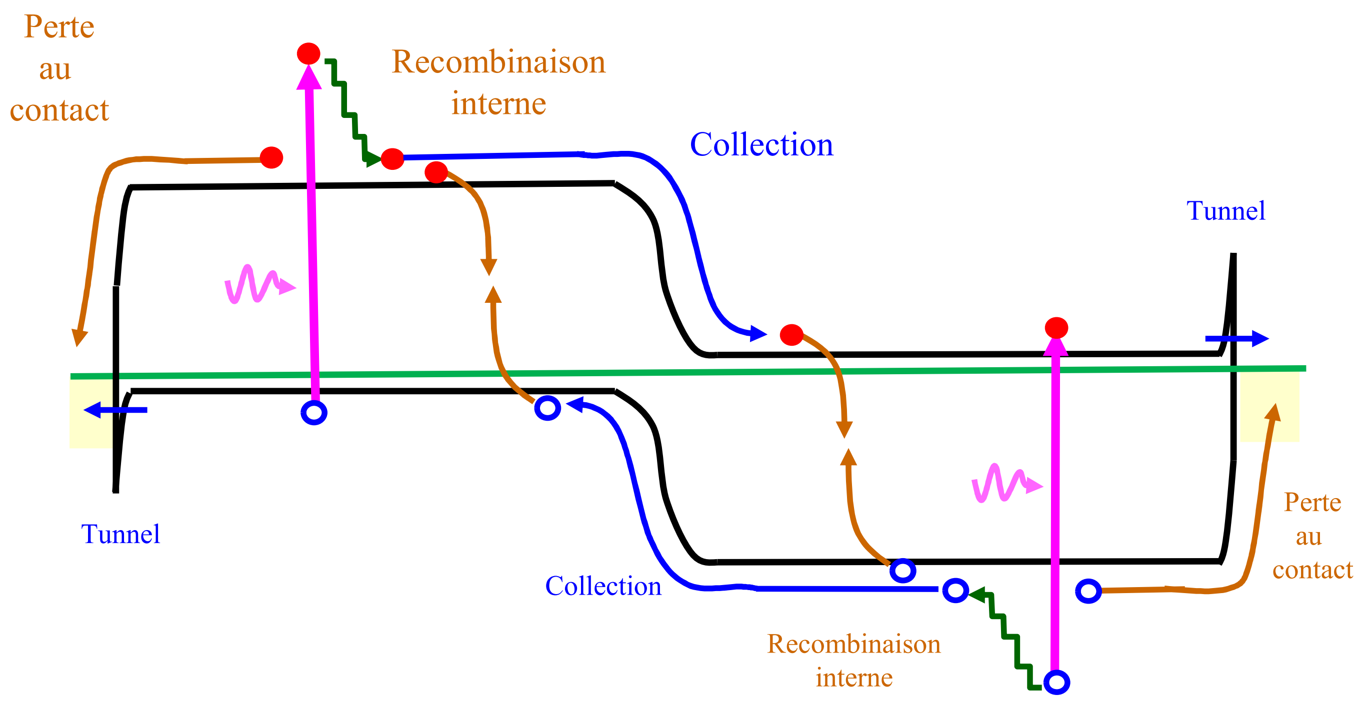


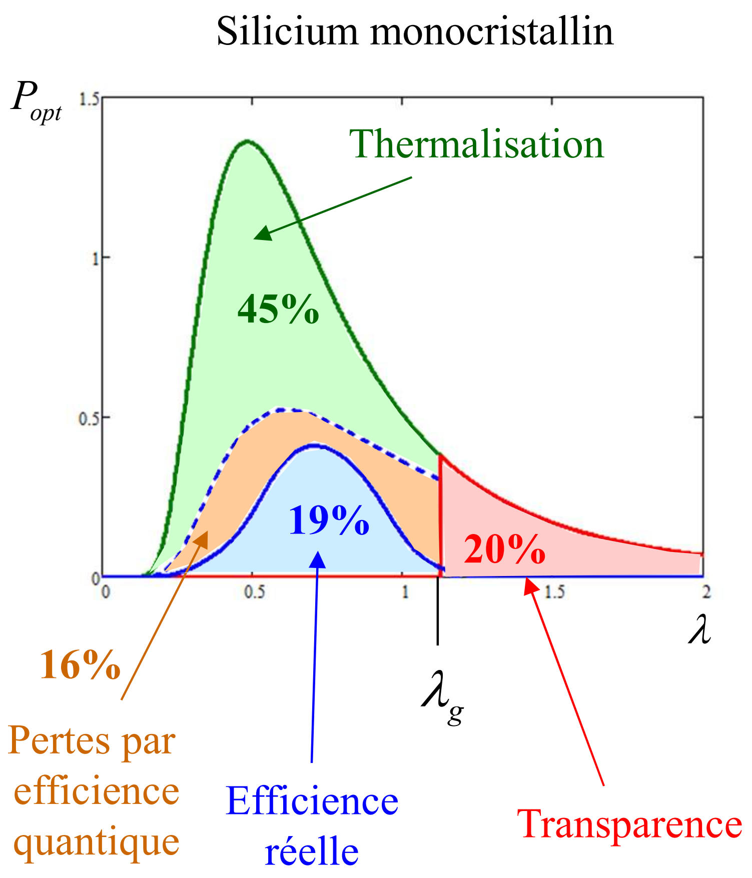
Silicium monocristallin



Investir : $E_\gamma = h\dfrac{c}{\lambda}$ pour récolter : $q \cdot V_{bi}$ $\Longrightarrow$ $\eta_{el,idéale}(\lambda) = \dfrac{qV_{bi}}{hc} \cdot \lambda$

Pertes: (3) par efficience quantique

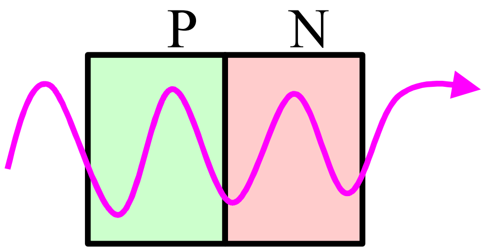




$$\eta_{el,réelle}(\lambda) = \eta_Q \cdot \frac{qV_{bi}}{hc} \cdot \lambda = R_I \cdot V_{bi}$$

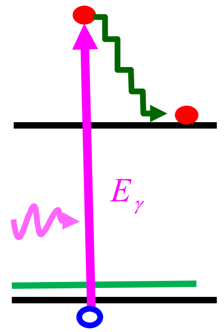
Résumé des pertes d'efficience électriques

