

**PHYSIQUE DES  
COMPOSANTS  
SEMI-CONDUCTEURS**

**VIII) Cellules solaires**

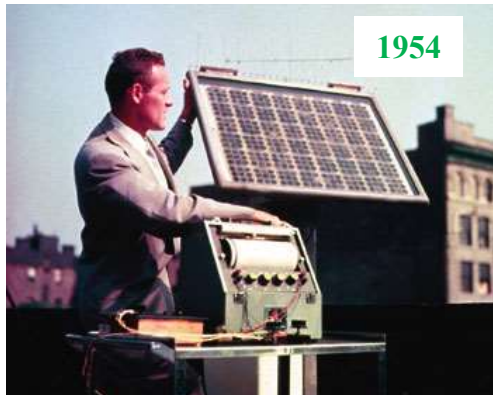
P.A. Besse

EPFL

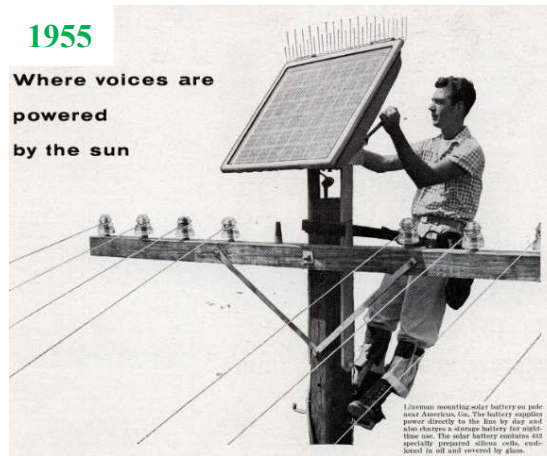
# 8.1 Premières cellules solaires p/n en silicium

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

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



Chapin, Fuller,  
Pearson  
1954  
 $\eta_{el}=5\%$   
(50W/m<sup>2</sup>)



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

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



Sun-powered  
radio

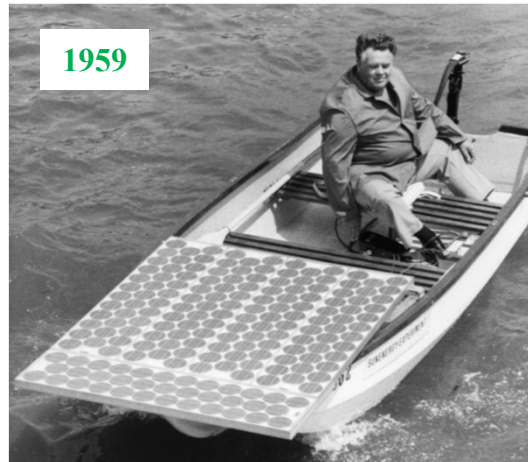


<https://www.gizmodo.com.au/2014/04/60-years-ago-today-bell-labs-unveiled-the-solar-cell/>

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



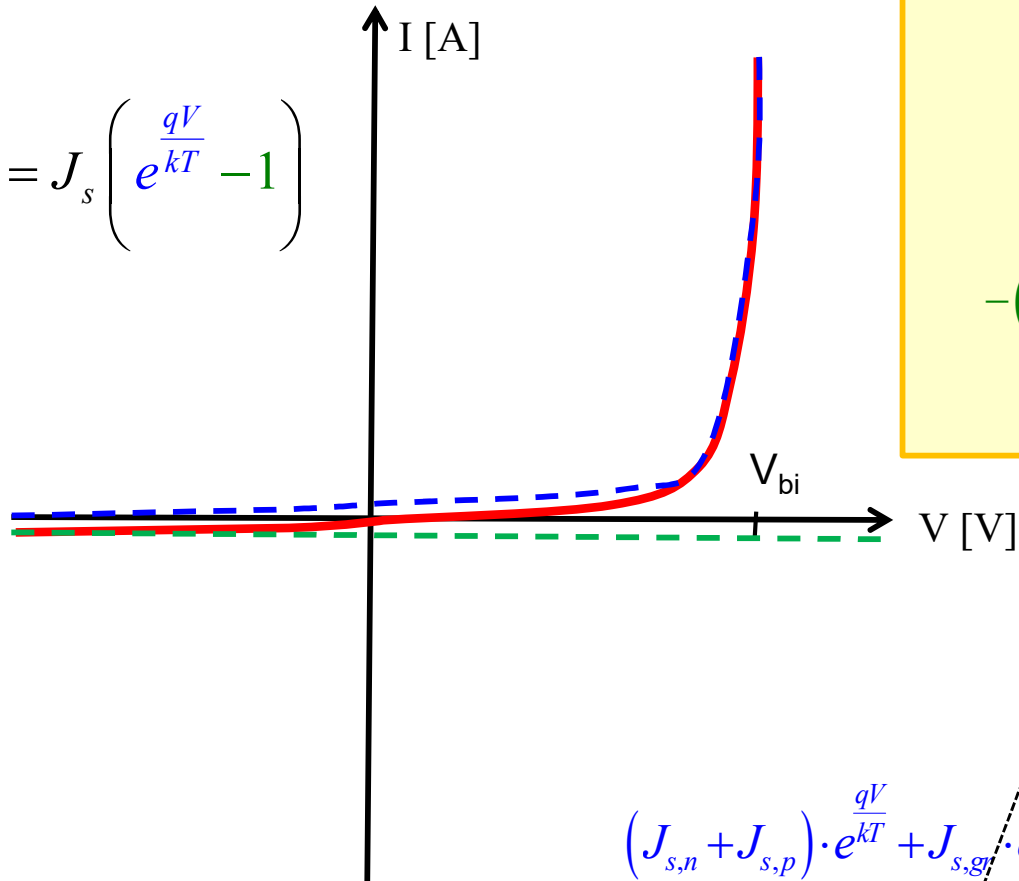
<https://www.thehenryford.org/collections-and-research/digital-collections>



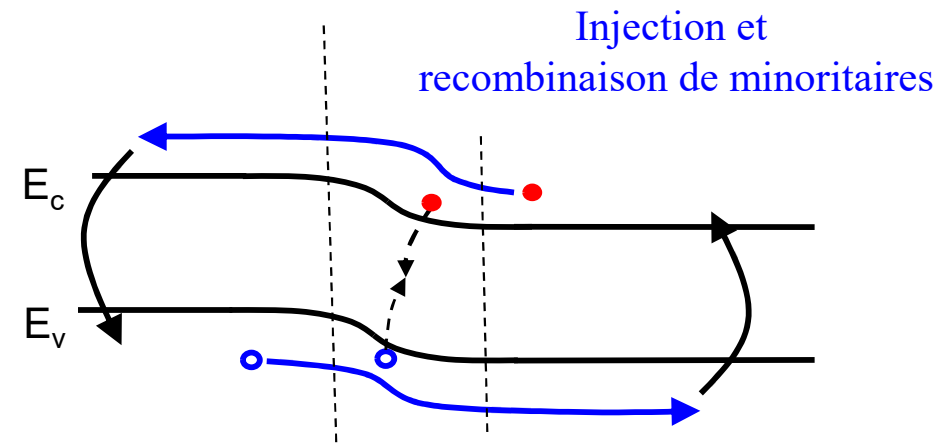
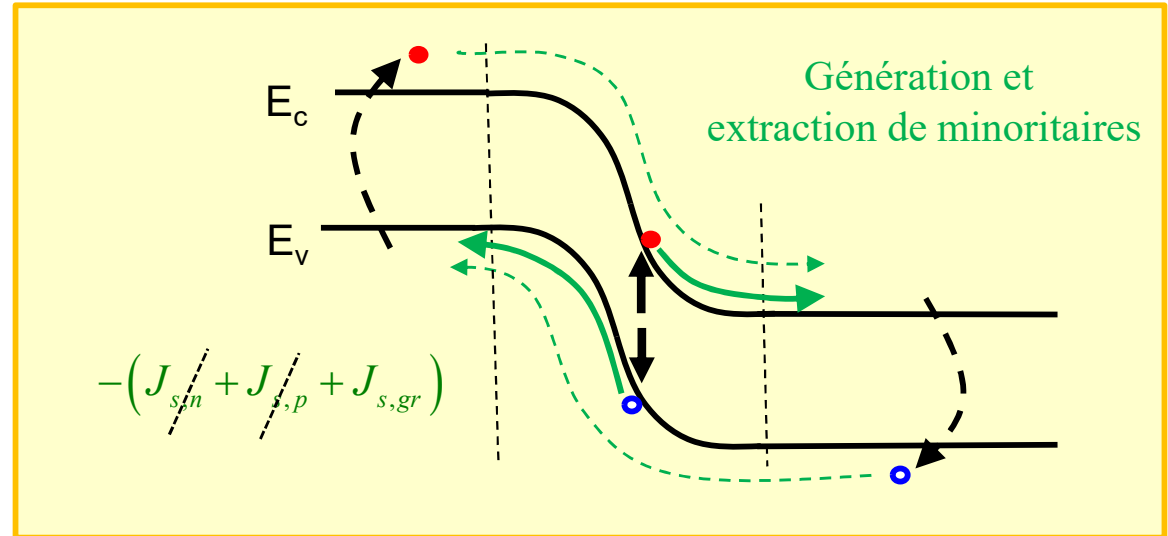
«Phoenix»: Trans-american Solar Auto Run (TSAR)

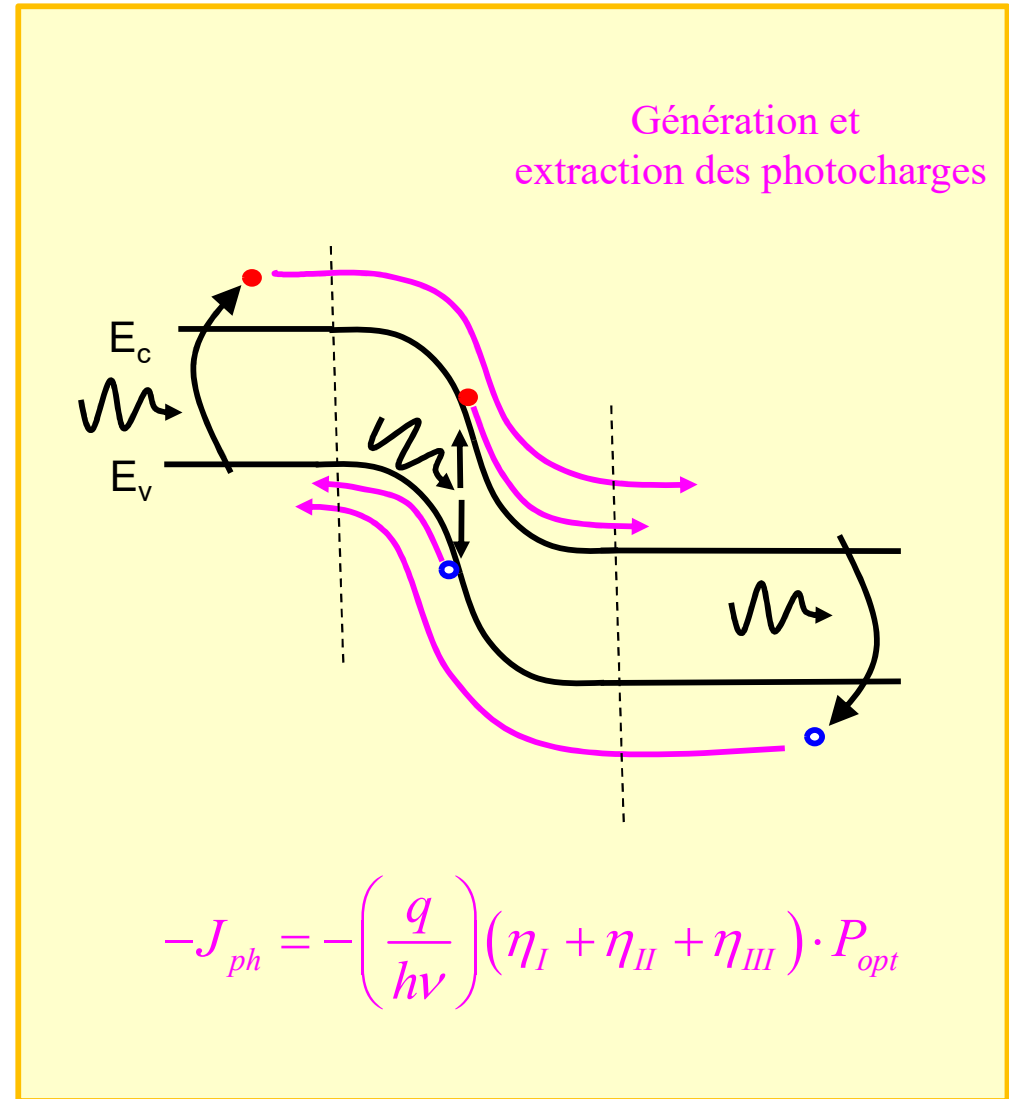
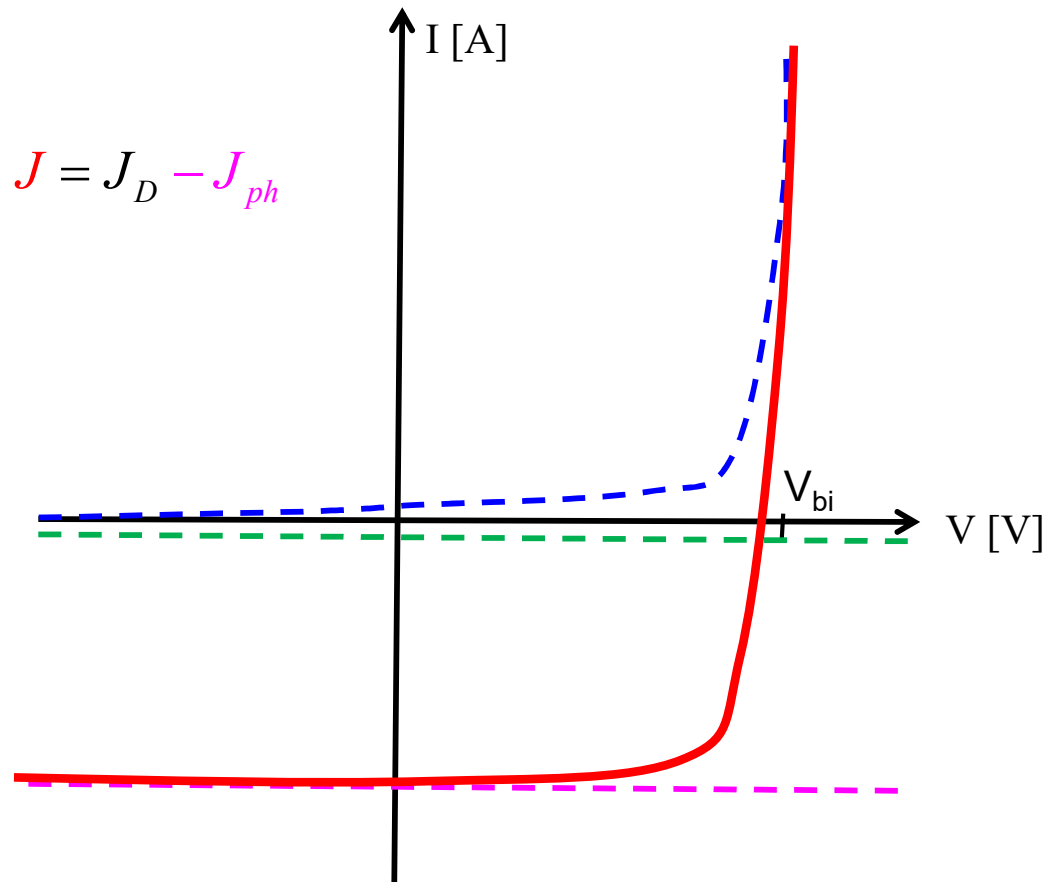
## 8.2: Courant dans une diode

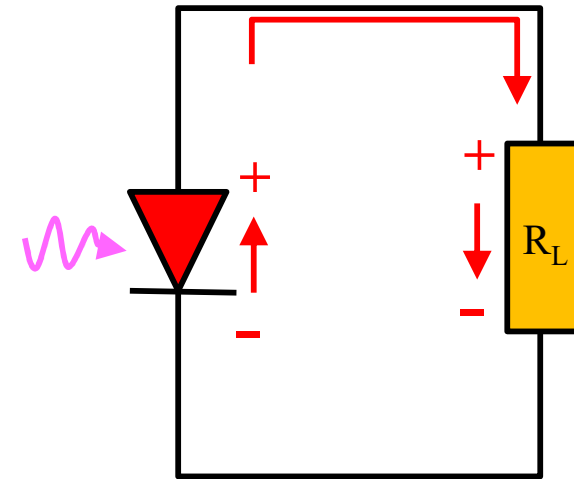
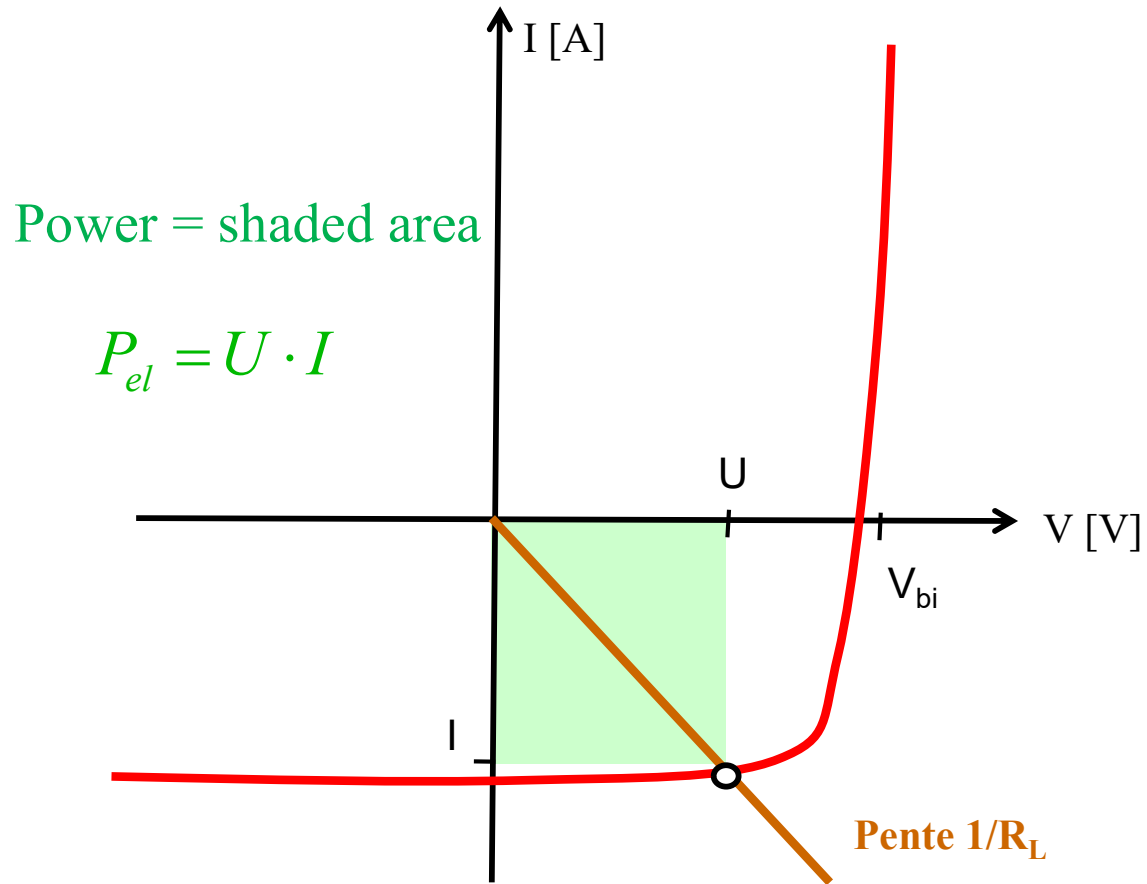
$$J_D = J_s \left( e^{\frac{qV}{kT}} - 1 \right)$$