1) transparence



⇨ Petit bandgap

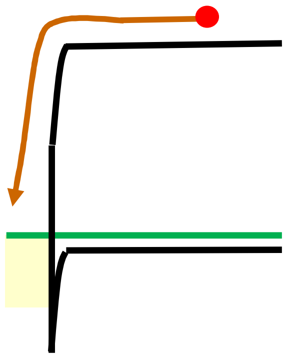
2) thermalisation

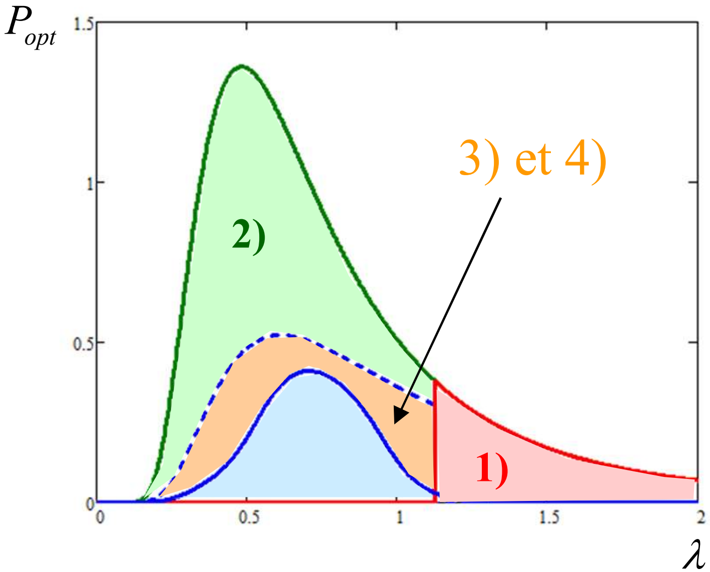


⇨ Grand bandgap

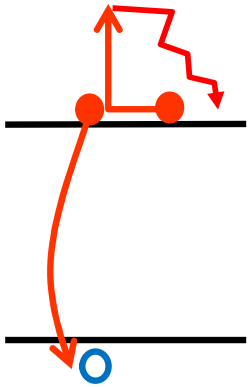
2/3

3) Pertes aux contacts



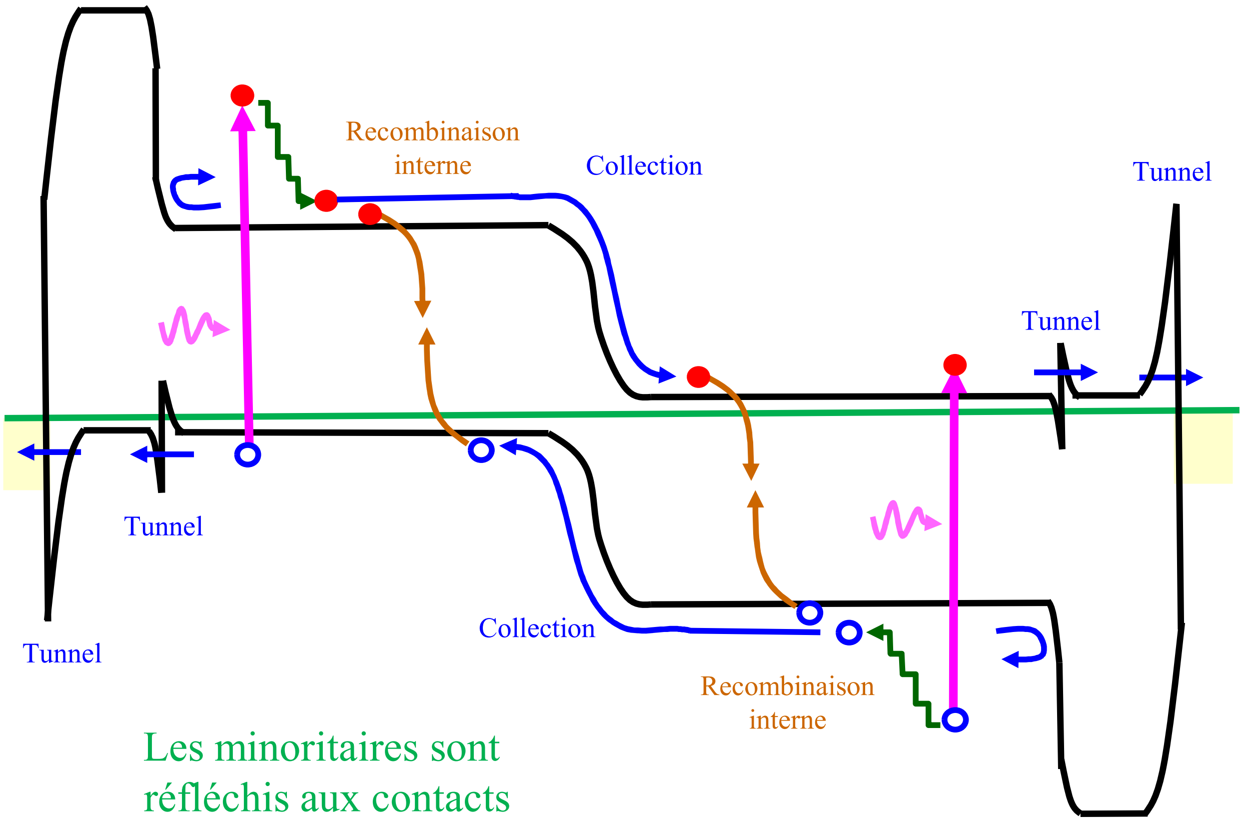


4) Recombinaisons internes



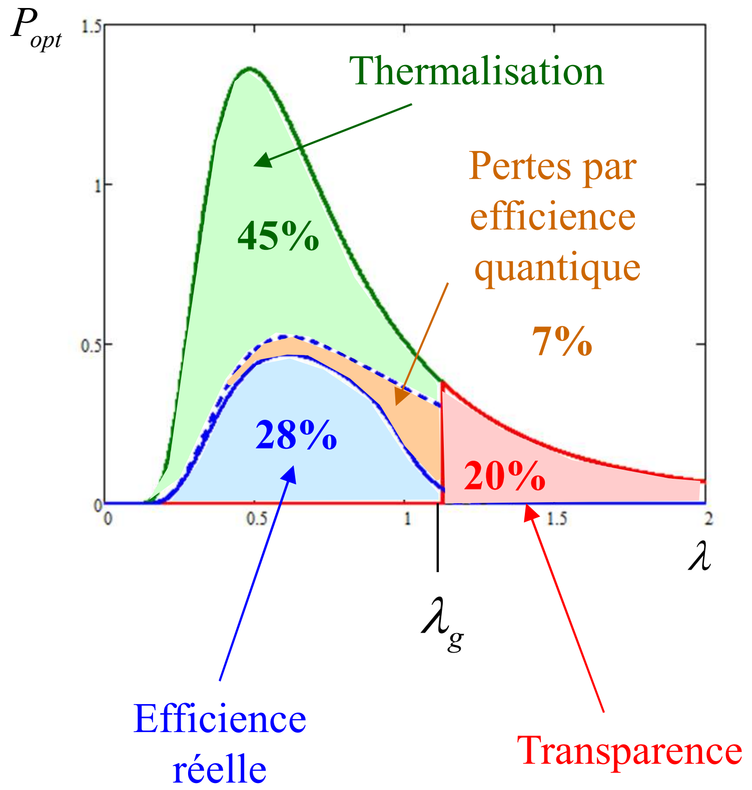
8.7: Cellule solaire par hétérostructure «réflective»

Suppression des pertes aux contacts

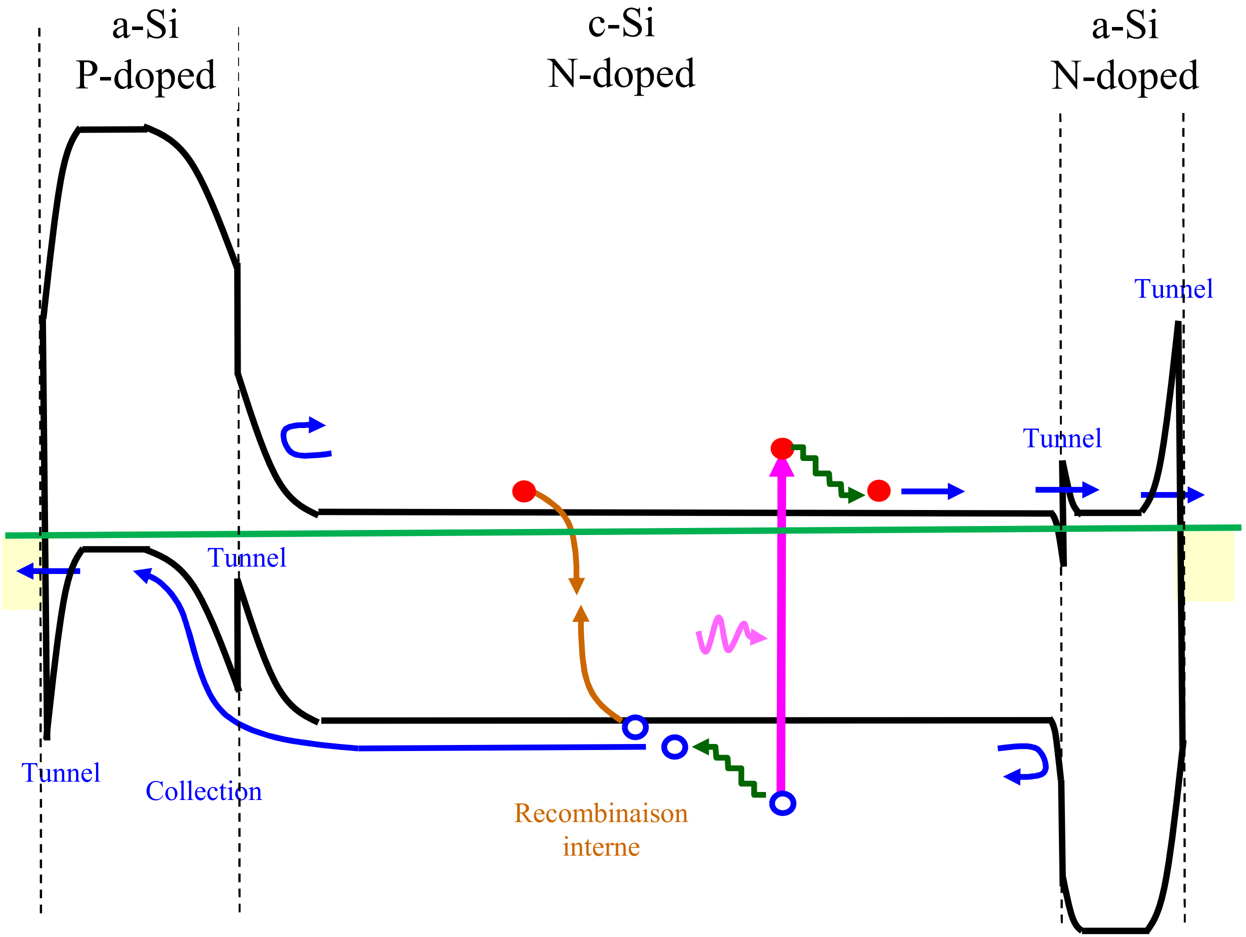


Les minoritaires sont réfléchis aux contacts

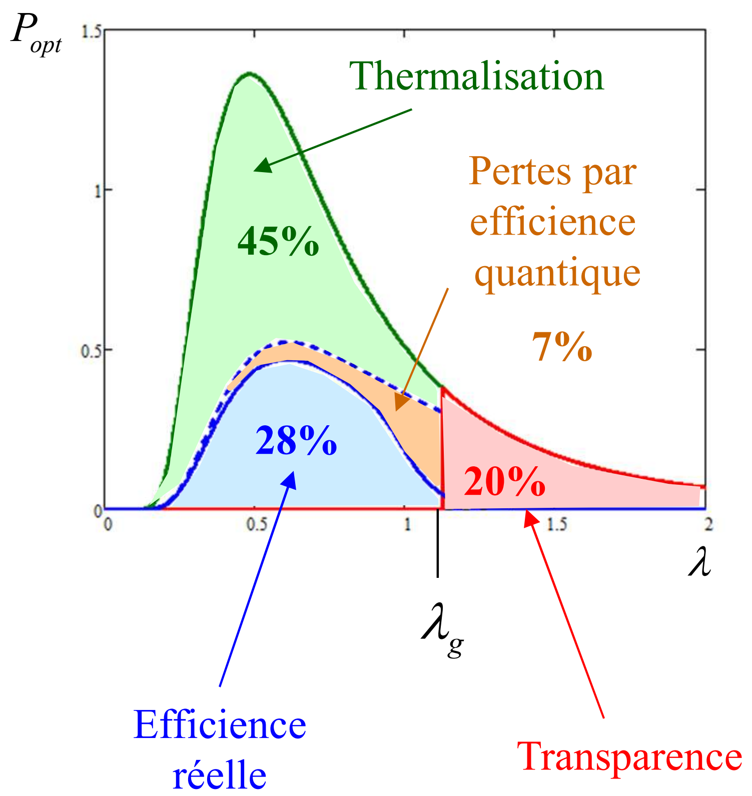
Silicium monocristallin + amorphe



Cellule solaire par hétérostructure «PV-lab»

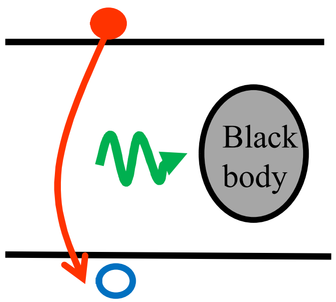


Silicium monocristallin + polycristallin



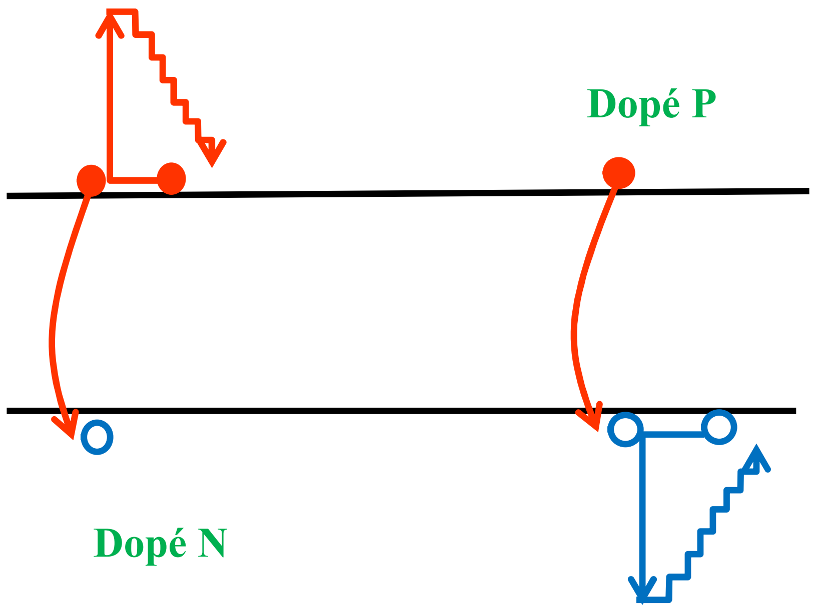
Processus de recombinaison

Recombinaison directe



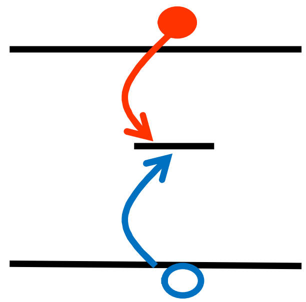
Dominant en III-V

<u>Recombinaisons Auger</u>



Dominant en silicium

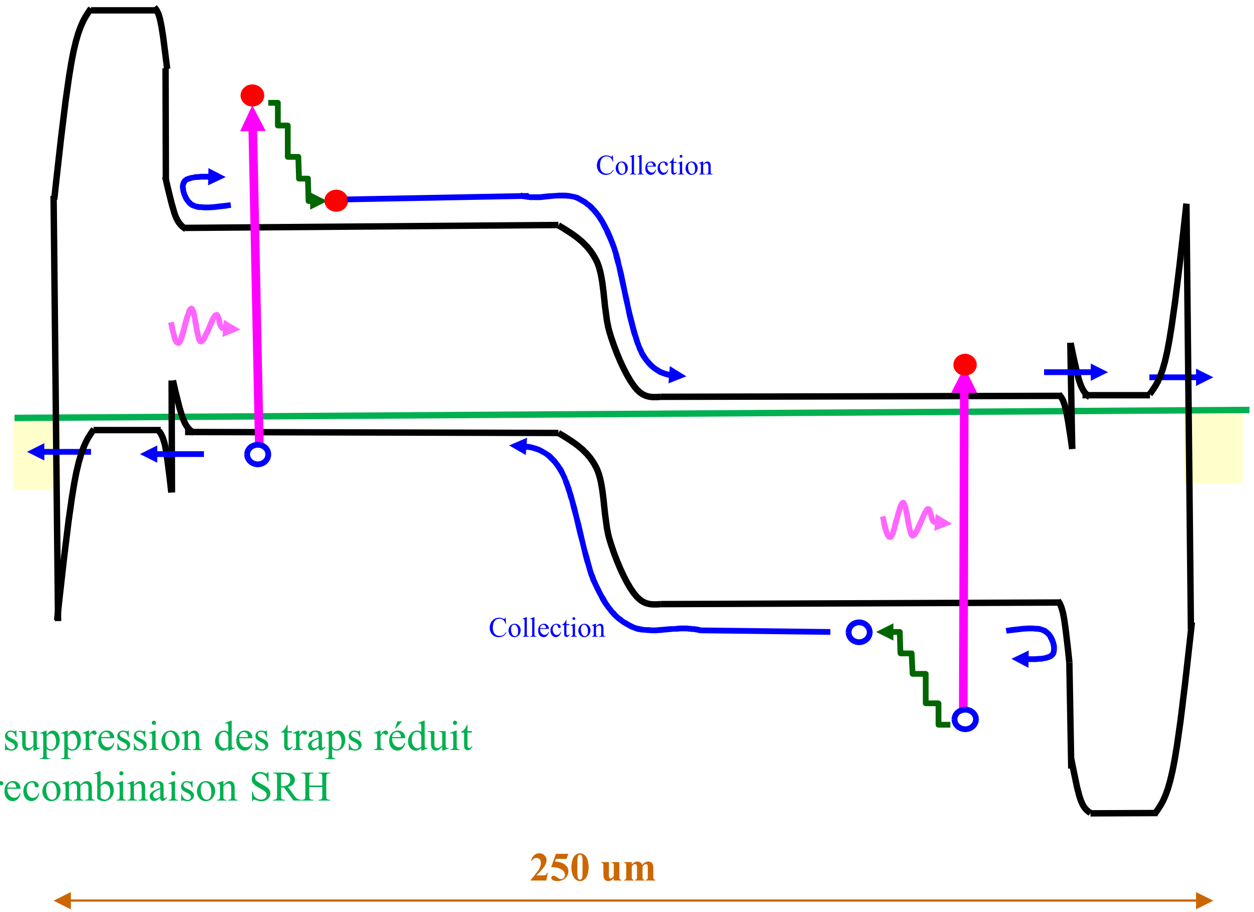
Recombinaisons «trap assisted»
SRH-recombinations