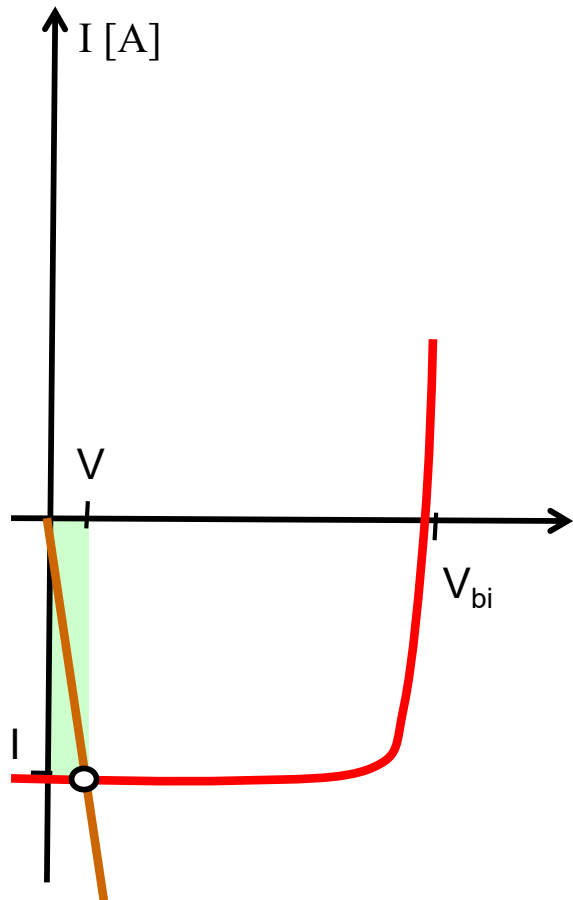
$$\left( J_{s,n} + J_{s,p} \right) \cdot e^{\frac{qV}{kT}} + J_{s,gr} \cdot e^{-\frac{qV}{kT}}$$



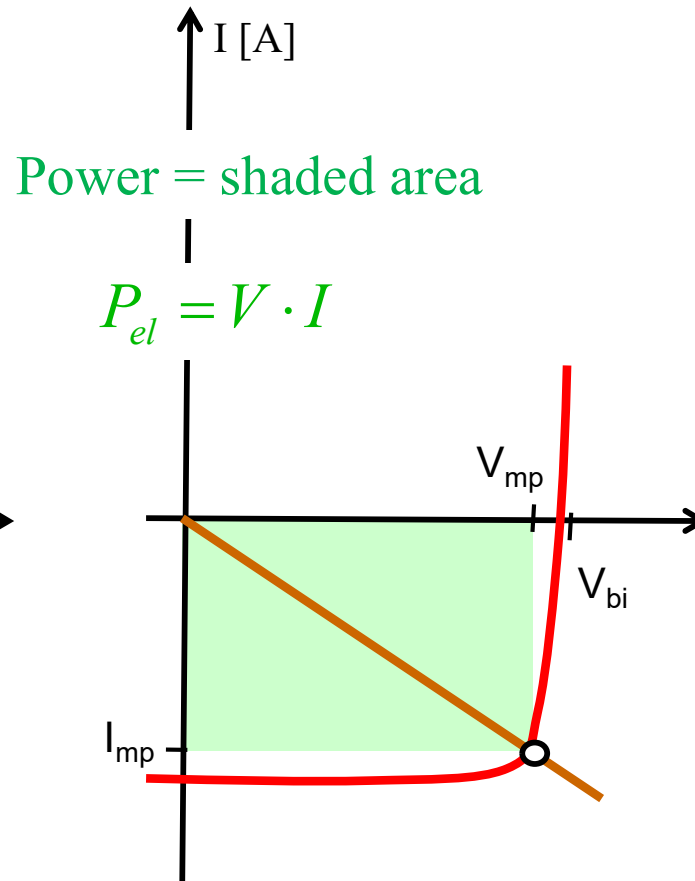




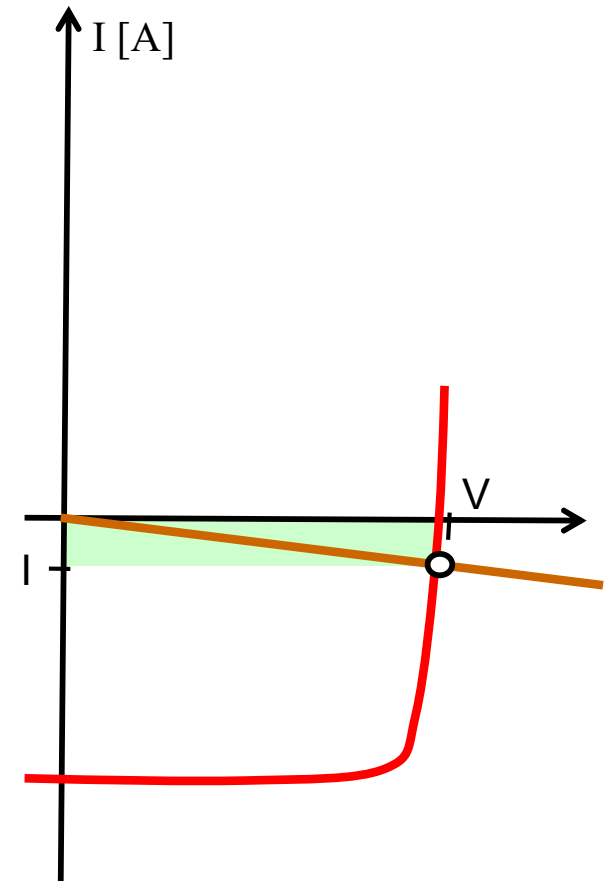
$R_L$  petit

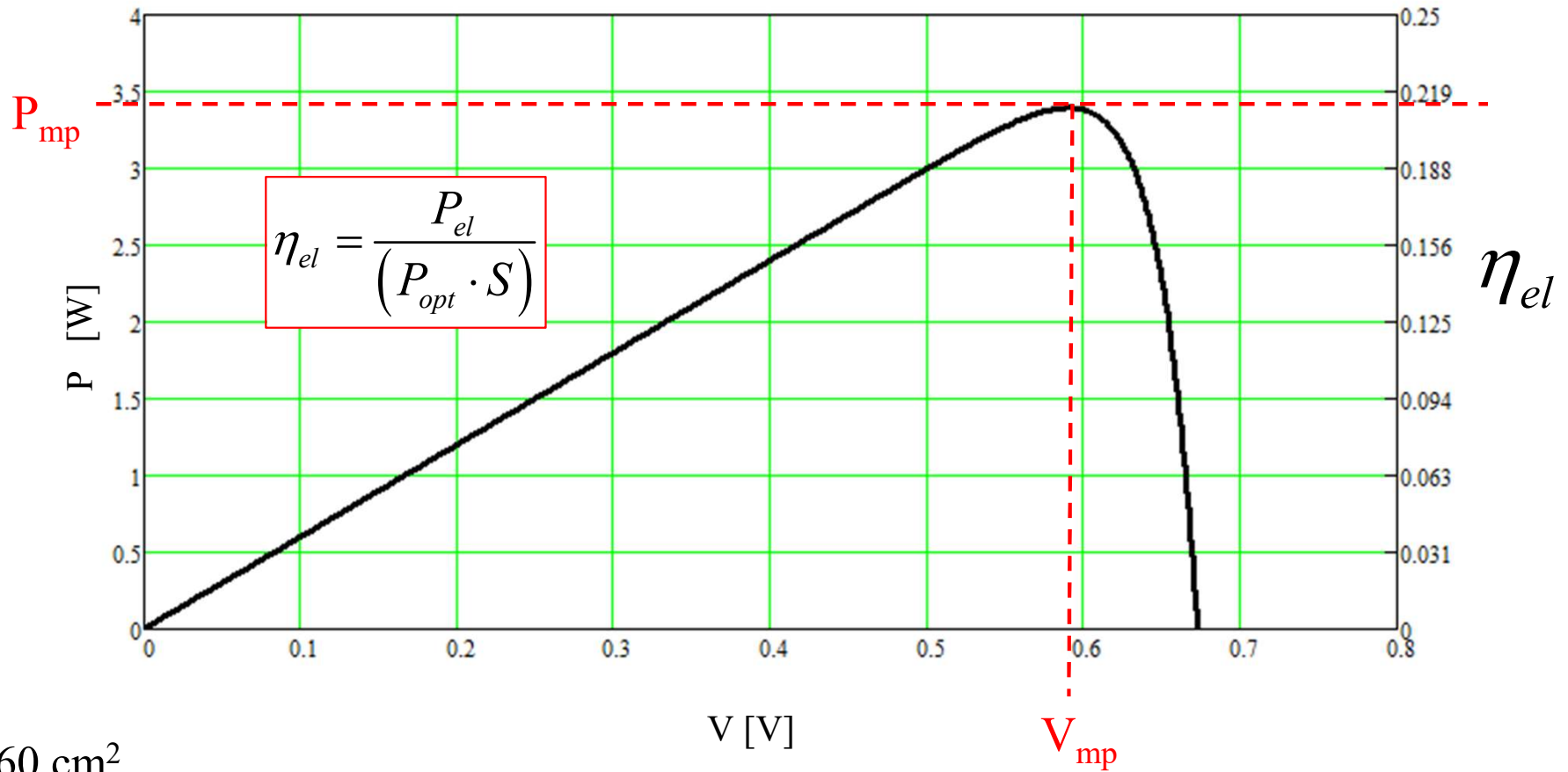


$R_L$  optimal



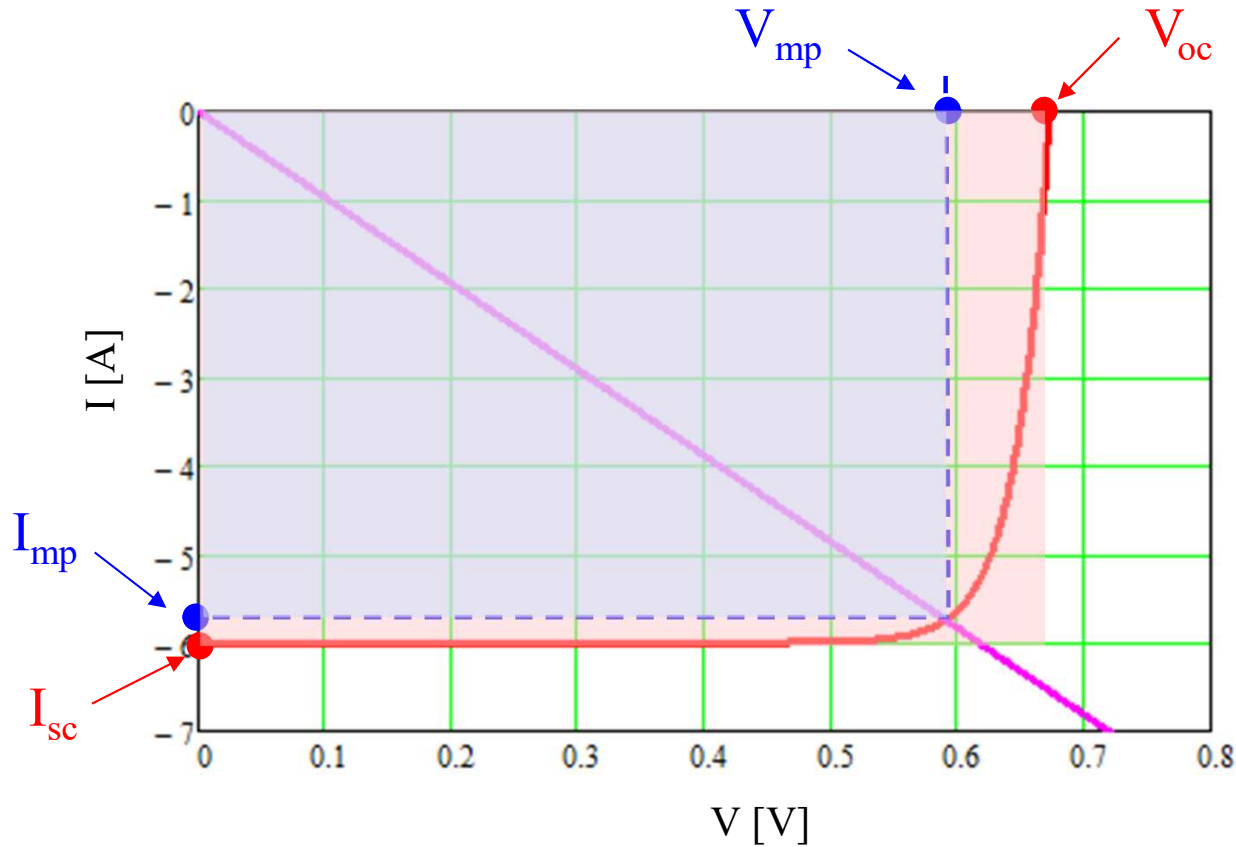
$R_L$  grand





$S=160 \text{ cm}^2$

$P_{opt} = 1 \text{ kW/m}^2$



$I_{sc}$  = short-circuit current ( $R_L=0$ )

$V_{oc}$  = open-circuit current ( $R_L=\infty$ )

$I_{mp}$  = maximal power current

$V_{mp}$  = maximal power voltage

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

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

$S=160 \text{ cm}^2 = 25 \text{ pouces}^2$

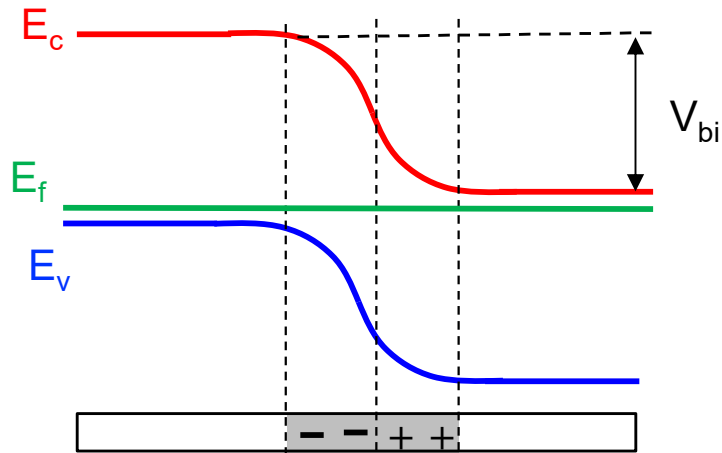
$\eta_{el} \cong 20\%$

$P_{opt}=1 \text{ kW/m}^2$

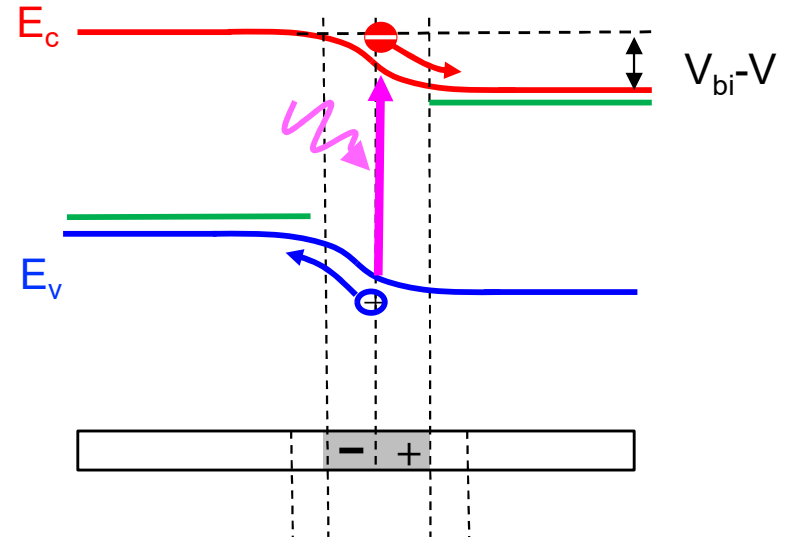
# 8.3: Solar cell: principe

## Récupérer $V_{bi}$ en réduisant la zone de déplétion

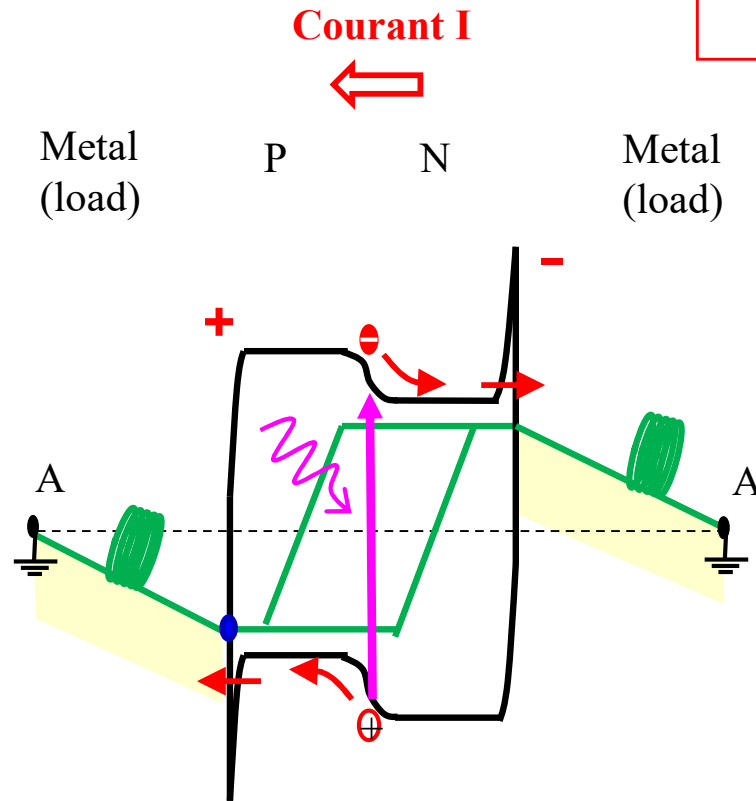
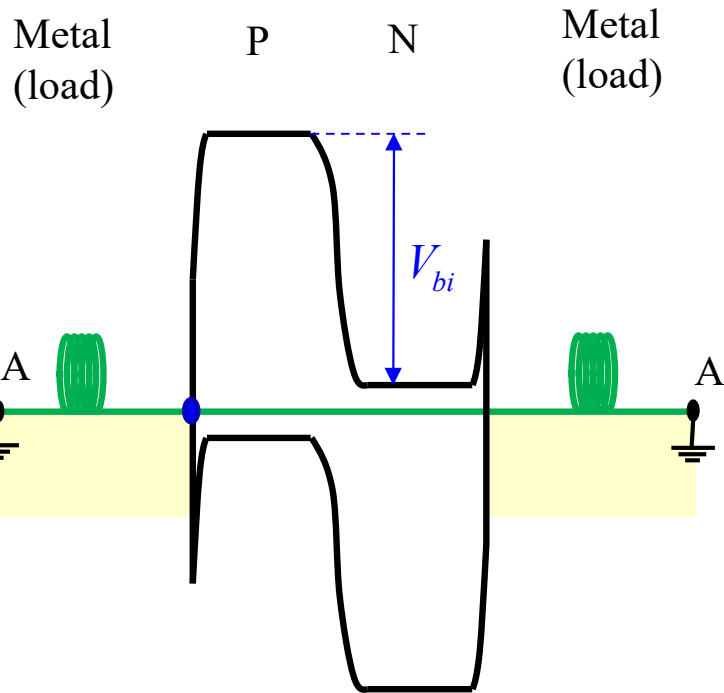
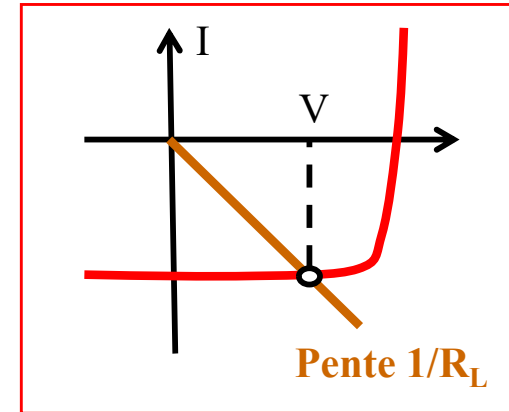
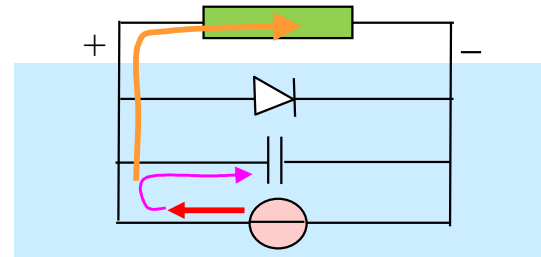
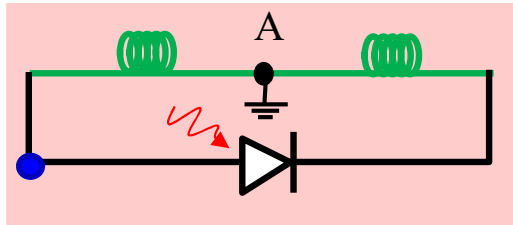
Solar cell: no illumination

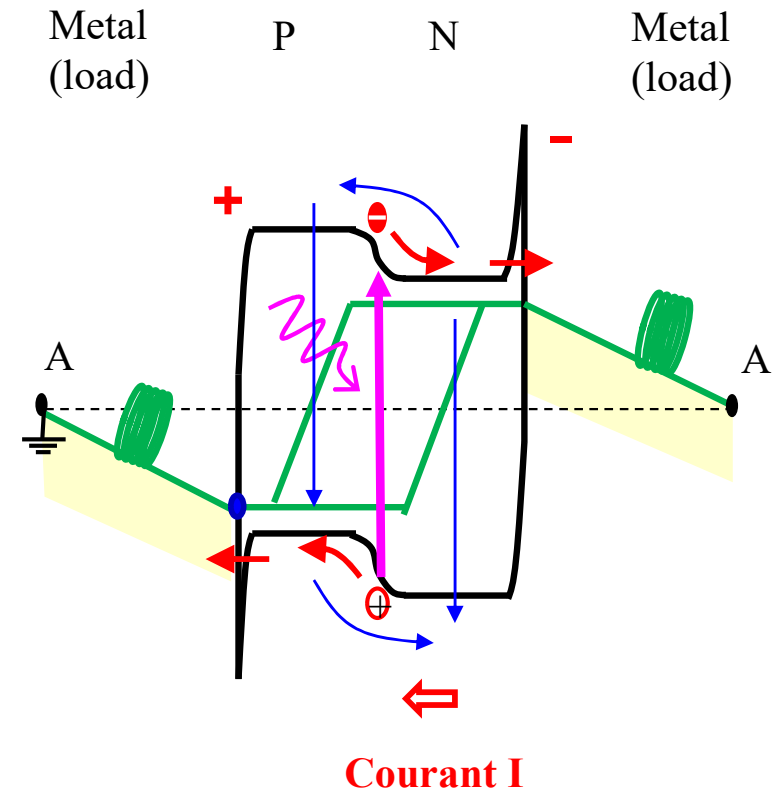
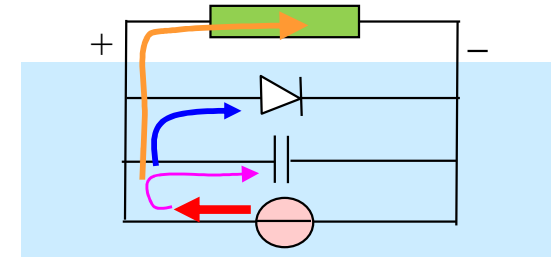
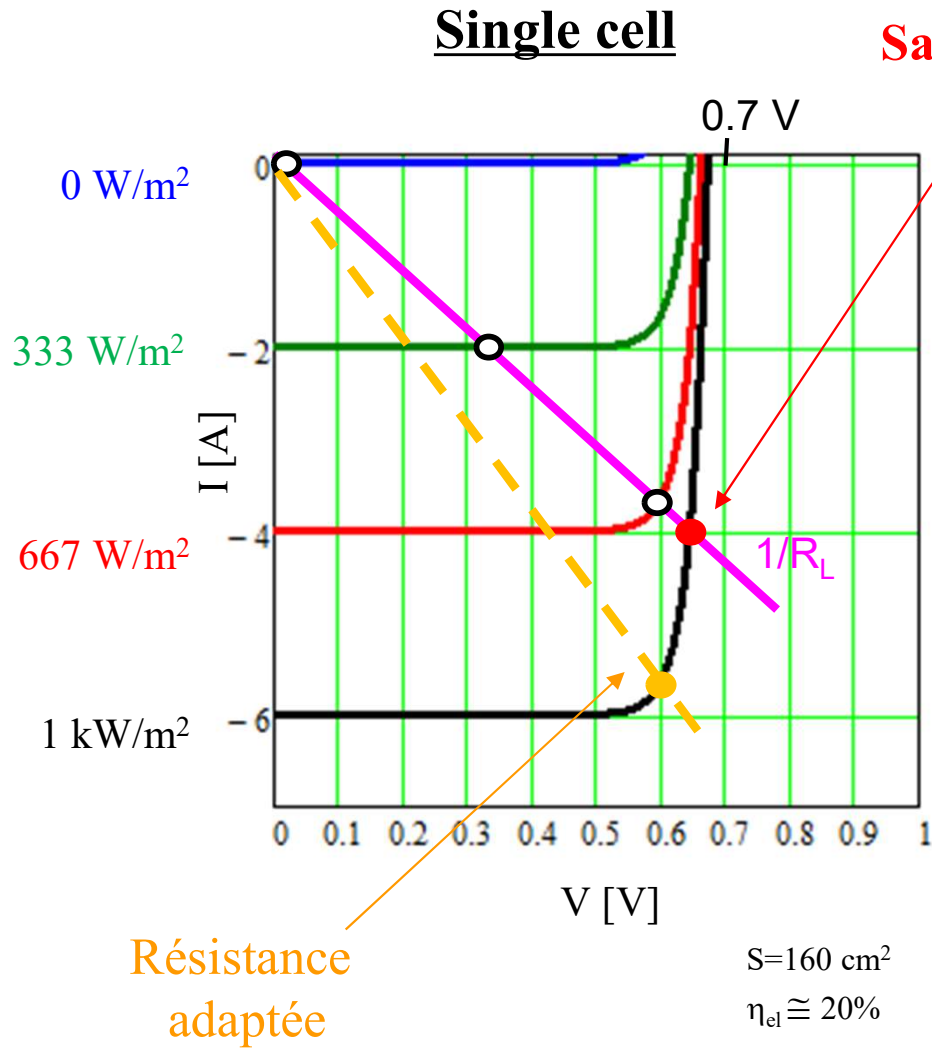


Solar cell: with illumination



# Solar cell: principe





# 8.4: Exercice: Solar calculator

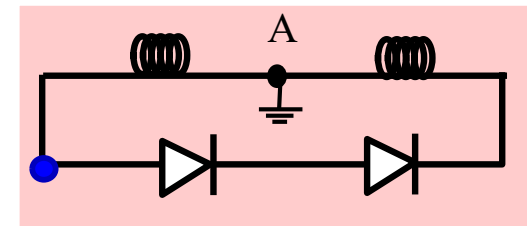
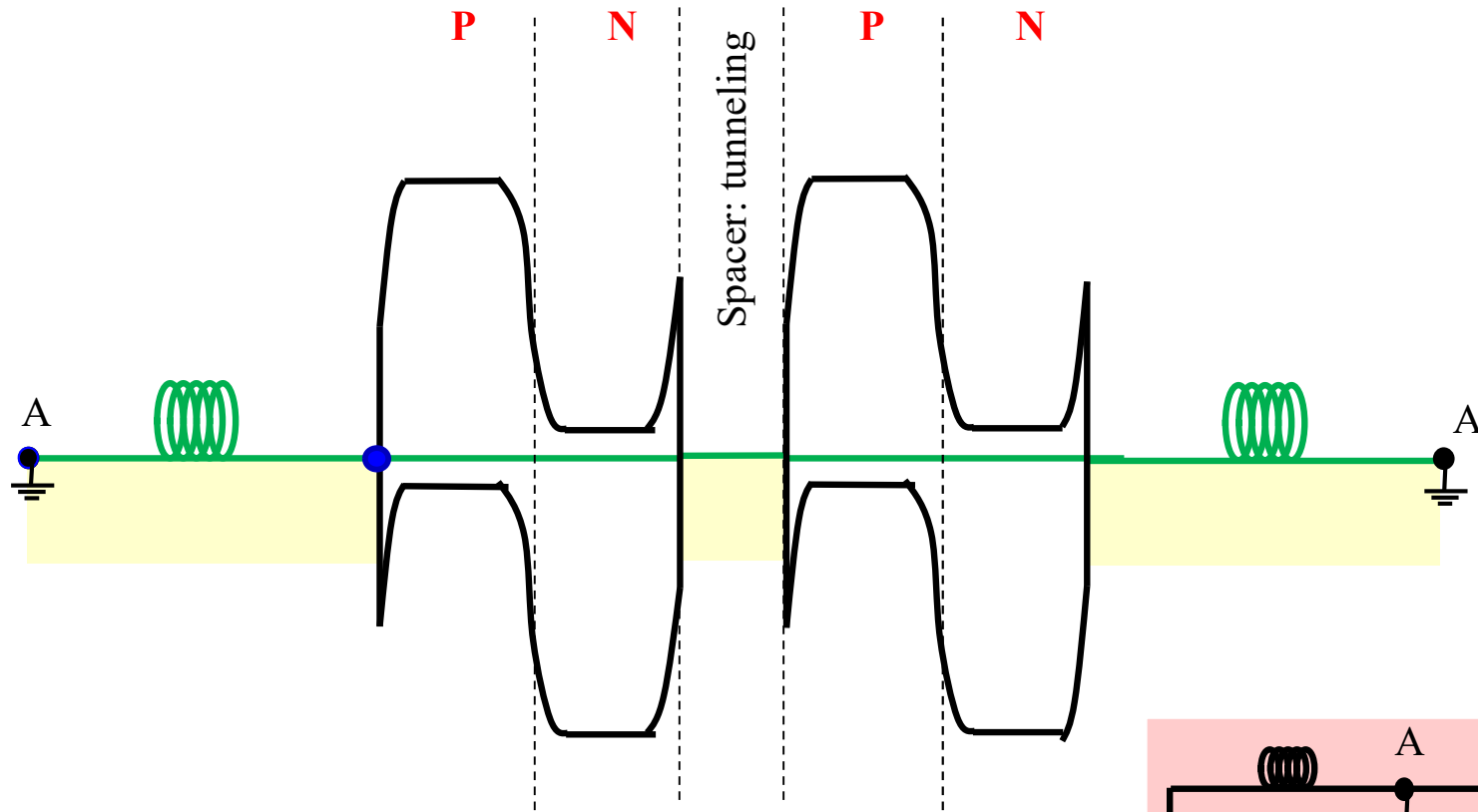
Why ?



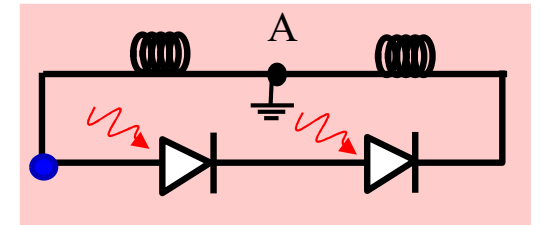
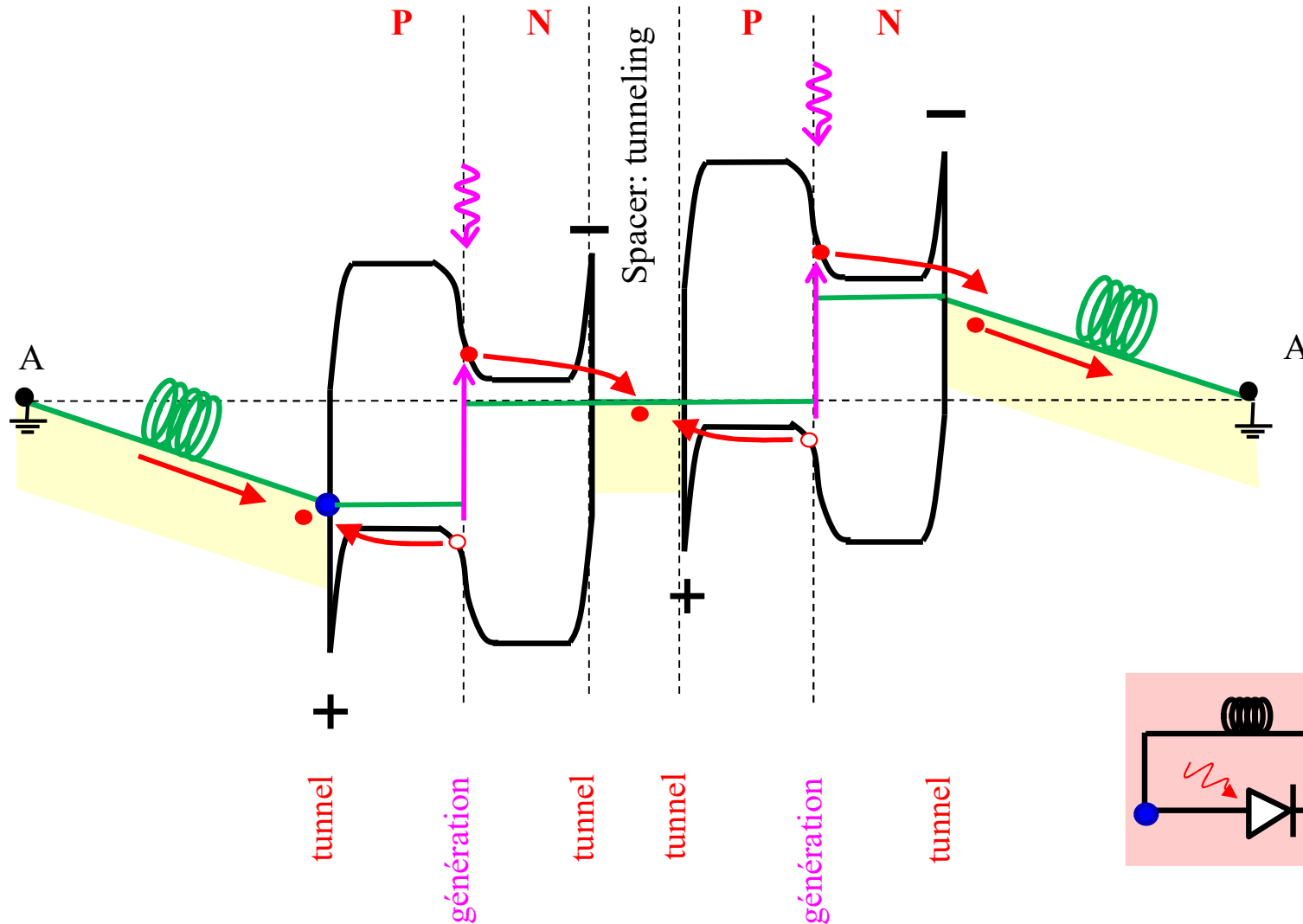
Vintage calculator  
9 cells