Dominant:
- aux interfaces
- dans les cellules low costs

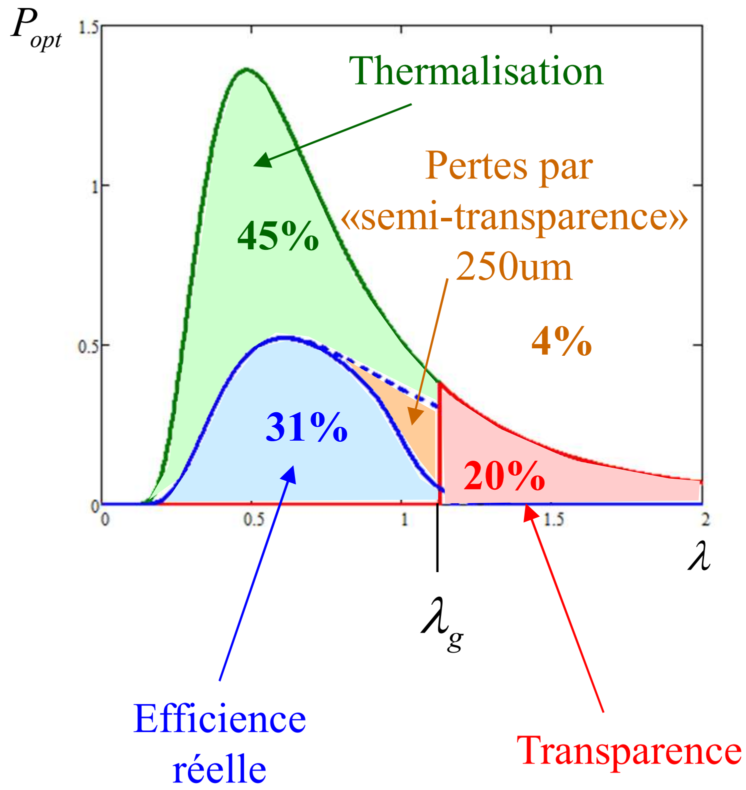
Cellule solaire par hétérostructure «réflective»

Suppression de la recombinaison interne et de la réflexion à l'entrée (R=0)

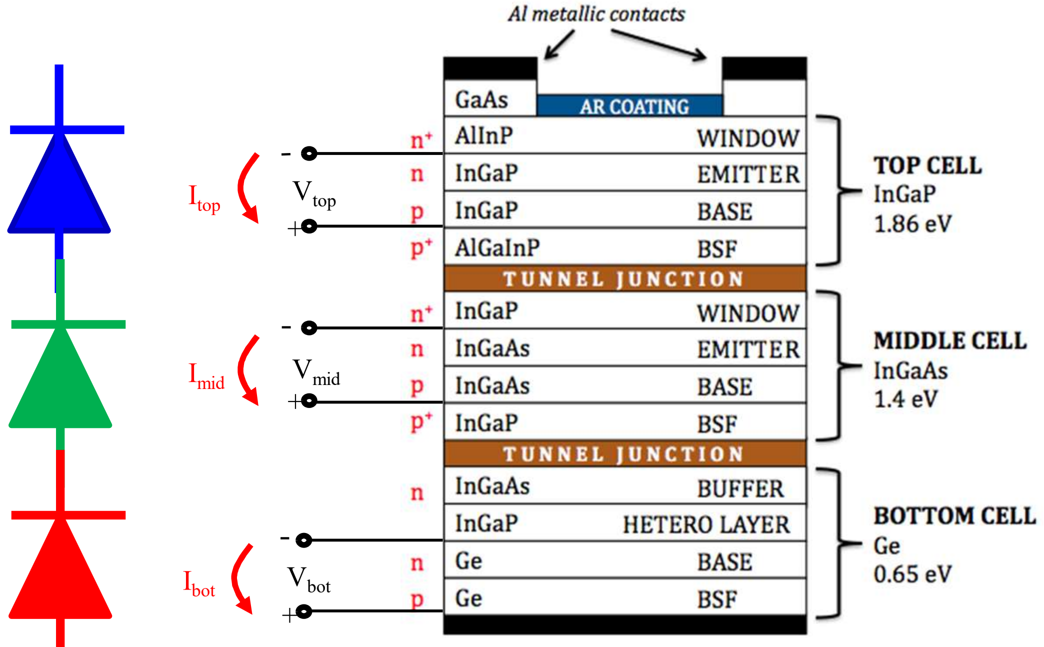


La suppression des traps réduit la recombinaison SRH

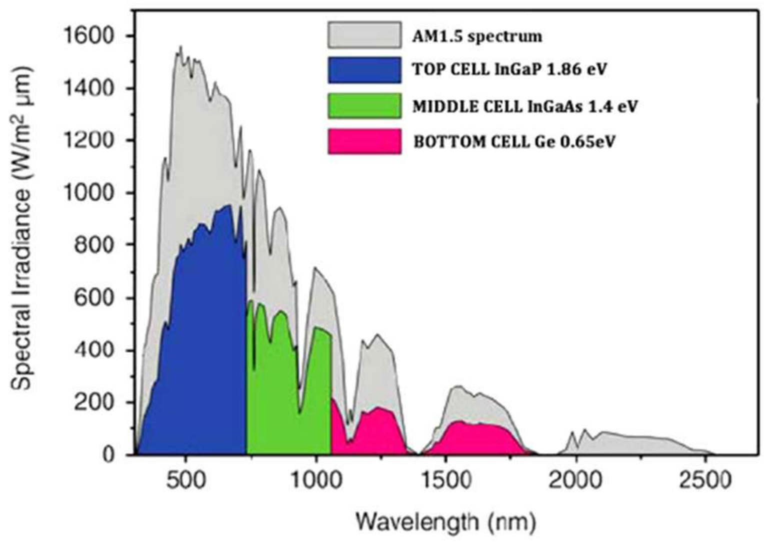
Silicium monocristallin + polycristallin



8.8: Multi-junctions solar cells



(a)



(b)

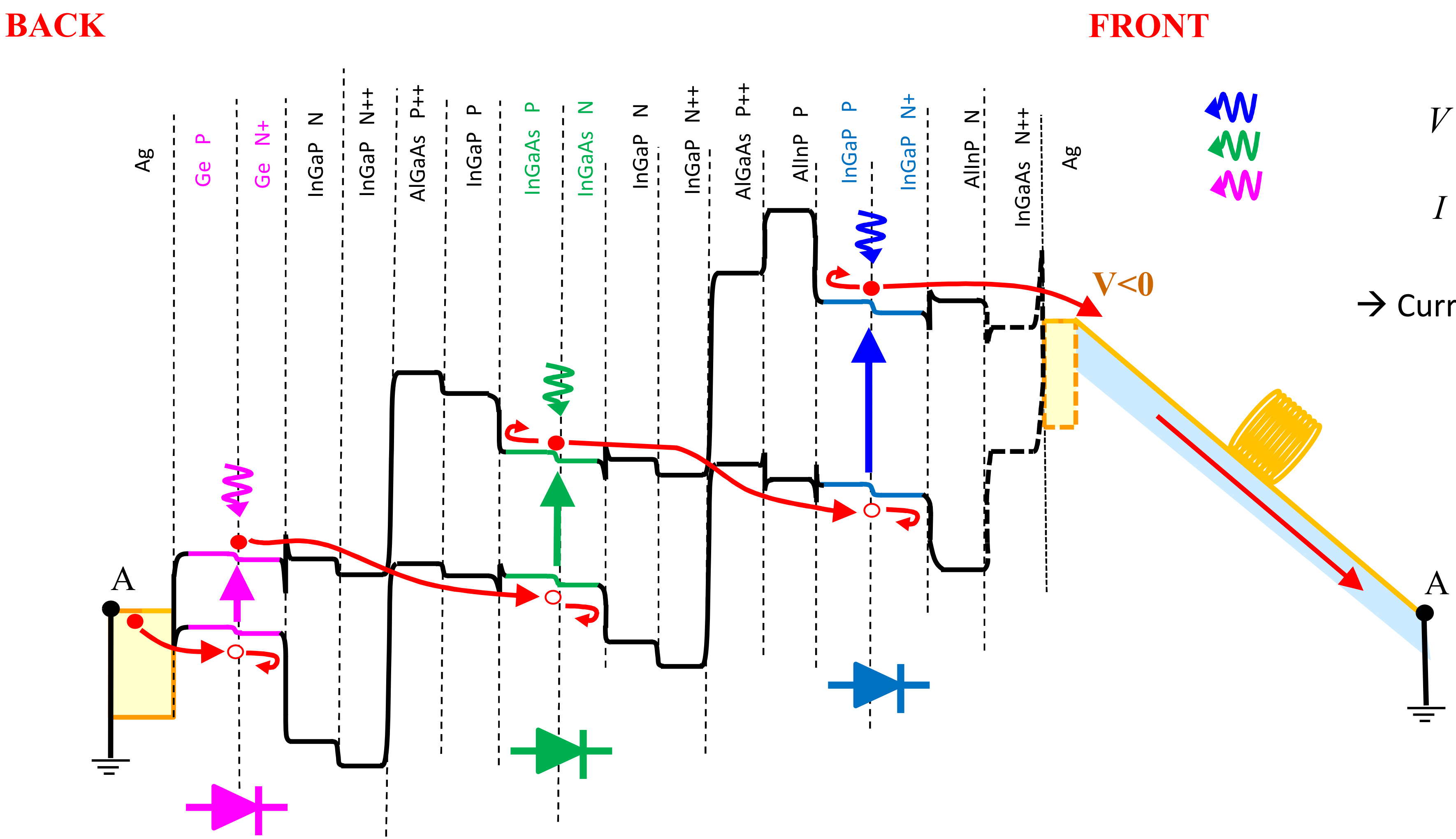
Les tensions des trois cellules s'additionnent

$$I_{tot} = \min\left[I_{top}, I_{mid}, I_{bot}\right]$$

$$V_{tot} = V_{top} + V_{mid} + V_{bot}$$

https://en.wikipedia.org/wiki/Multi-junction_solar_cell
https://www.youtube.com/watch?v=2U8BxI5RmLc

Multi-junctions solar cells: with illumination

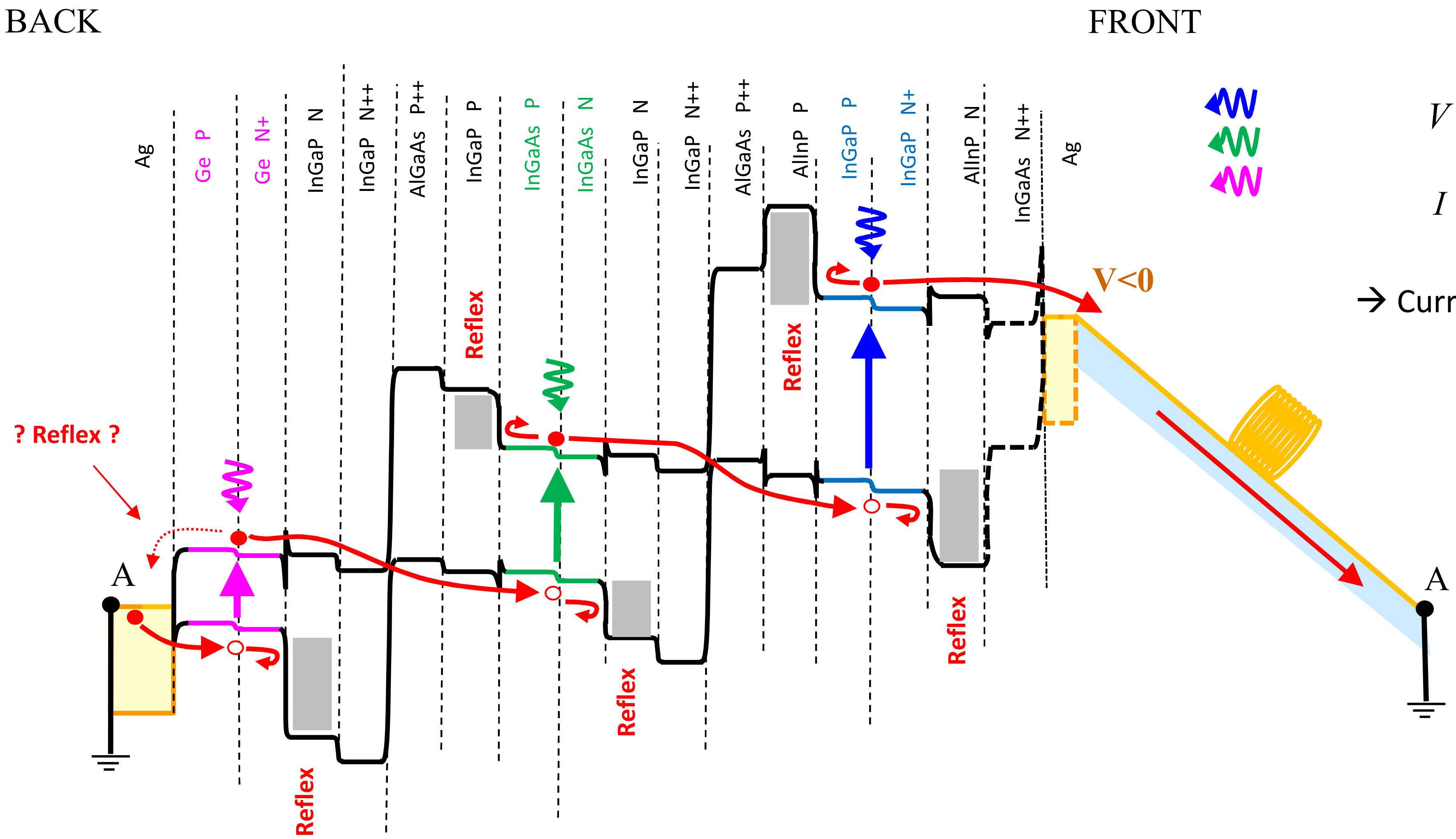


$$V = V_{bleu} + V_{vert} + V_{rouge}$$

$$I = \min\left[I_{bleu}, I_{vet}, I_{rouge}\right]$$

→ Current matching required

Multi-junctions solar cells: with illumination

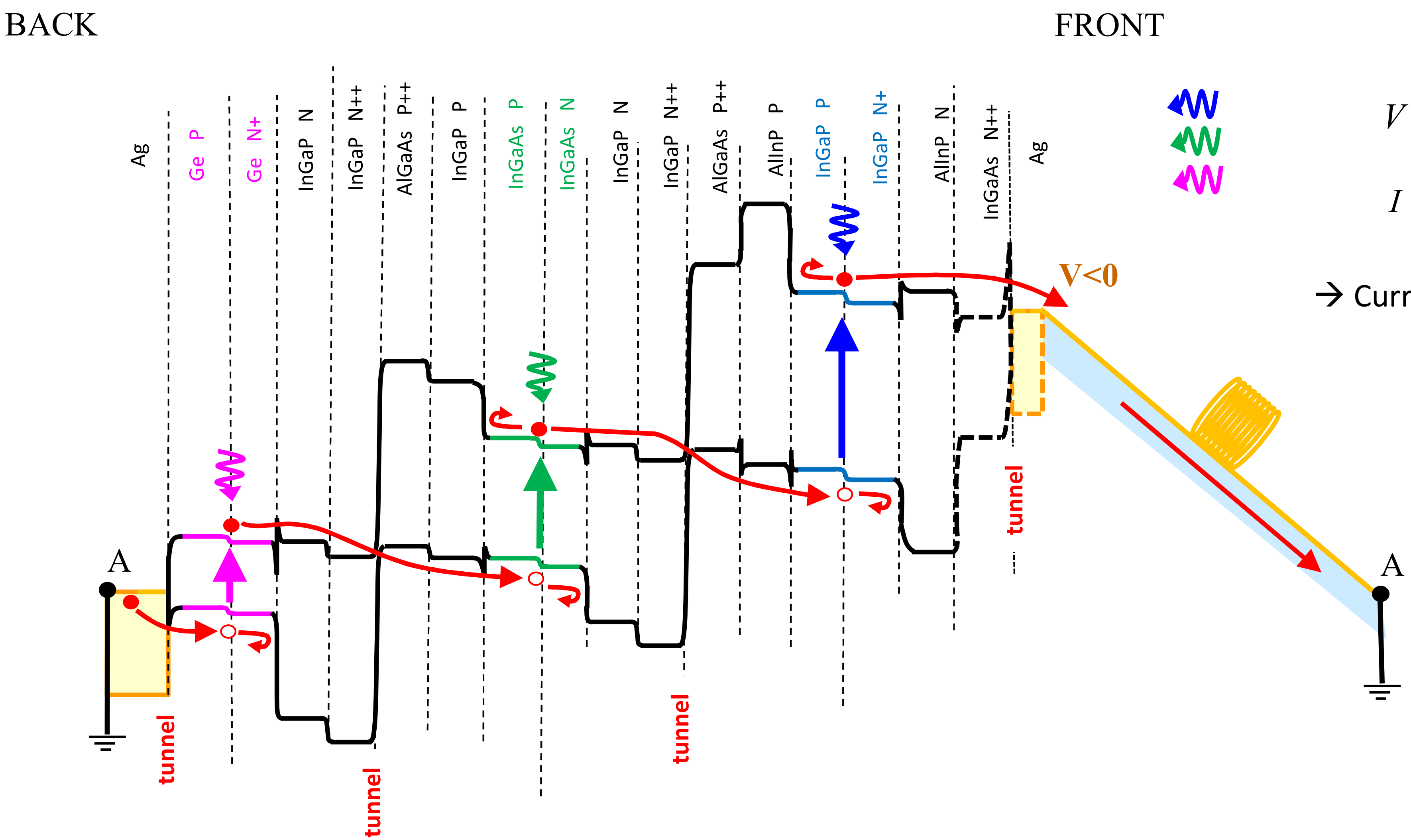


$$V = V_{bleu} + V_{vert} + V_{rouge}$$

$$I = \min\left[I_{bleu}, I_{vet}, I_{rouge} \right]$$

→ Current matching required

Multi-junctions solar cells: with illumination



$$V = V_{bleu} + V_{vert} + V_{rouge}$$

$$I = \min\left[I_{bleu}, I_{vet}, I_{rouge}\right]$$

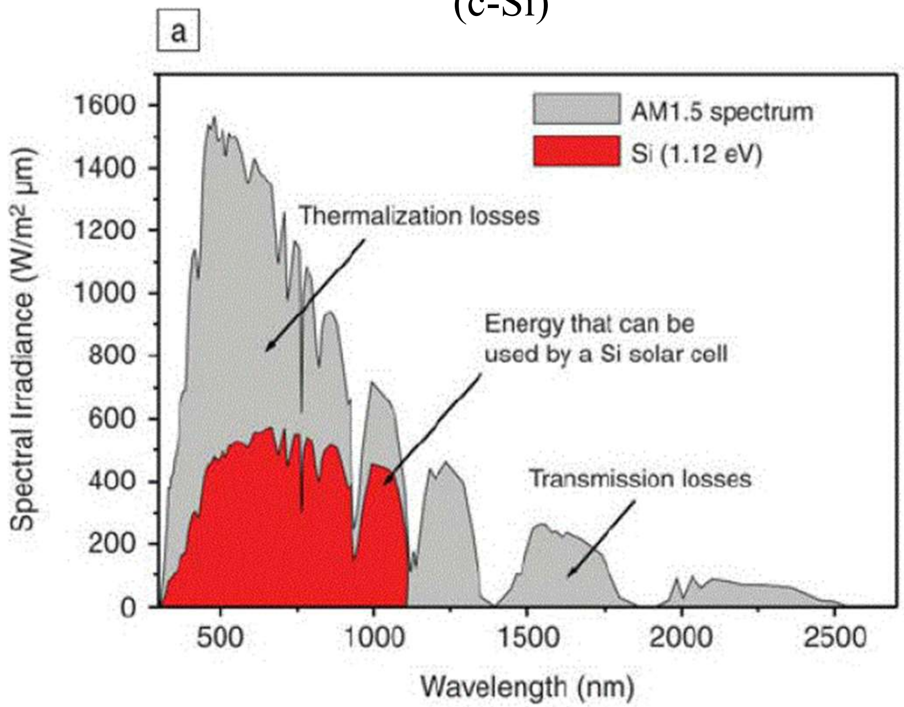
→ Current matching required