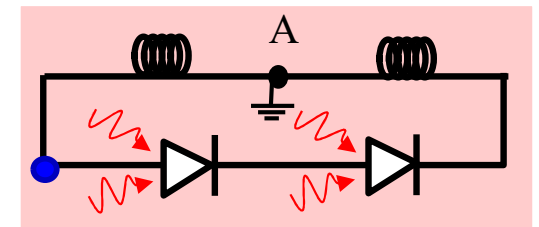
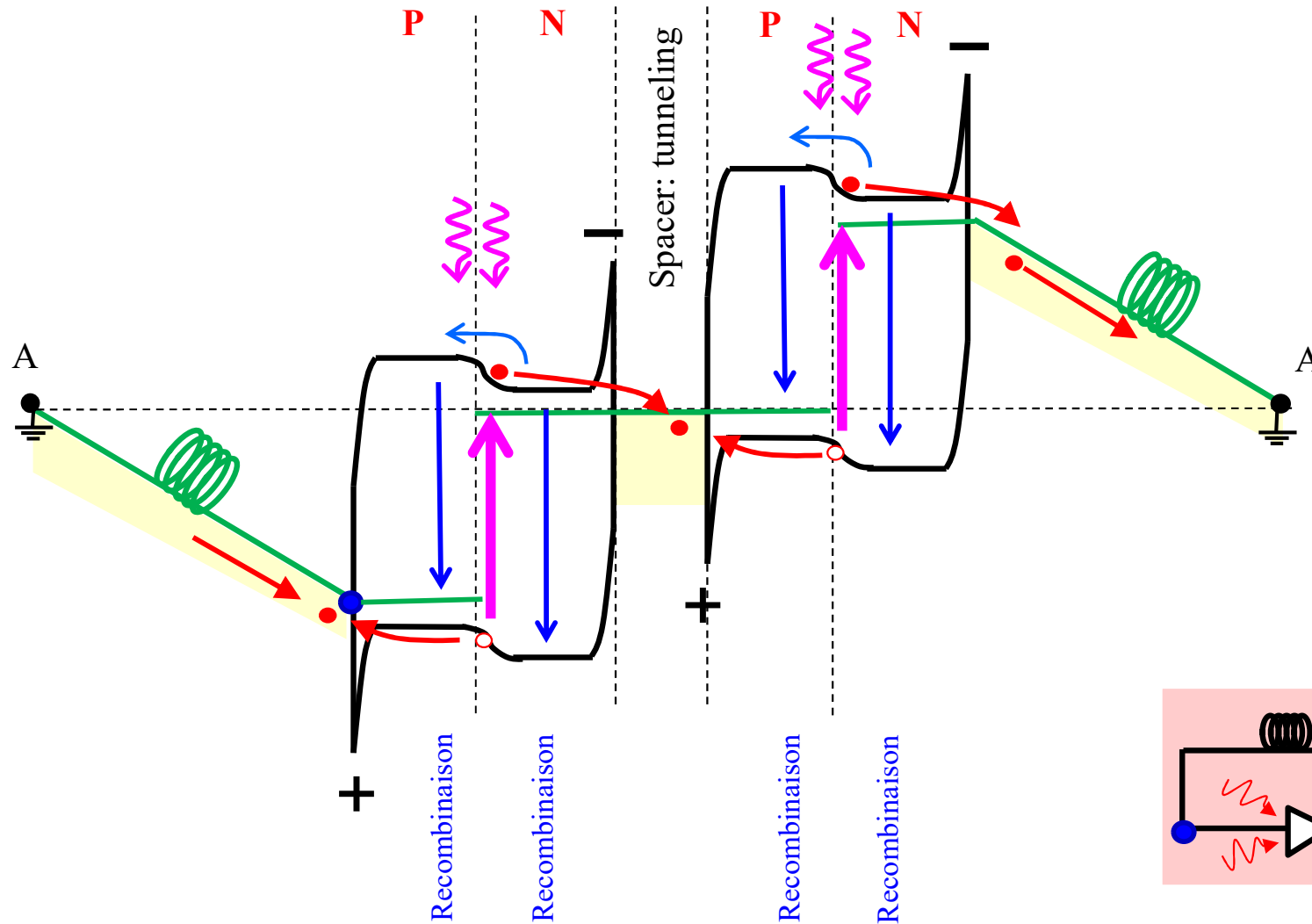
# Two Solar Cells in Series (1): no illumination



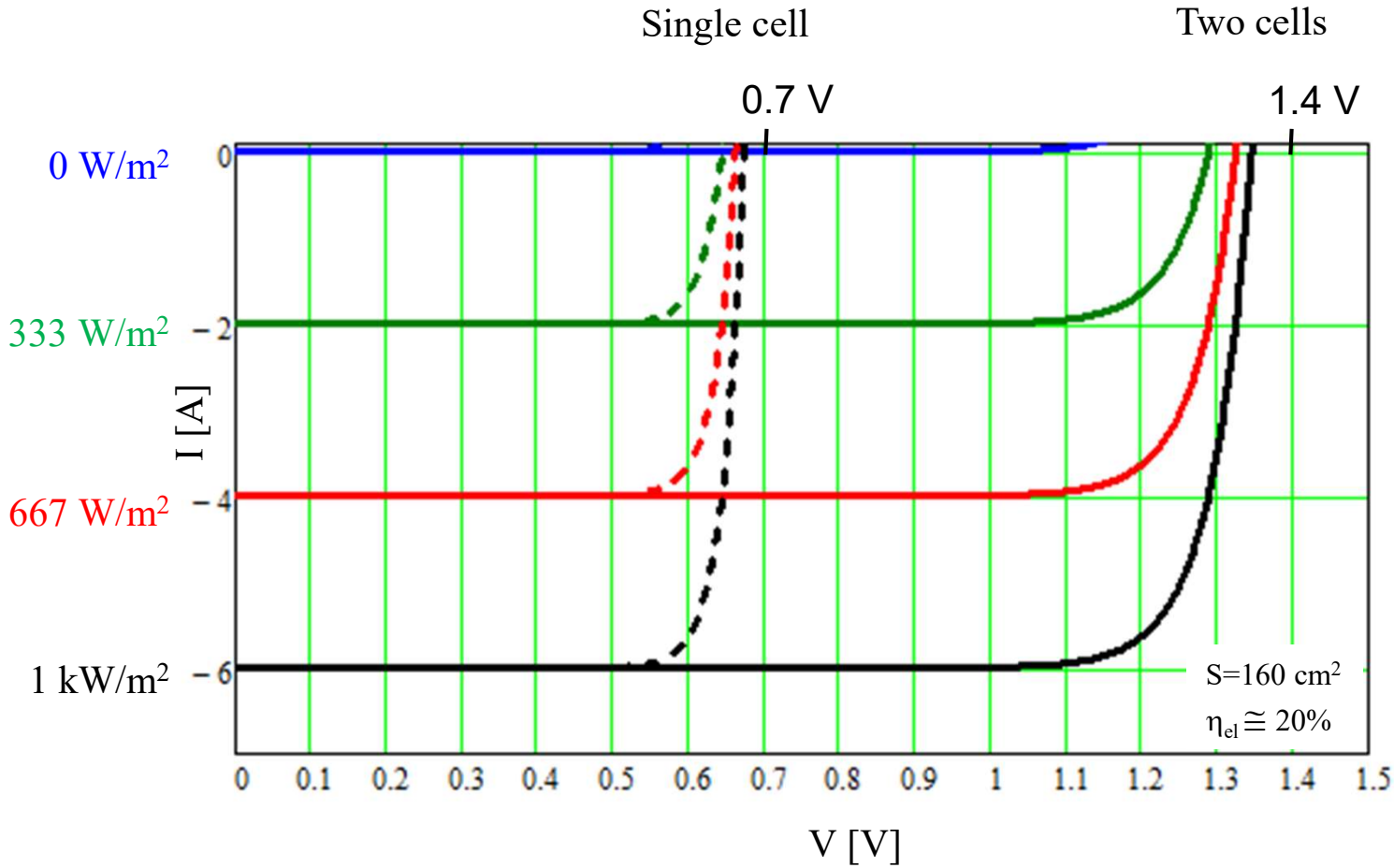
# Two Solar Cells in Series (2): under illumination



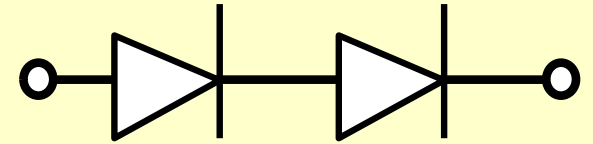
# Two Solar Cells in Series (3): saturation



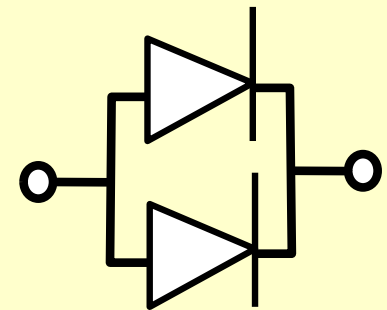
# Two Solar Cells in Series (4)



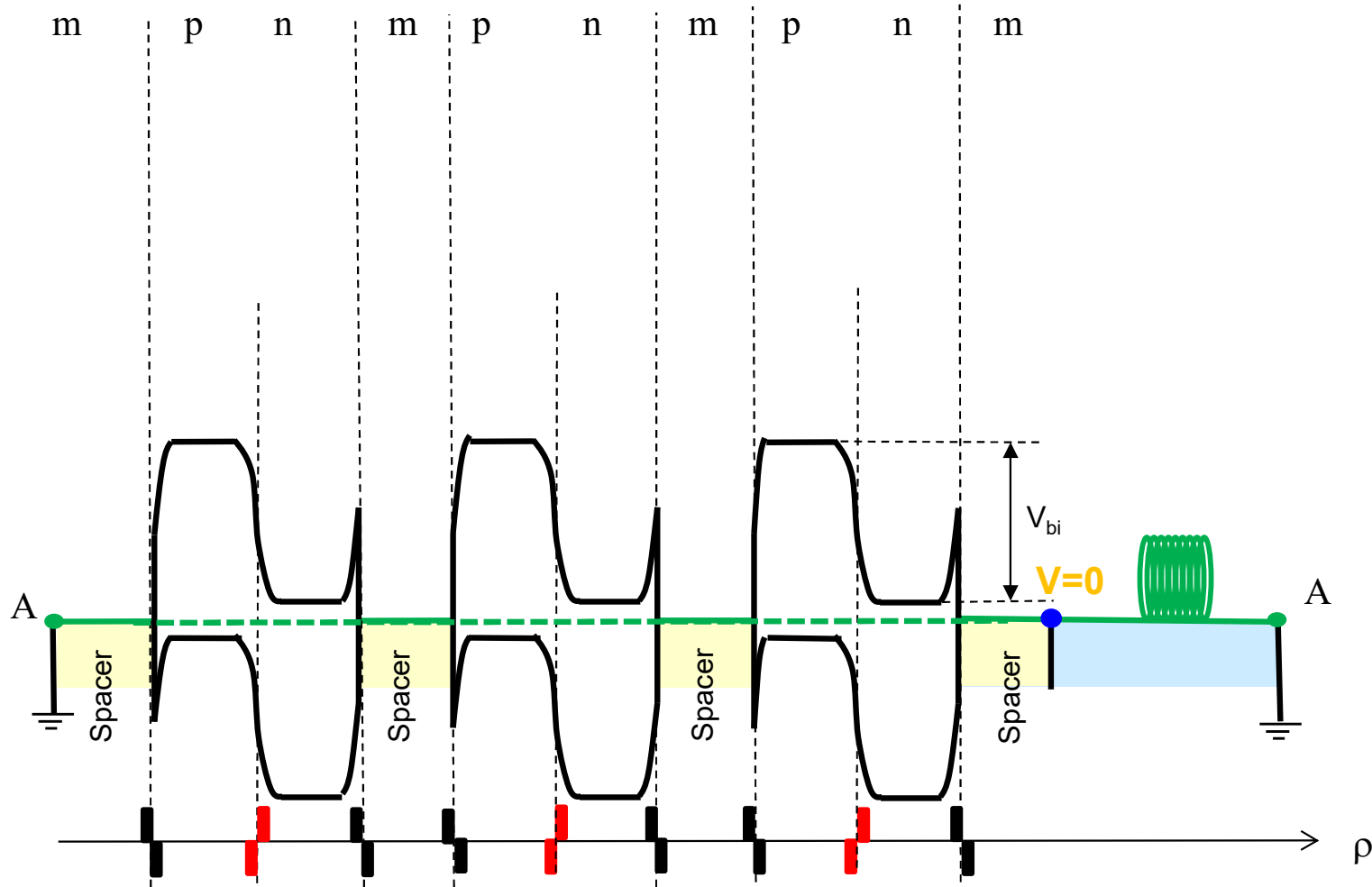
- n cells in series  
→ same current  
at n times the voltage



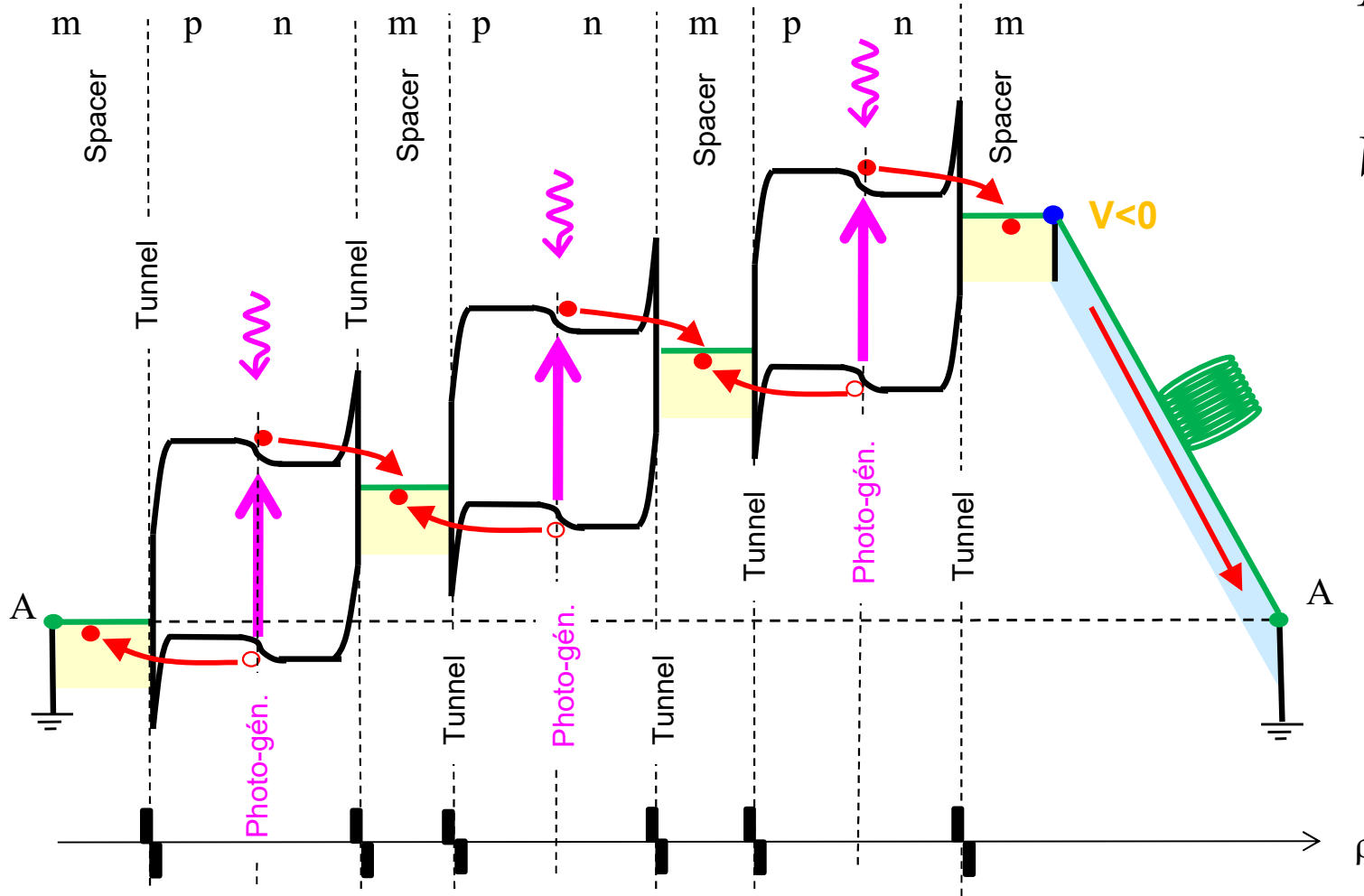
- n cells in parallel  
→ n times the current  
at the same voltage



# Solar cells in series: no illumination



# Solar cells in series: under illumination

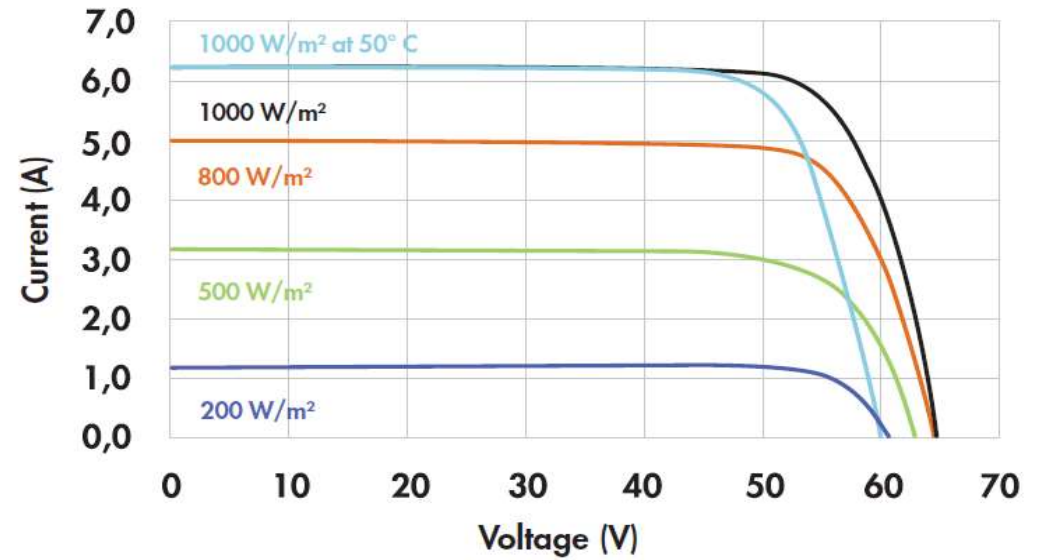
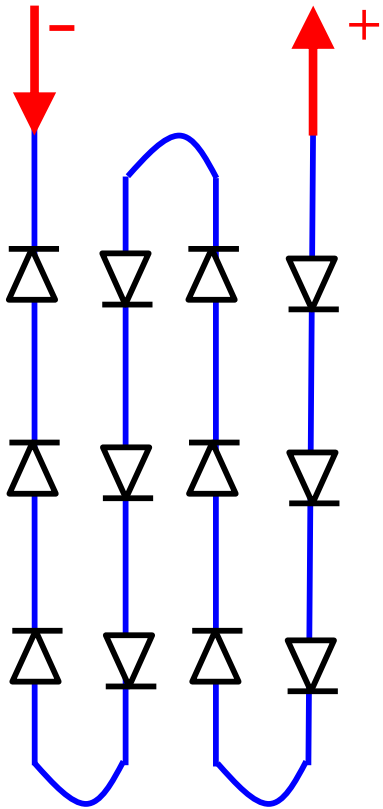


$$I = I_1 = I_2 = I_3 \dots = I_n$$

$$V = \sum_n V_n$$



# Example of a Panel: Sun Power 315



96 cells in series  $\rightarrow 96 \times V_{oc} = \text{env. } 60\text{V}$

( 1 cell = 5" x 5" )

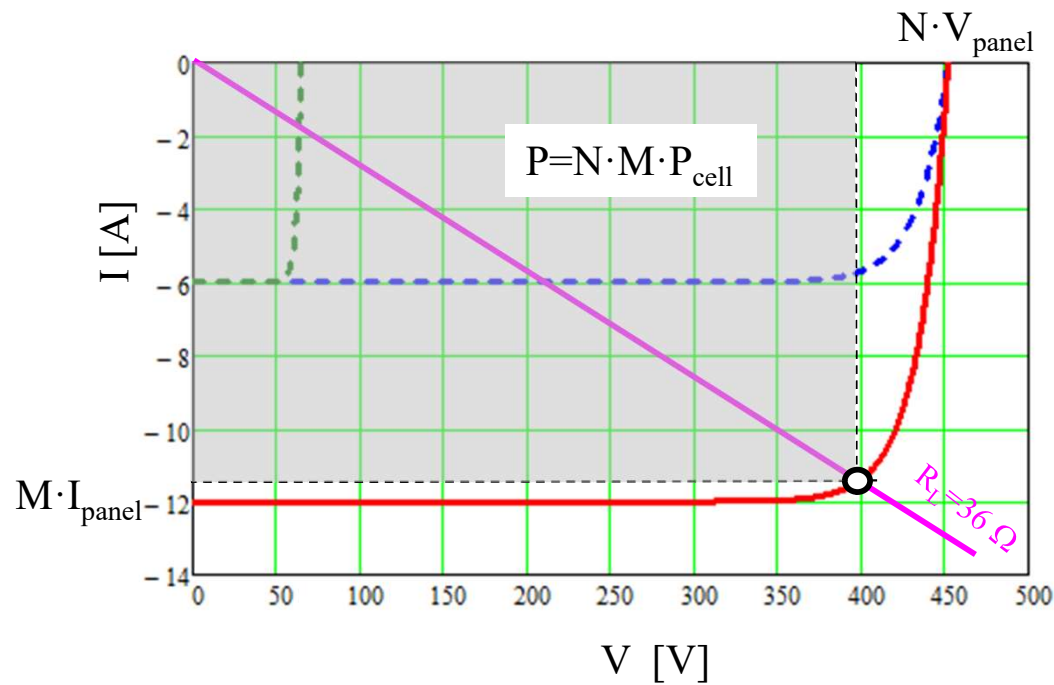
# Series of solar panels

N panels in series: → same current,

sum of all voltages

M panels in parallel: → sum of the currents

same voltage

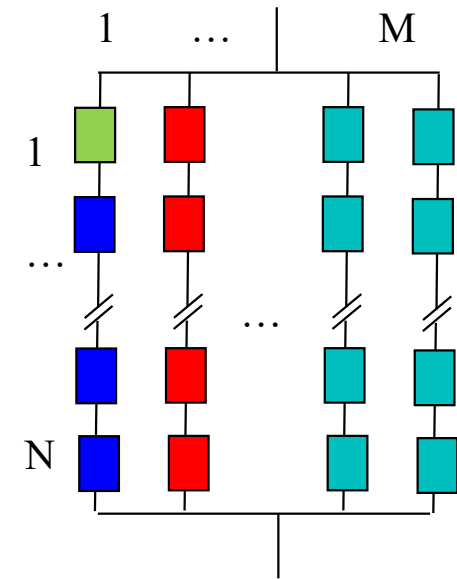


$N=M=1$

$N=7, M=1$

$N=7, M=2$

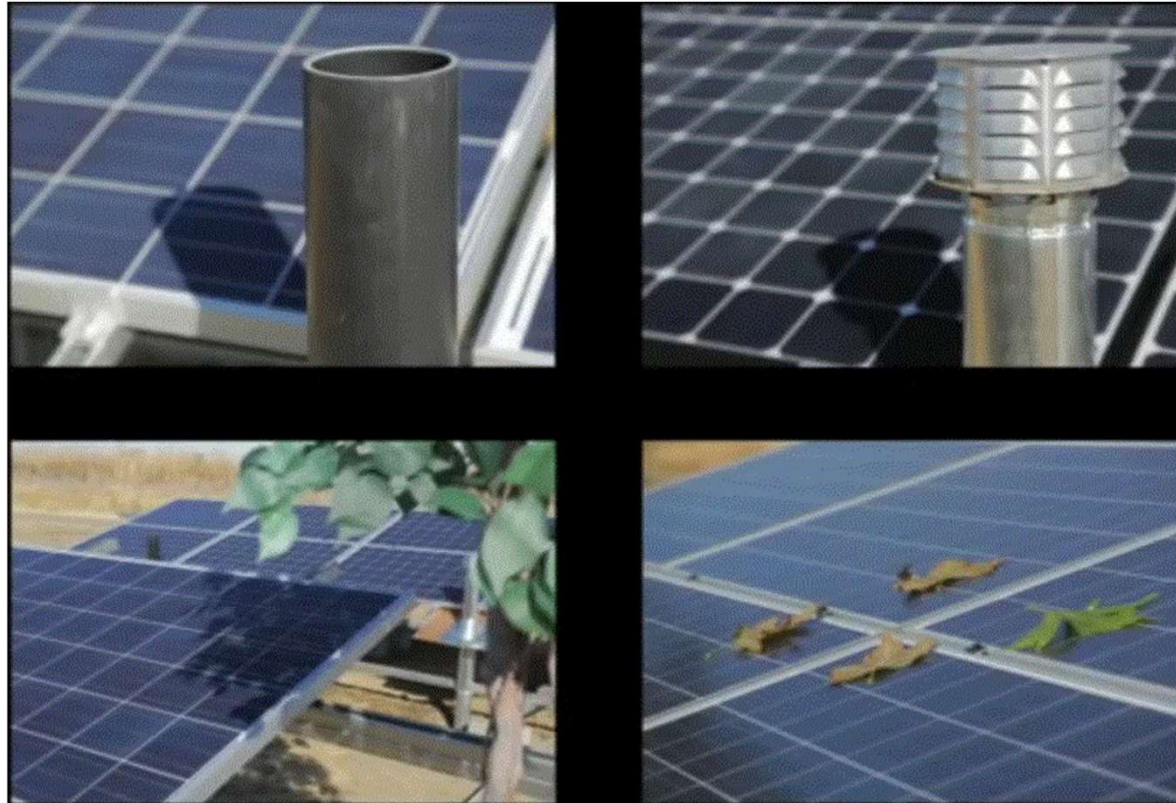
$1 \text{ kW/m}^2$   
 $I_{\text{panel}}=6\text{A}$   
 $V_{\text{panel}}=64\text{V}$



## 8.5: Solar Cell with a Defect

**Ombres:**

- Cheminée
- Arbres
- Feuilles
- ...

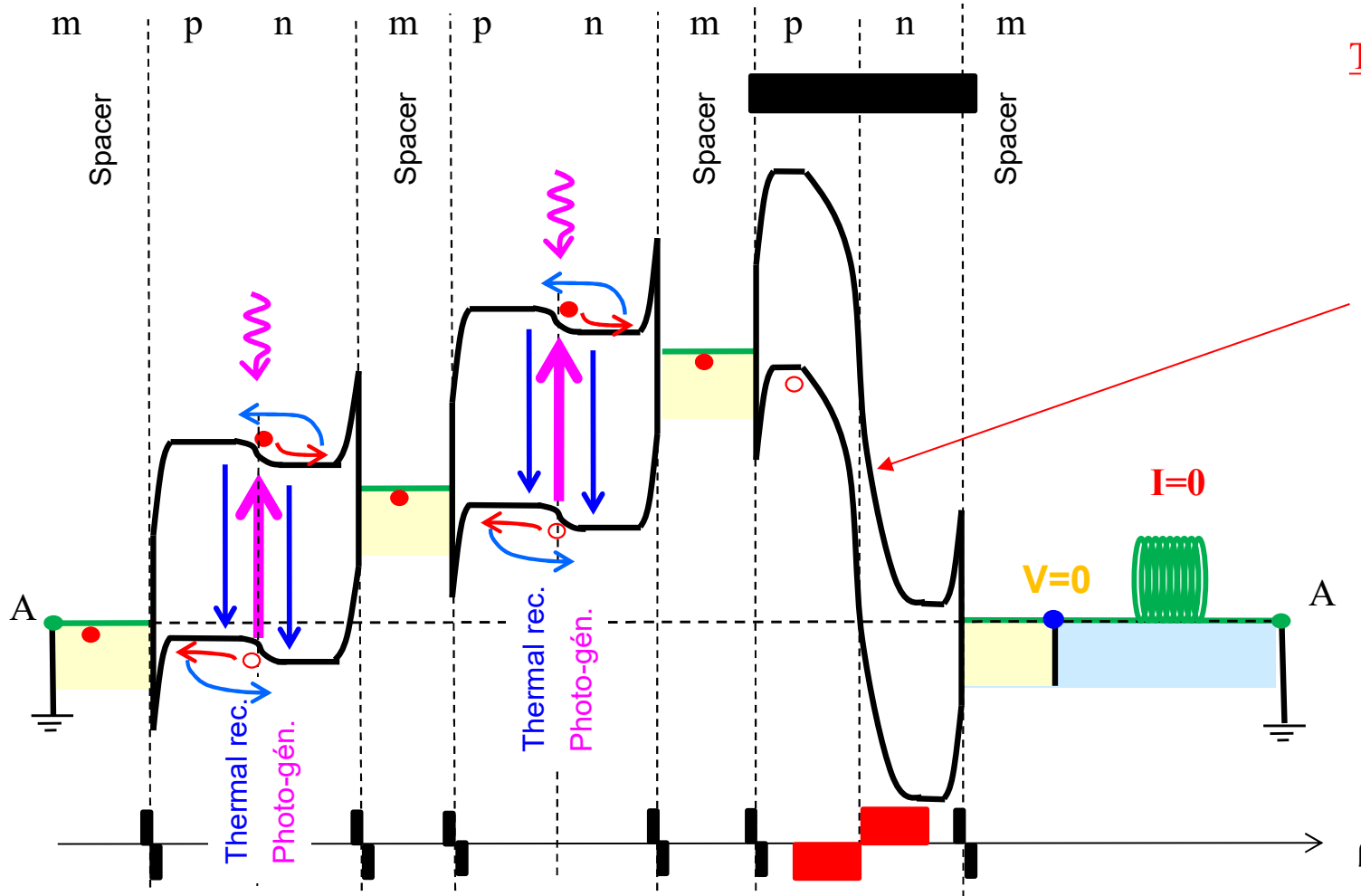


**Question:**

**Quels effets ?**

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

# Solar cells in series: one defect



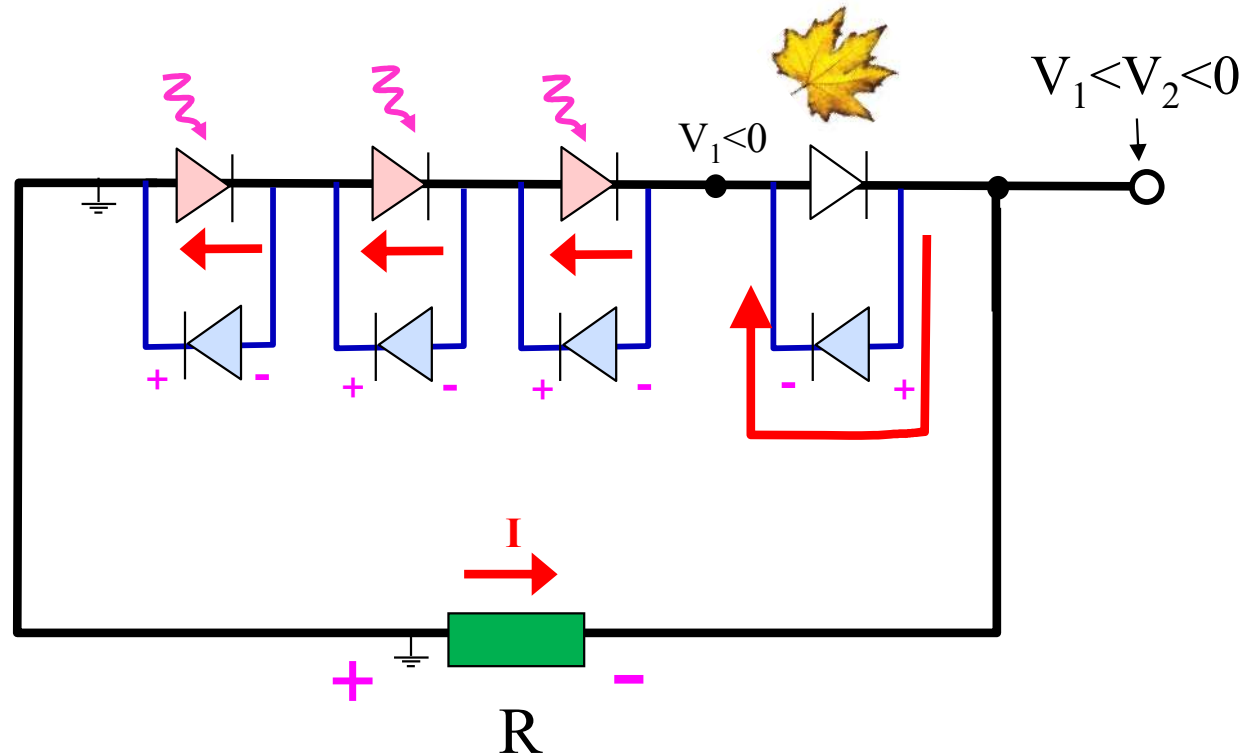
Tension sur la dernière cellule:

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

→ Risque de claquage

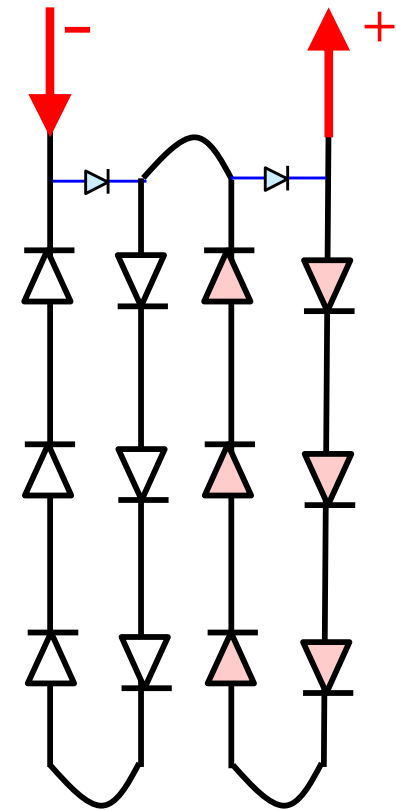
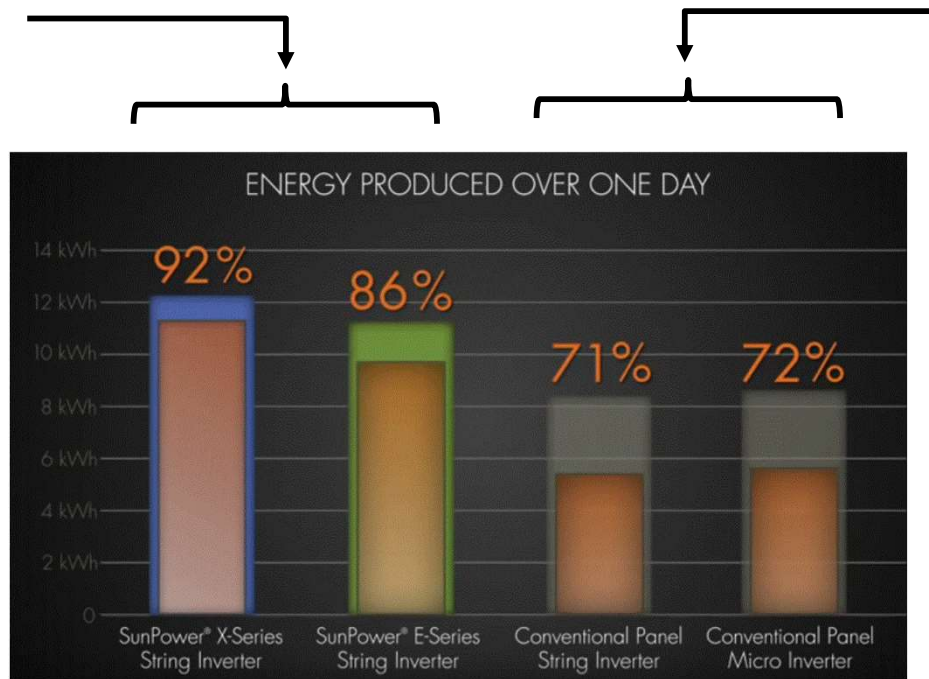
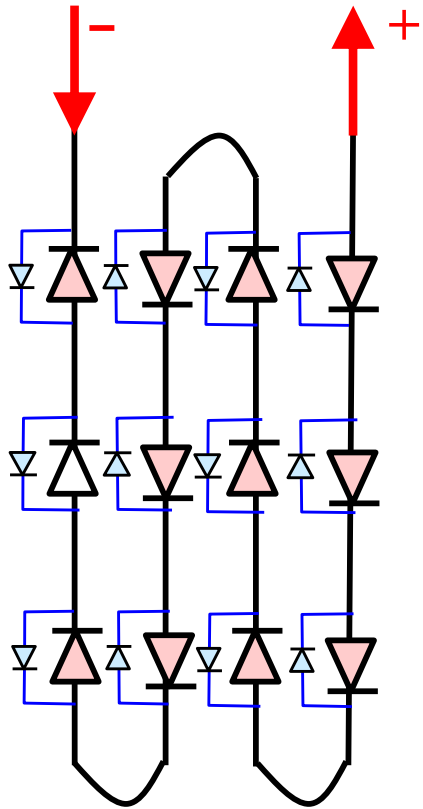
$$I = \min [I_1, I_2, I_3, \dots, I_n] = 0$$