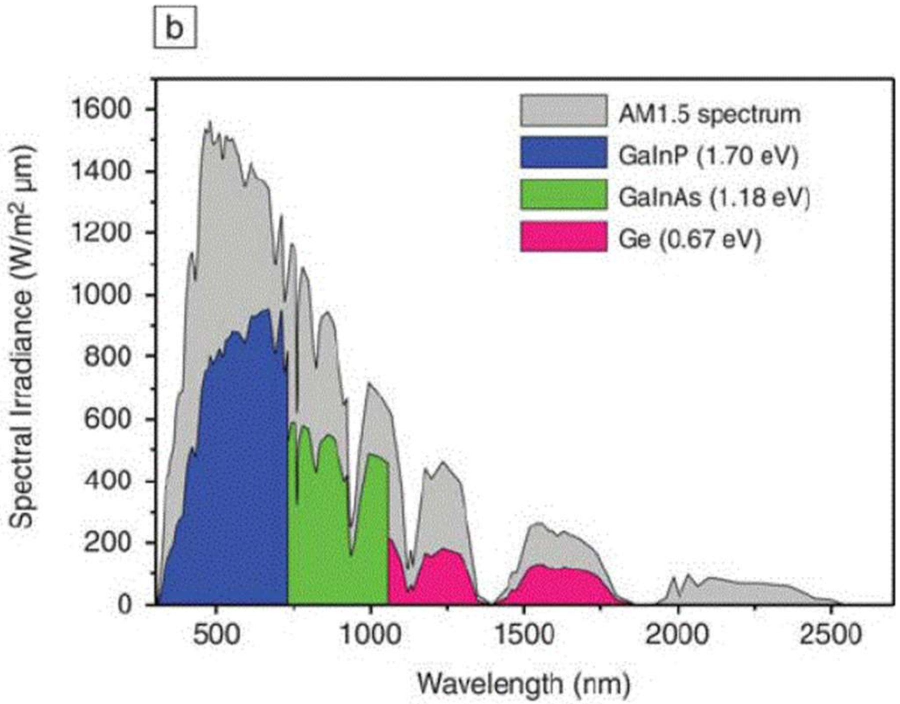
Multi-junctions solar cells: spectral behavior

N.V.Yastrebova (2007). High-efficiency multi-junction solar cells: current status and future potential

Single junction (c-Si)

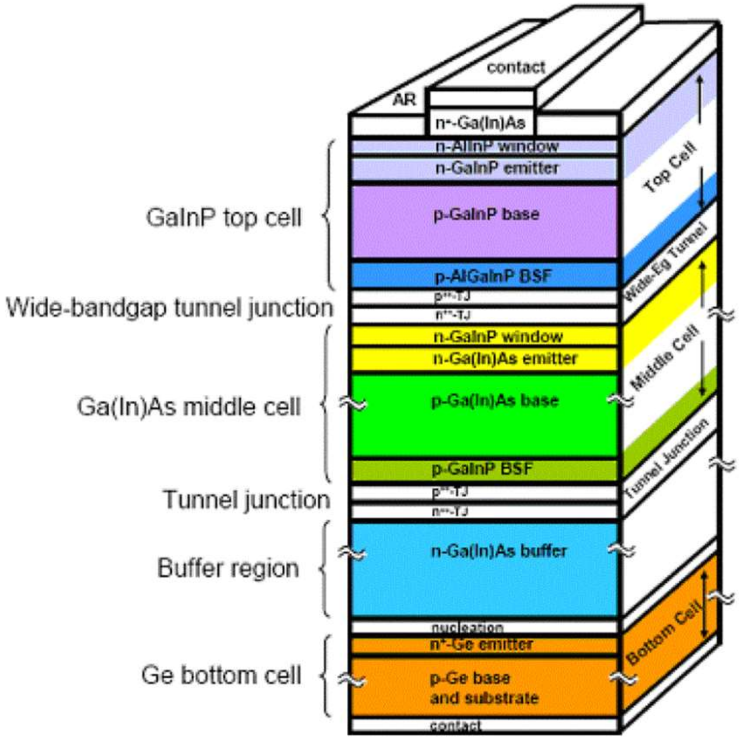
Triple junction

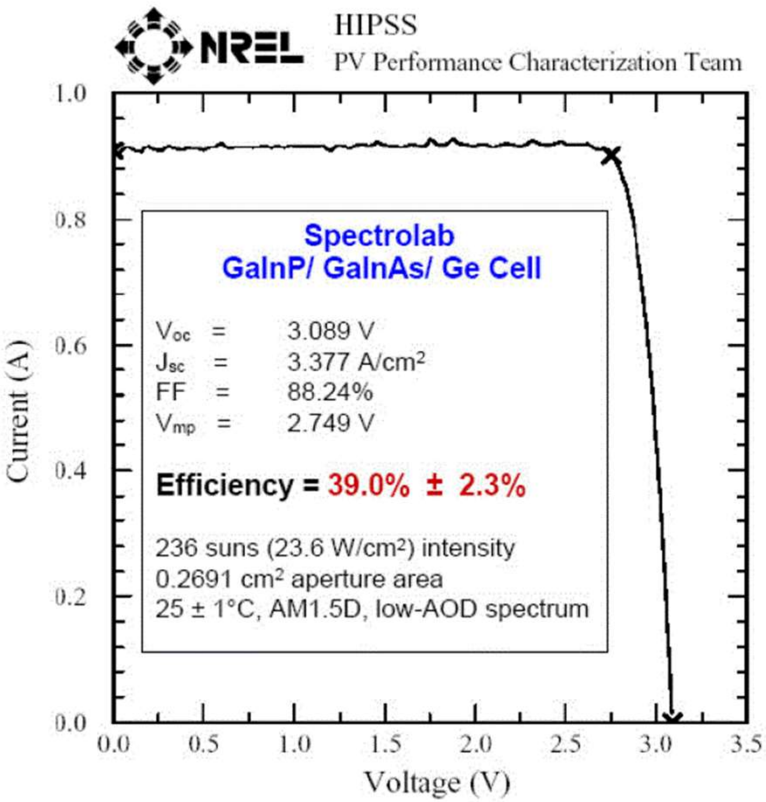




Triple-junctions solar cells: spectral behavior

N.V.Yastrebova (2007). High-efficiency multi-junction solar cells: current status and future potential





$$\eta_{el} = 39\%$$

Tandem: Perovskite / Silicon Hetero-Junction

F. Sahli et al., «Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency» Nature Materials, 2018 https://doi.org/10.1038/s41563-018-0115-4