# Solar Cell with protection



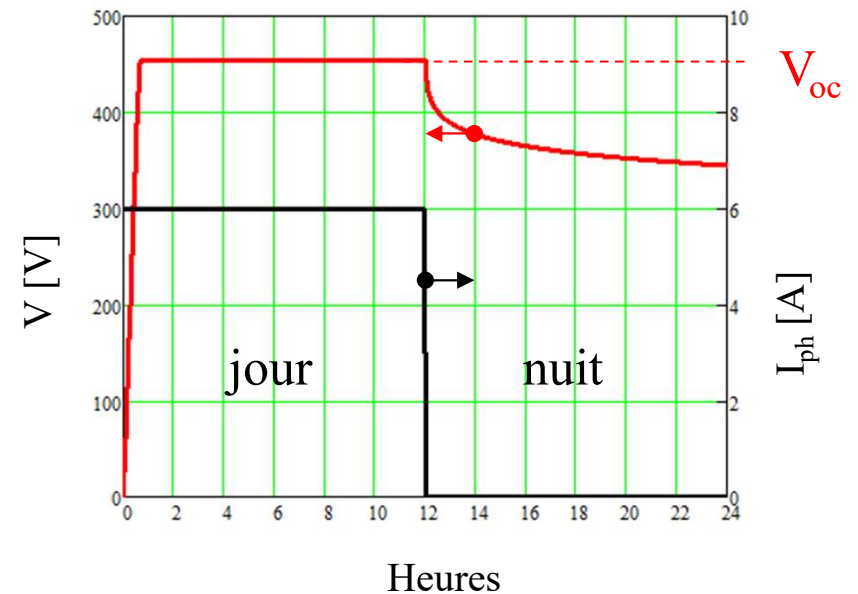
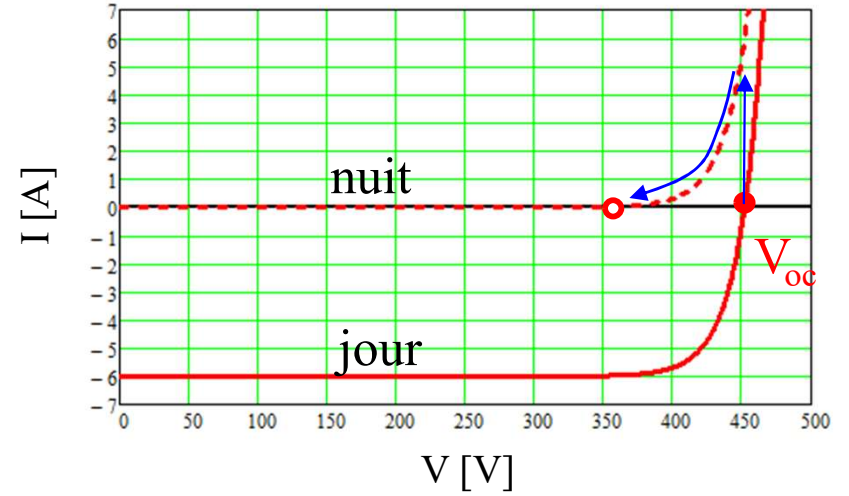
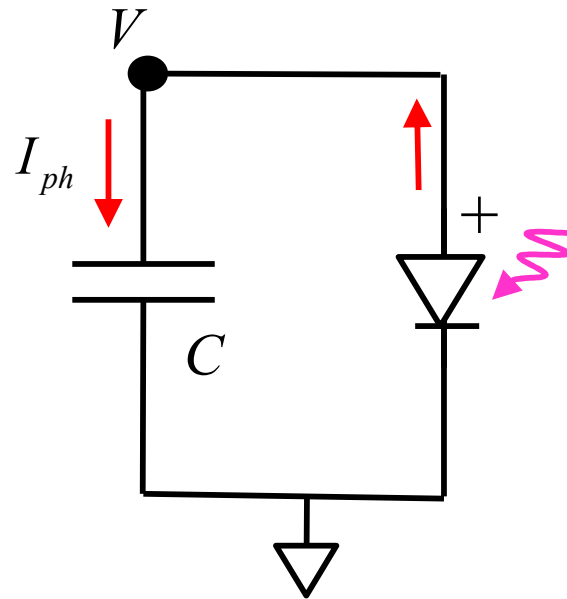
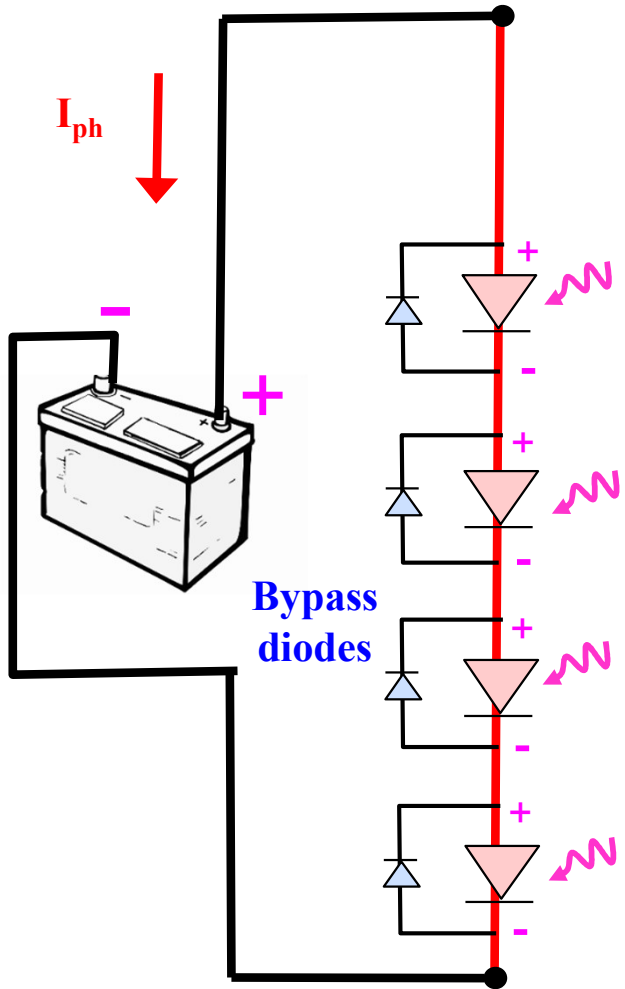
By-pass diodes

# Panneaux solaires avec diodes de by-pass



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

# Charge et décharge de la batterie

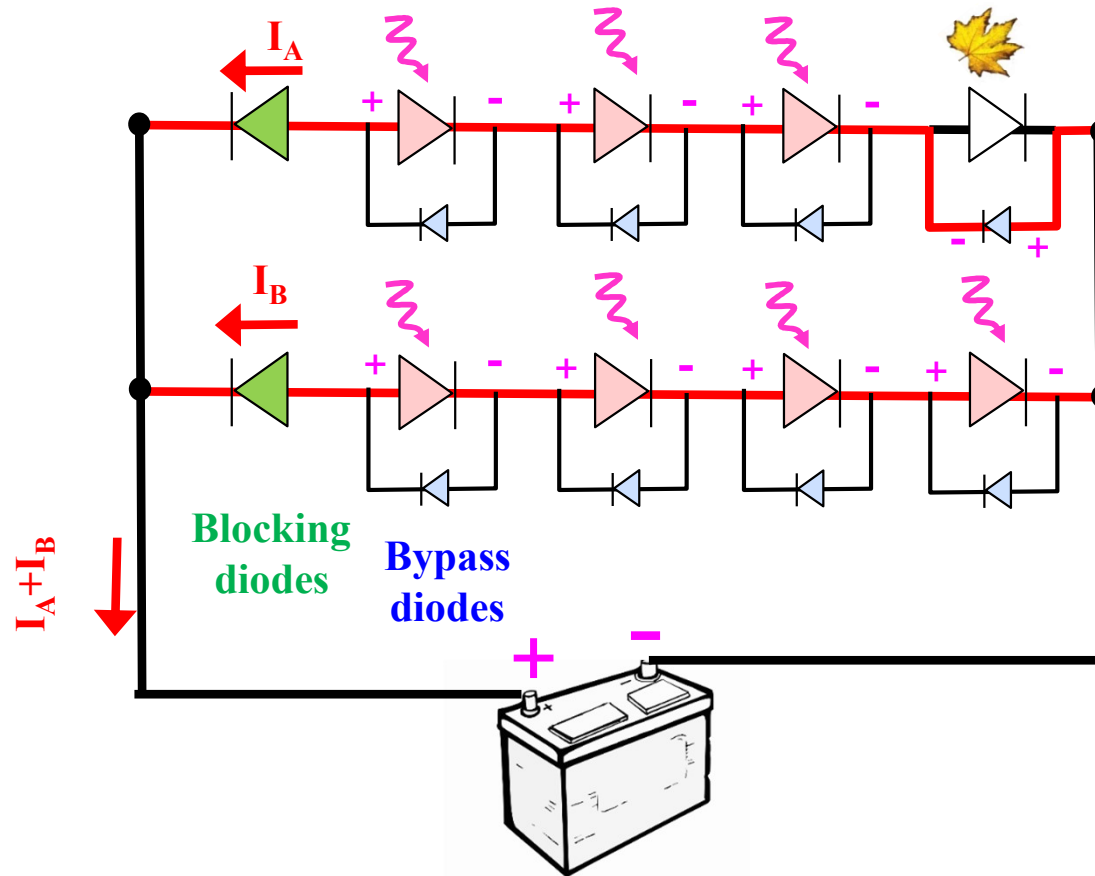


# Blocking and bypass diodes

Blocking diodes:

→ Eviter:

- Décharge de nuit
- Courant inverse dans la branche faible



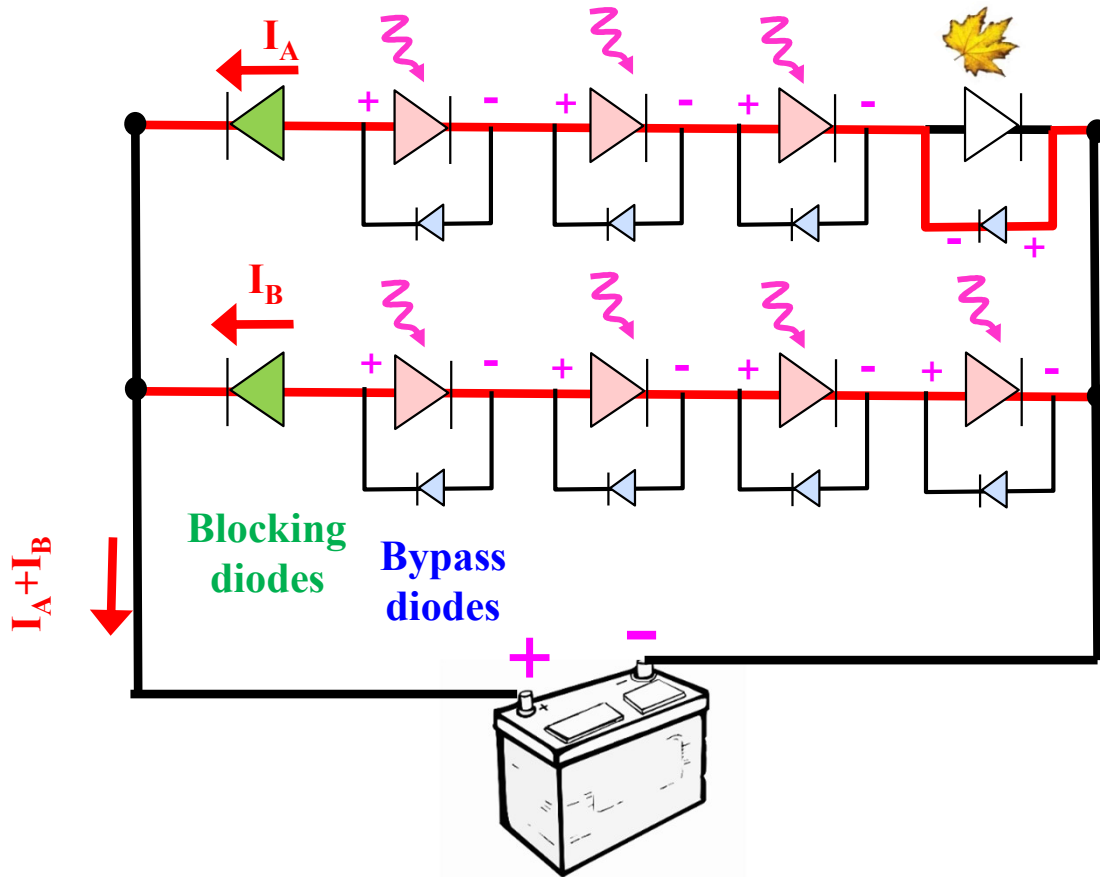
Low corner voltage  
→ Schottky diodes as:

- bypass and
- blocking

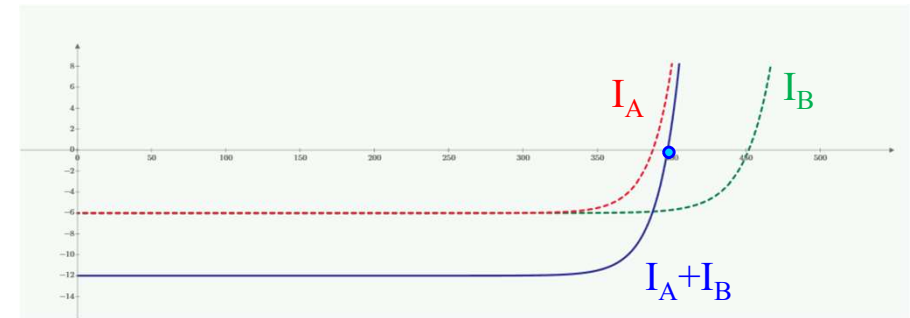


PV lab, Prof.. Ballif et Dr. Haug

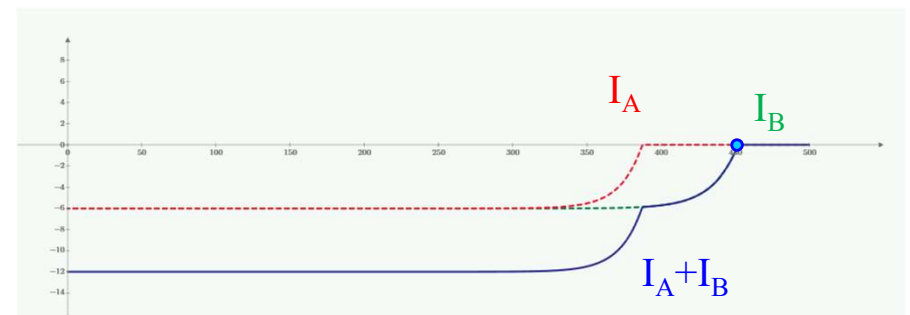
# Blocking and bypass diodes



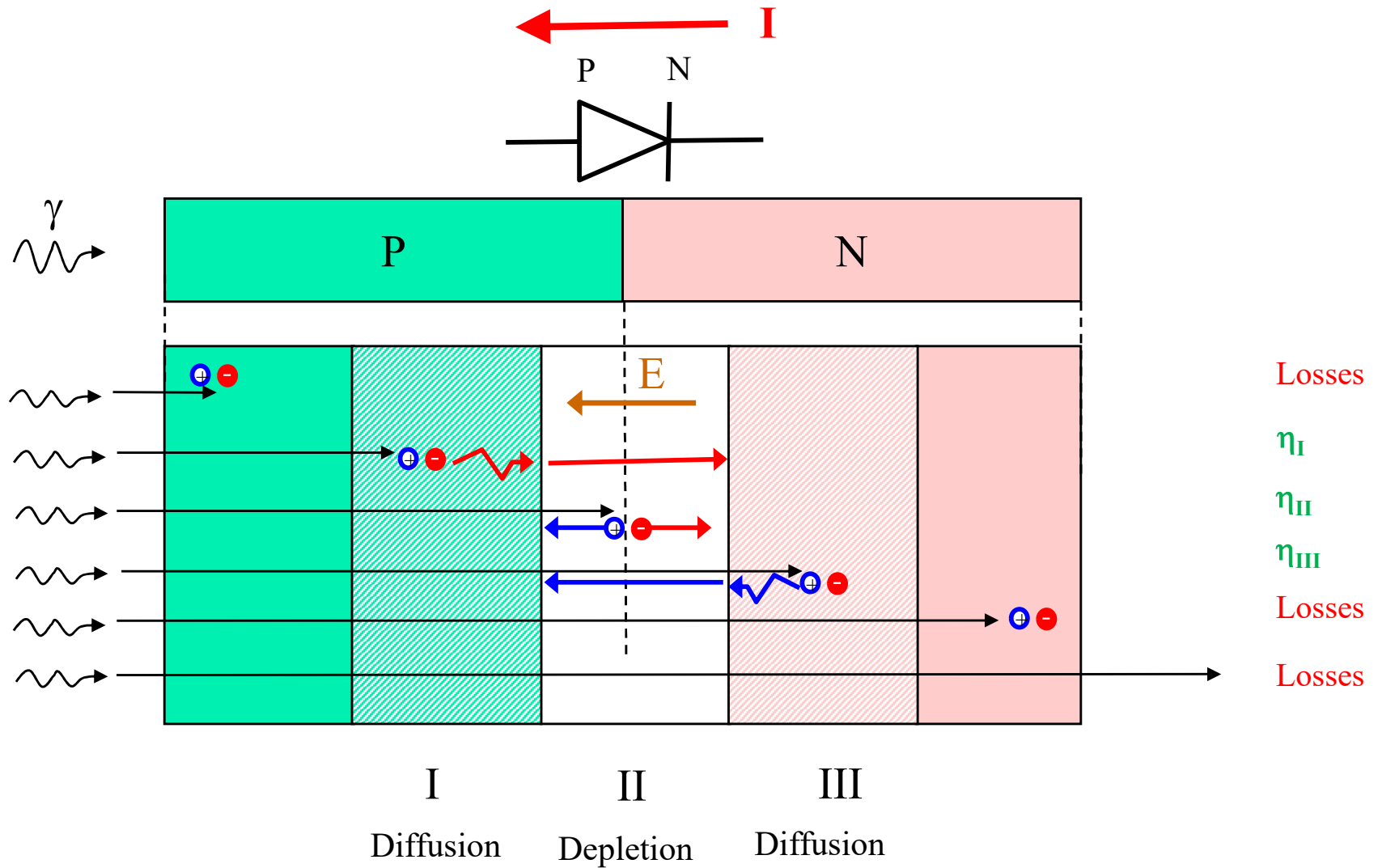
Sans blocking diodes:  $V_{oc}=390V$



Avec blocking diodes:  $V_{oc}=450V$



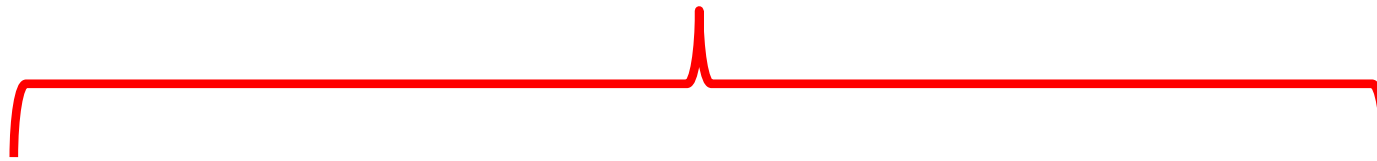
# 8.6: Schematic diagram of the working principle