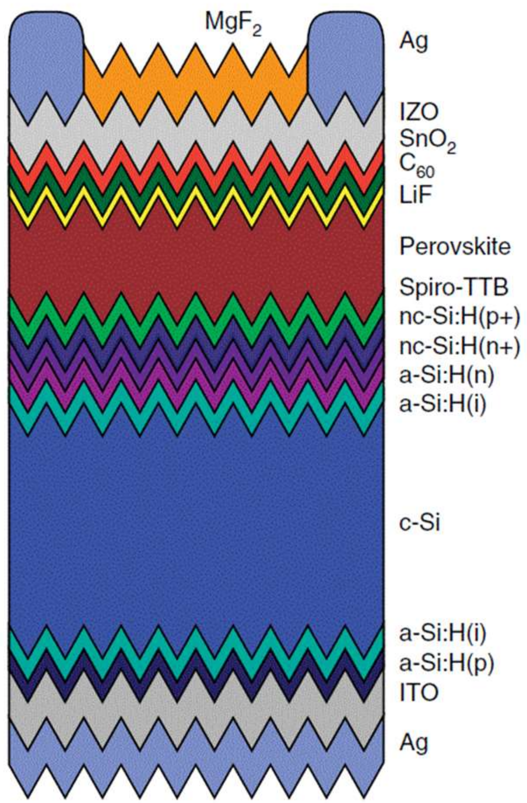
Top cell

Tunnel

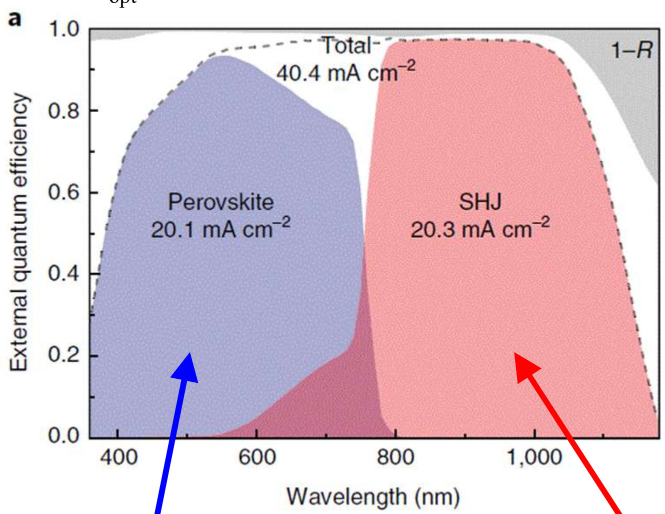
Reflex.

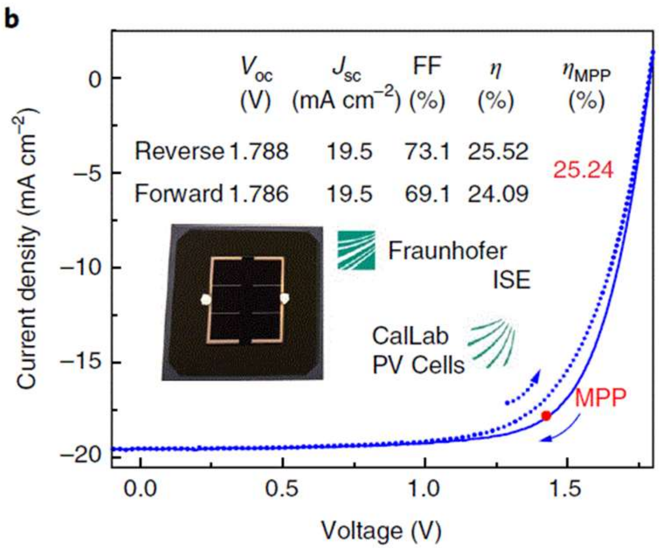
Bottom cell

Reflex.



P_{opt}=0.1 W/cm²





Top cell:
Perovskite
«visible light»

Bottom cell:
Silicon Hetero-Junction
«IR light»

$$V_{oc} = V_{Per} + V_{Si} \cong 1.78\,[V]$$

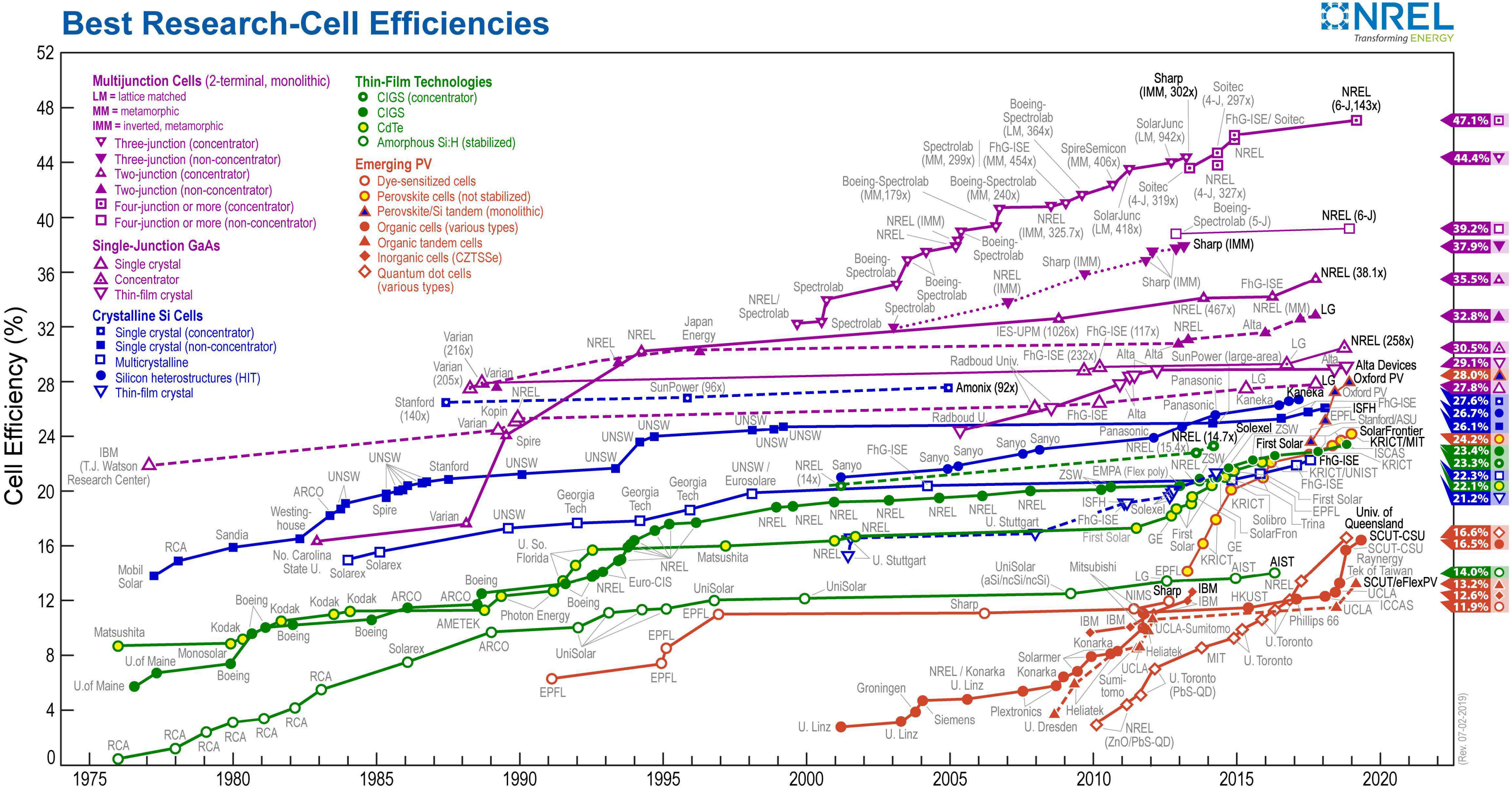
20.1 mA/cm²

Current matching

20.3 mA/cm²

$$\eta_{el} = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{opt}} \cong 25\%$$

8.9: State-of-the-art



https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20190703.pdf

Deuxième test à blanc

Envoyé par email et sur Moodle

Correction mardi prochain 12 nov.

Exercice 8.1: estimation «sur le pouce» de l'efficience électrique maximale

Estimez l'efficience électrique maximale

d'une cellule solaire en silicium monocristallin ?

Modèle «sur le pouce»:

- **Exprimez l'énergie d'un photon solaire typique en eV.**
- **Estimez le gain d'énergie d'un photo-électron en eV.**
- **Comparez les deux énergies.**

Exercice 8.2: influence du gap

Comparons deux cellules solaires avec des énergie de gap différentes.