# Pertes et efficacité optimal d'une jonction unique

$2/3$

$1/3$

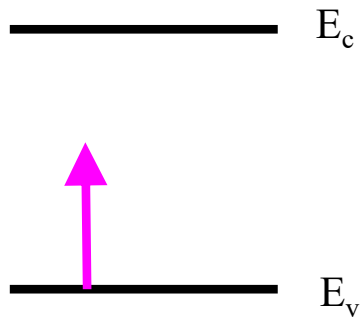


**Transparence**

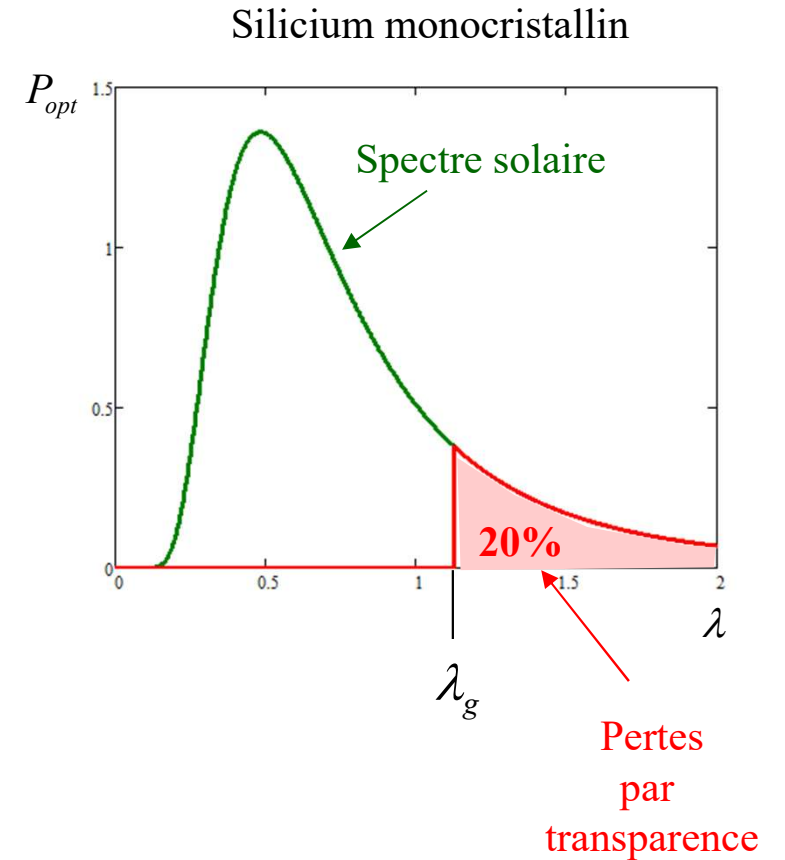
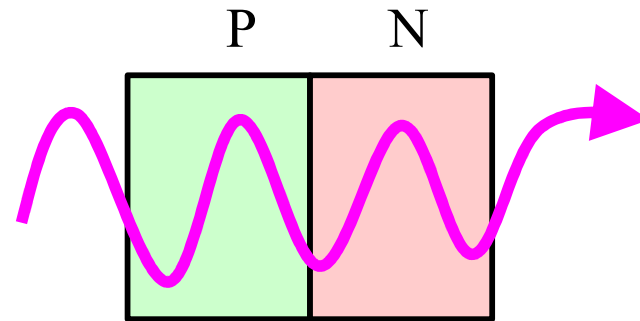
**Thermalisation**

**Optimal**

# Pertes: (1) par transparence



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

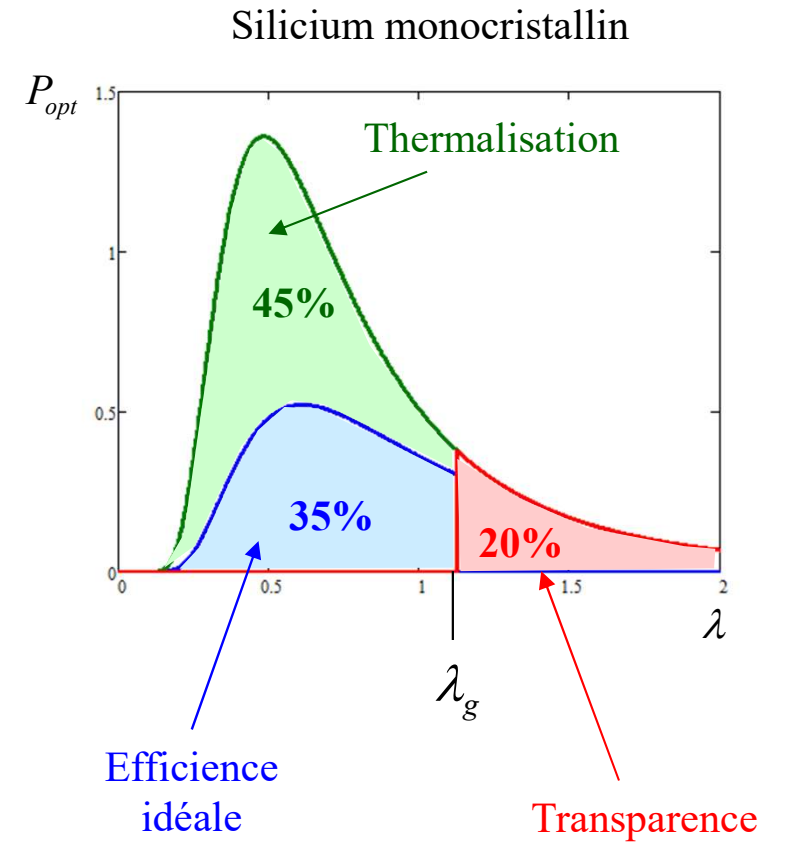


**Le semiconducteur est transparent pour  $\lambda > \lambda_g$**

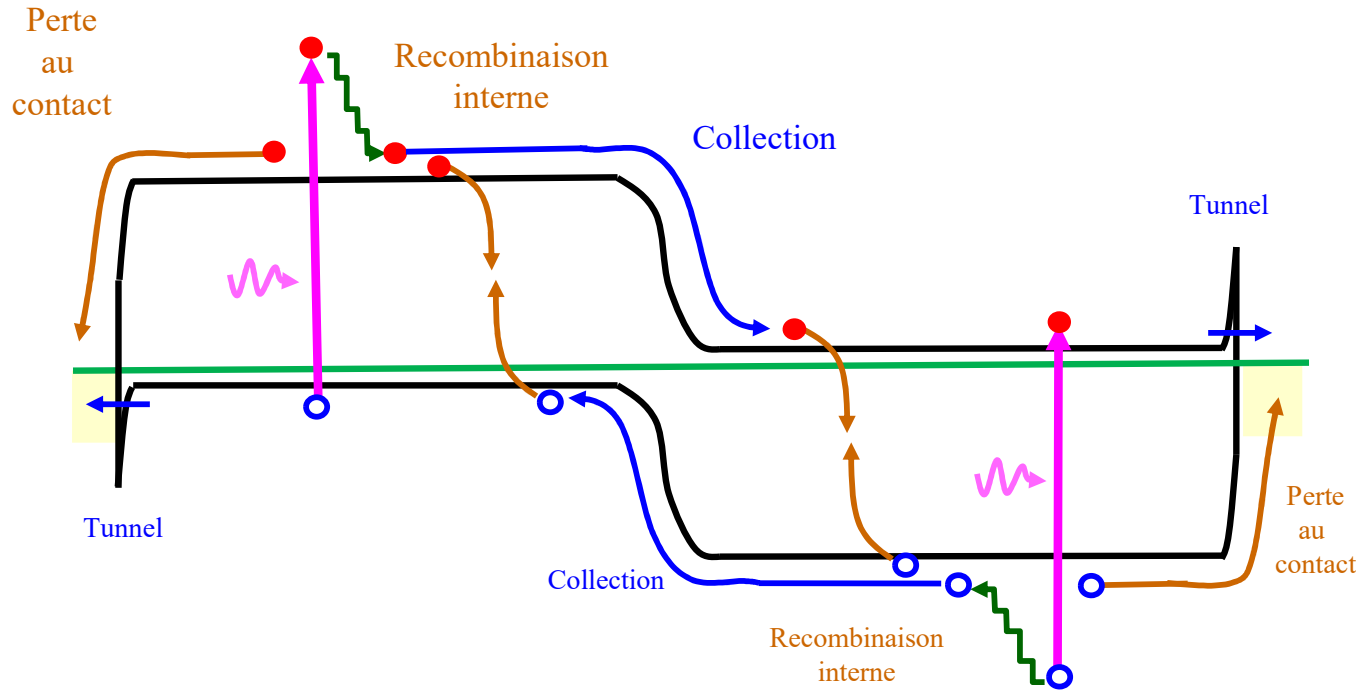
# Pertes: (2) par thermalisation



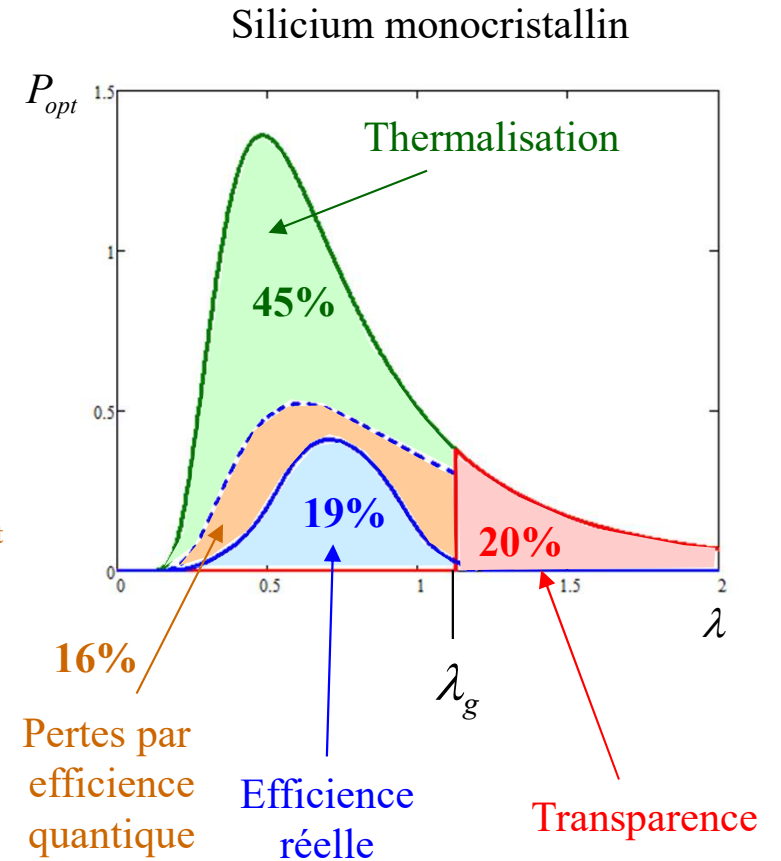
Investir :  $E_\gamma = h \frac{c}{\lambda}$  pour récolter :  $q \cdot V_{bi}$   $\implies$   $\eta_{el, idéale}(\lambda) = \frac{qV_{bi}}{hc} \cdot \lambda$



# Pertes: (3) par efficacité quantique

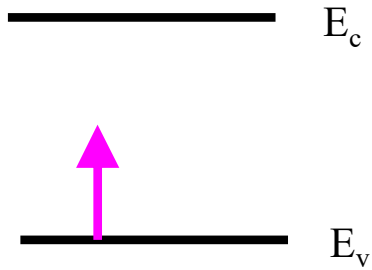


$$\eta_{el,réelle}(\lambda) = \eta_Q \cdot \frac{qV_{bi}}{hc} \cdot \lambda = R_I \cdot V_{bi}$$



# Résumé des pertes d'efficacité électriques

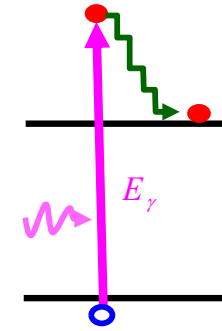
## 1) transparence



⇒ Petit bandgap

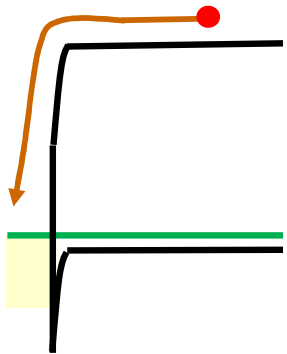
2/3

## 2) thermalisation

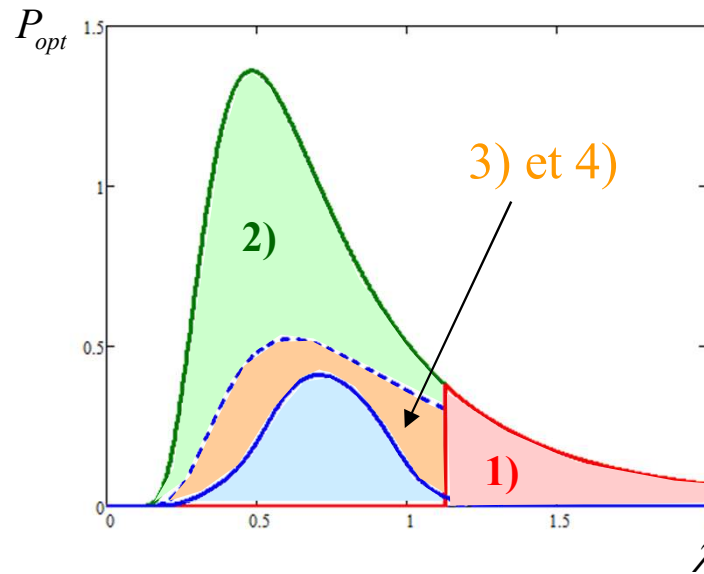
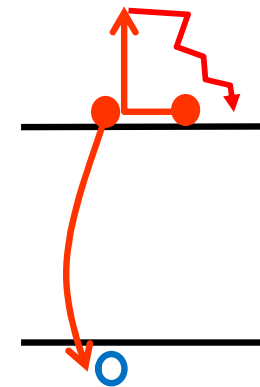