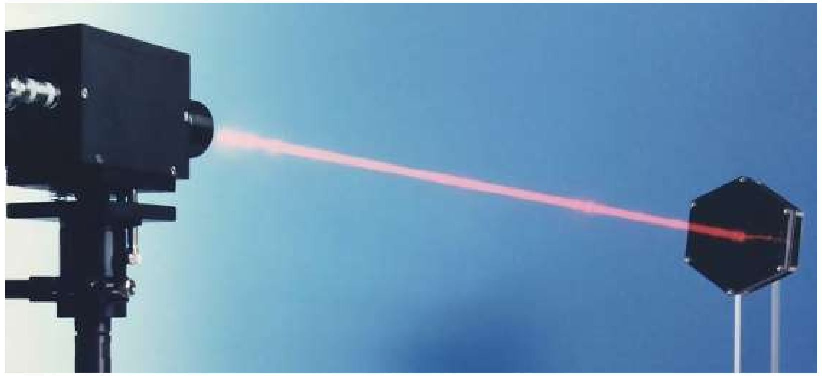
- La première cellule est en silicium monocristallin avec un gap de E_g=1.1 [eV] et une tension de built-in de V_{bi}=0.8.E_g=0.88 [eV].

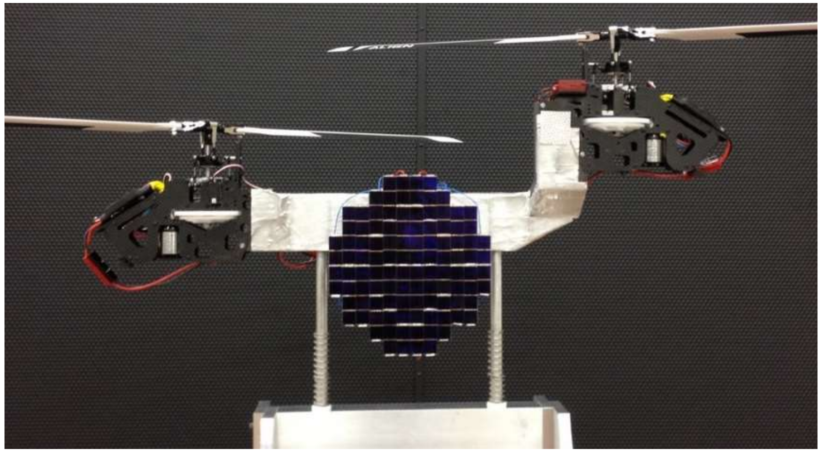
- La seconde cellule est en silicium amorphe avec un gap de E_g=1.7 [eV] et une tension de built-in de V_{bi}=0.8.E_g=1.36 [eV].

Comparez qualitativement les pertes par transparence et celles par thermalisation

Exercice 8.3:
Laser Power Converter (LPC)

Un laser est utilisé pour alimenter en énergie une batterie.
Discutez le design des cellules photovoltaiques (Laser Power Converter).



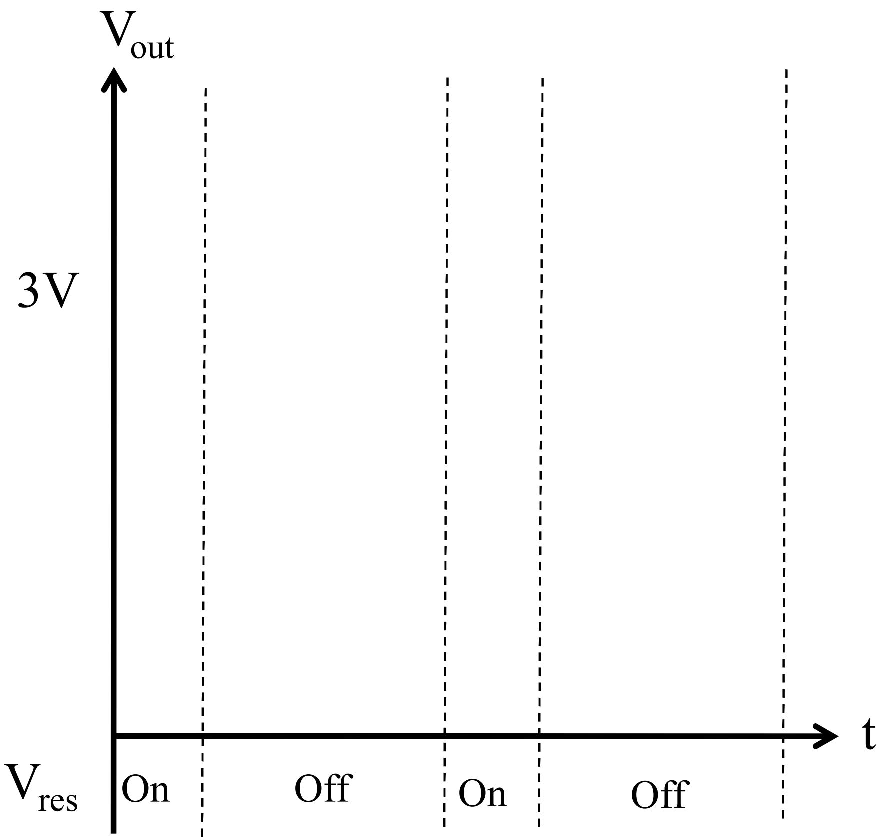


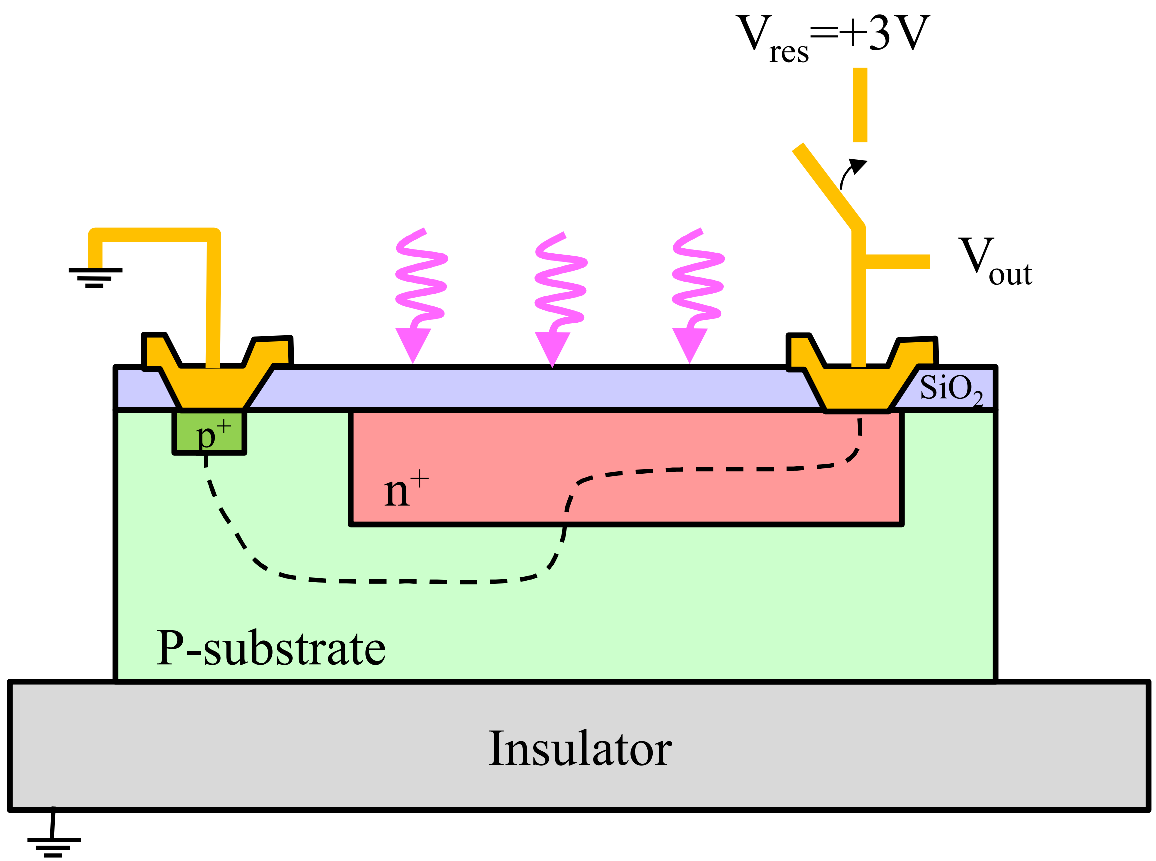
Le laser émet:
- une lumière monochromatique
- de puissance constante

1) Enoncez des lignes directrices
   pour le design de la cellule PV

2) Quels seraient les avantages d'une cellule
   photovoltaïque (PV) multi-jonction
   pour cette application ?

Exercise 8.4: CMOS Camera (Pixel)





- Draw the band diagram and the electrical charges along the dotted line and and analyze their temporal behavior when the pixel is illuminated.
- Plot the output voltage with and without light.