⇒ Grand bandgap

## 3) Pertes aux contacts

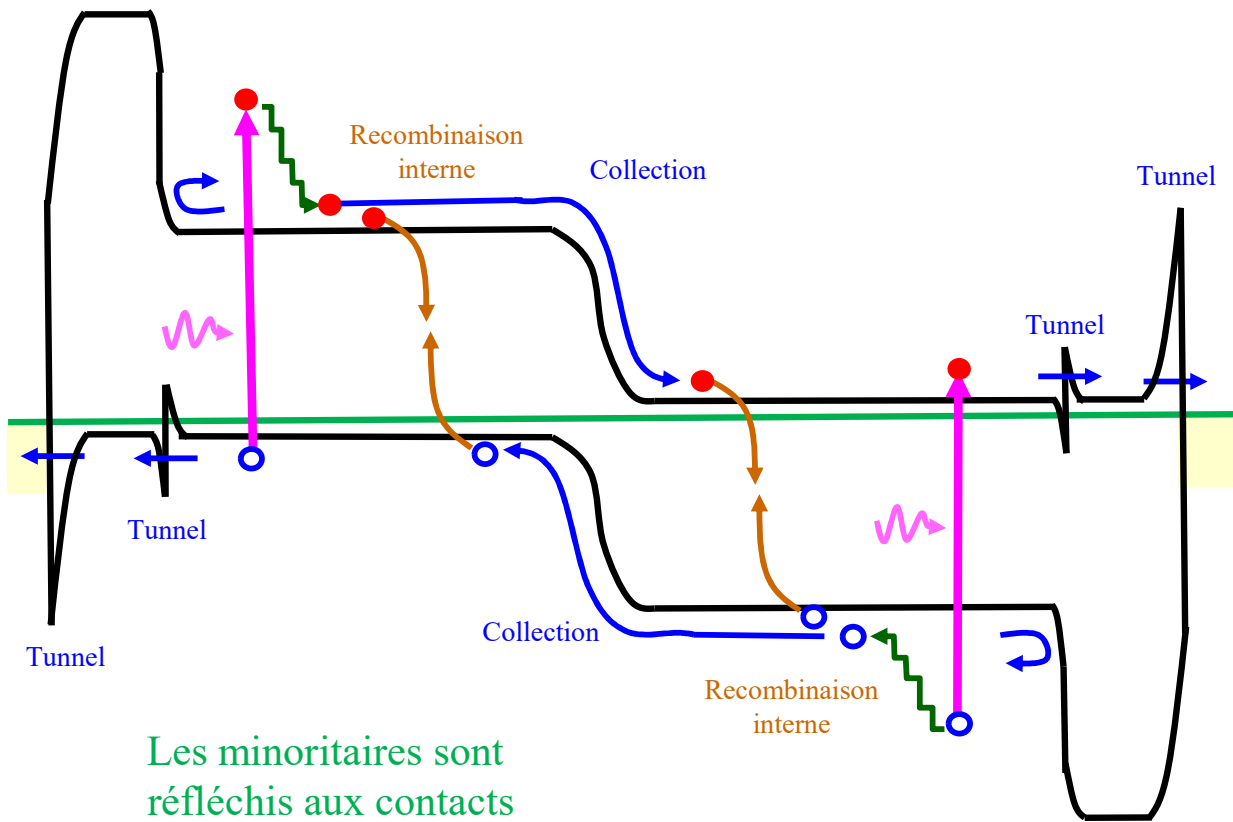


## 4) Recombinaisons internes

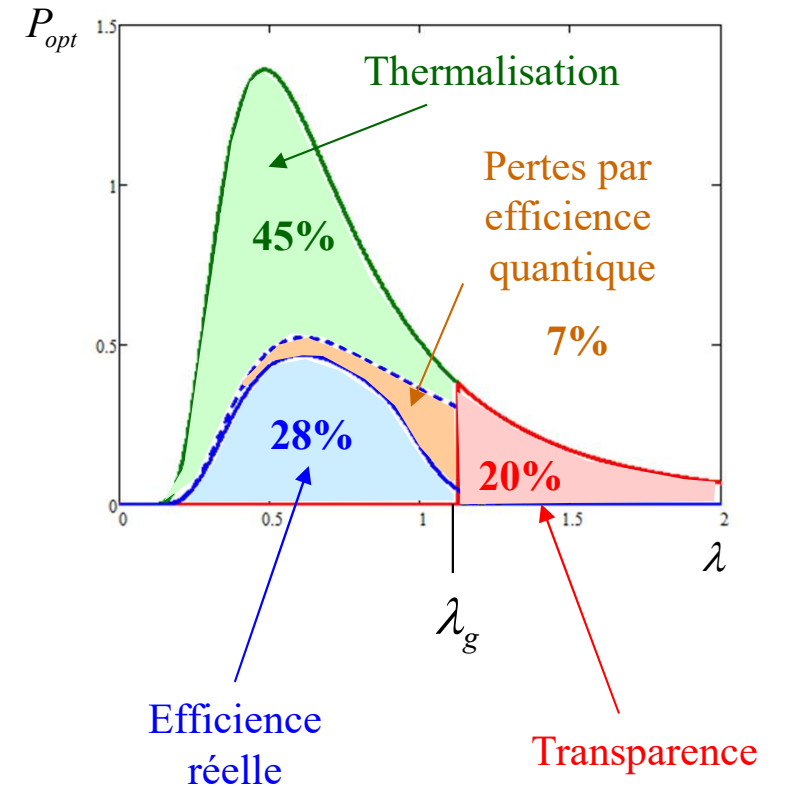


# 8.7: Cellule solaire par hétérostructure «réflective»

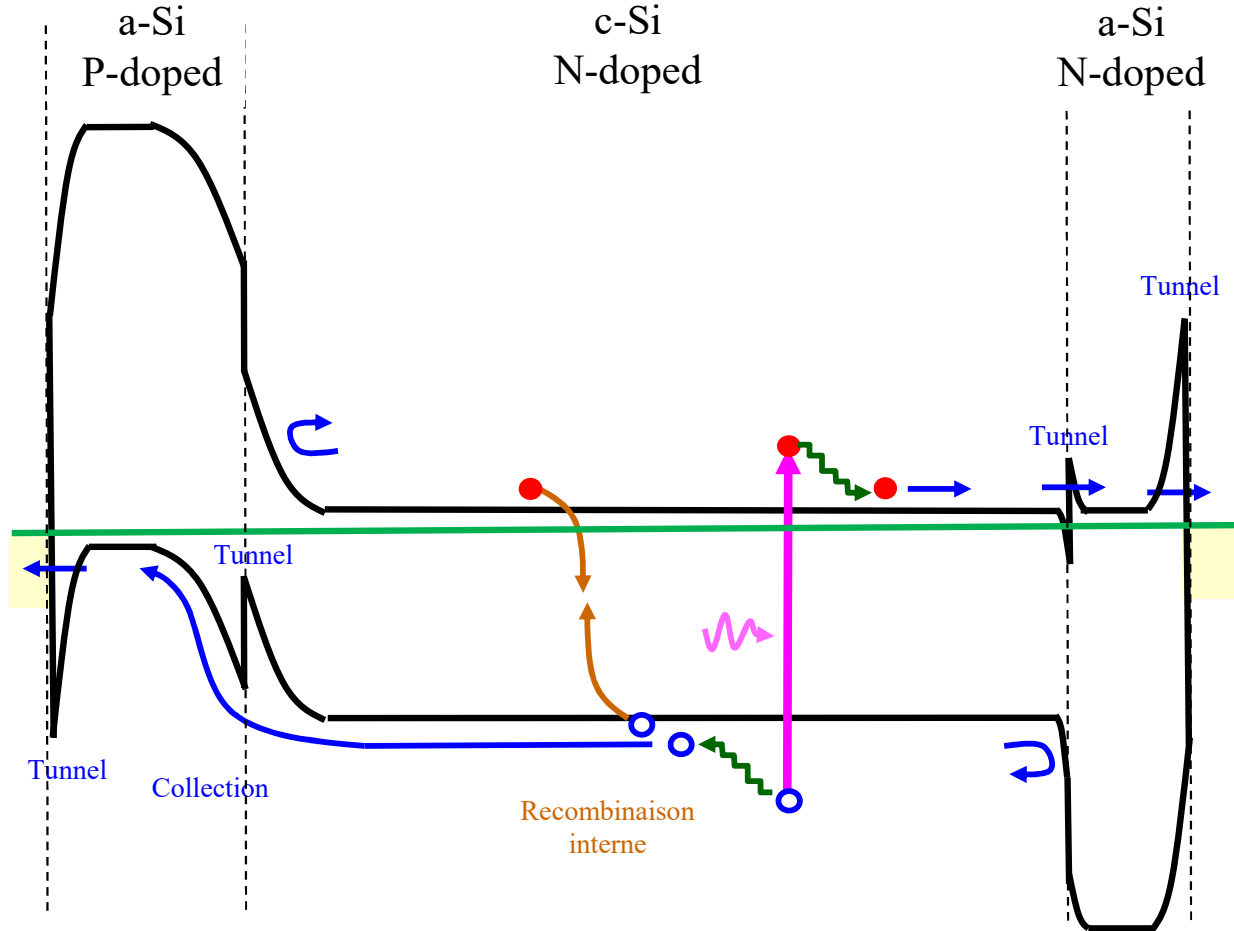
## Suppression des pertes aux contacts



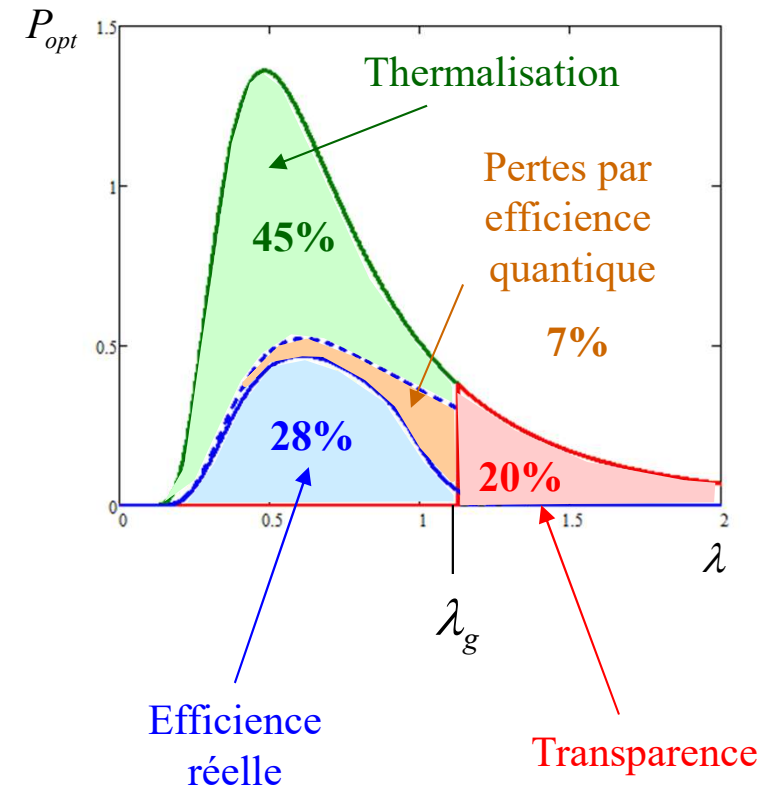
Silicium monocristallin + amorphe



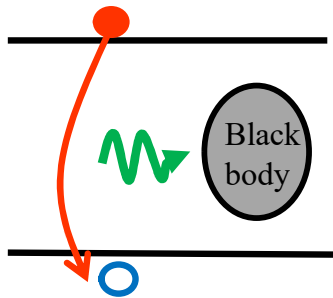
# Cellule solaire par hétérostructure «PV-lab»



Silicium monocristallin + polycristallin

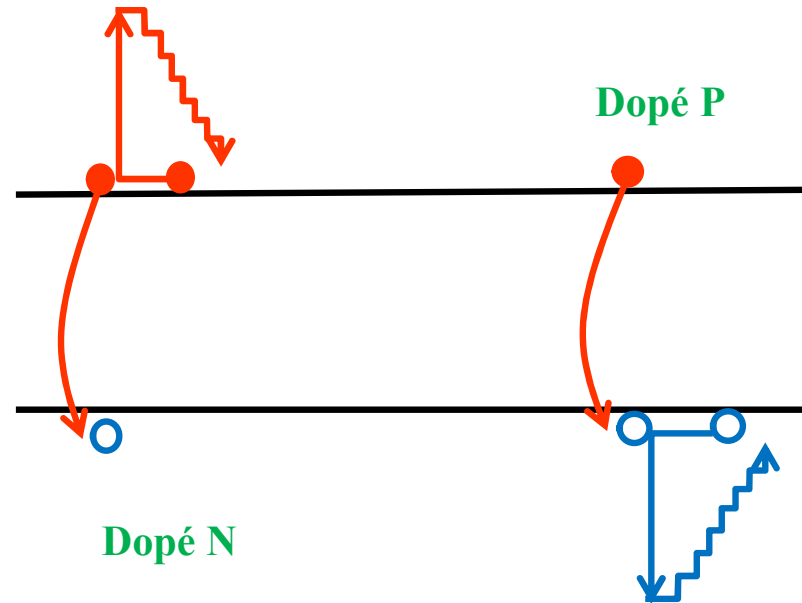


Recombinaison directe



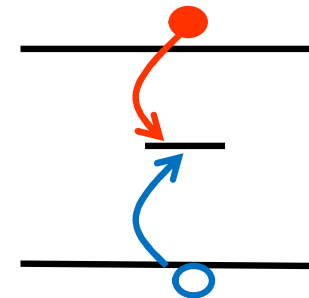
Dominant en III-V

Recombinaisons Auger



Dominant en silicium

Recombinaisons «trap assisted»  
SRH-recombinations

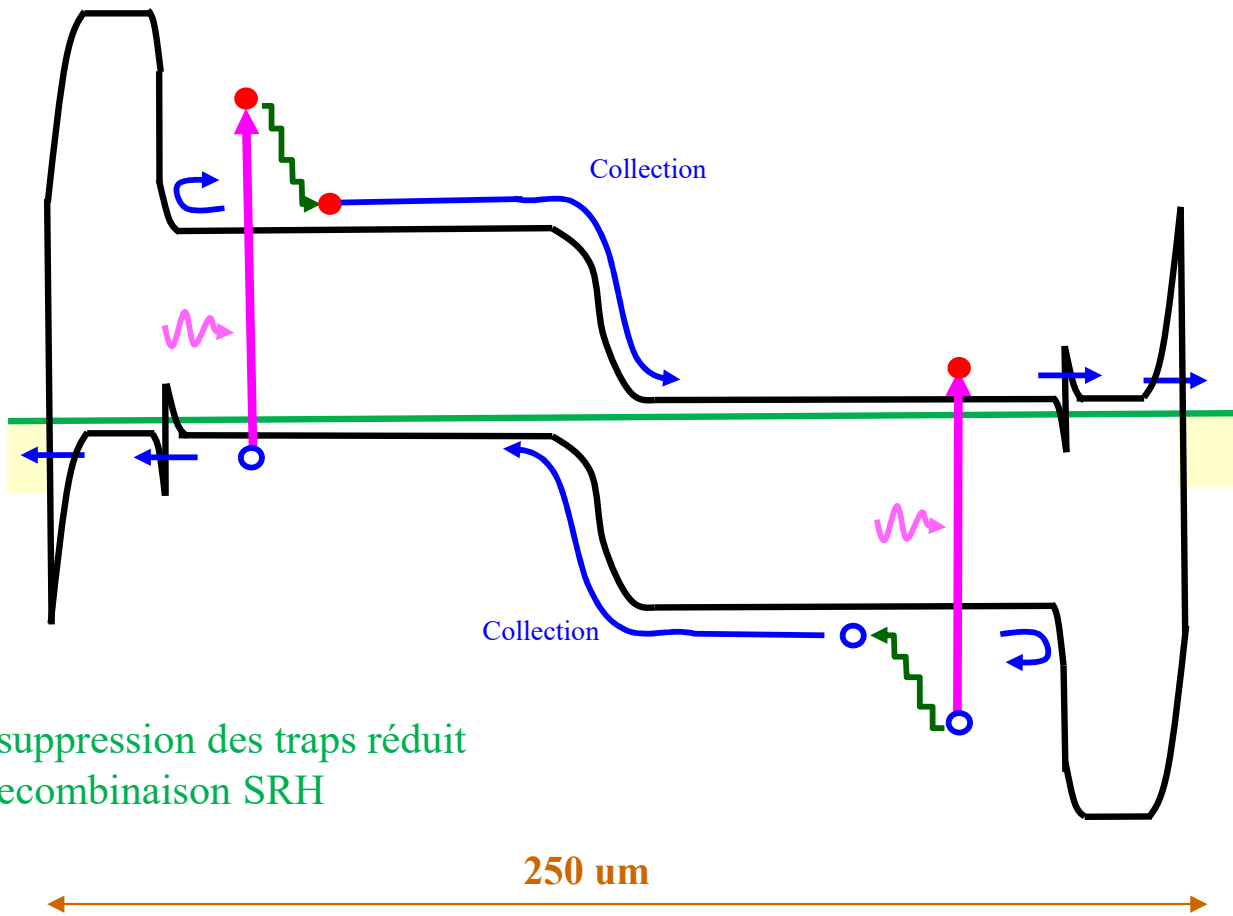


Dominant:

- aux interfaces
- dans les cellules low costs

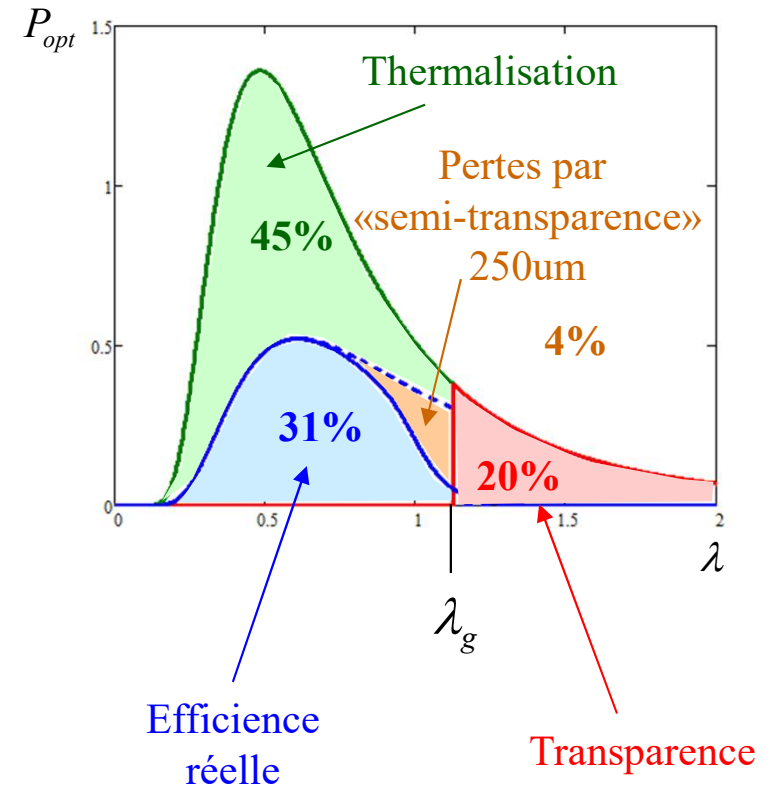
# Cellule solaire par hétérostructure «réflective»

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

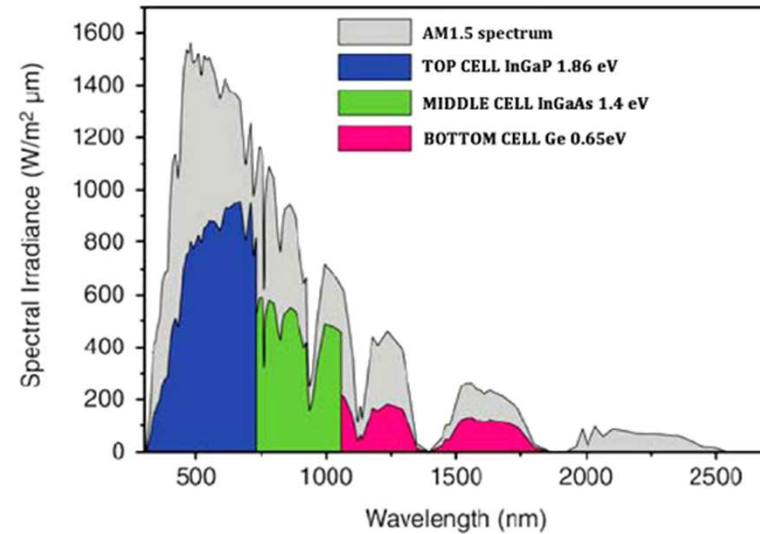
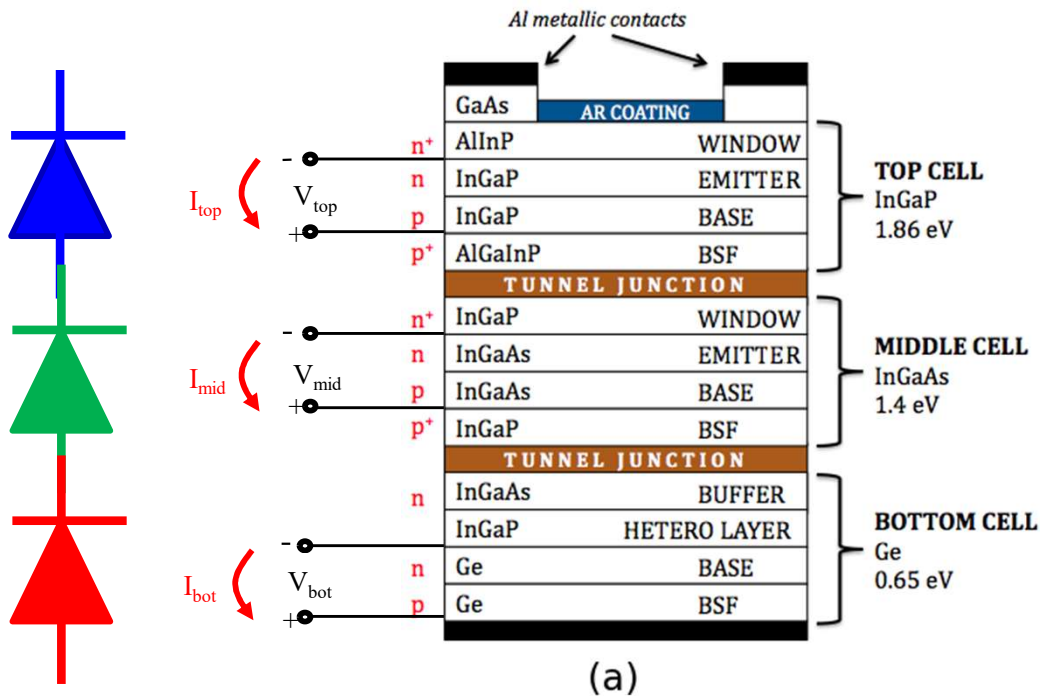


La suppression des traps réduit la recombinaison SRH

Silicium monocristallin + polycristallin



# 8.8: Multi-junctions solar cells



Les tensions des trois cellules s'additionnent

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

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

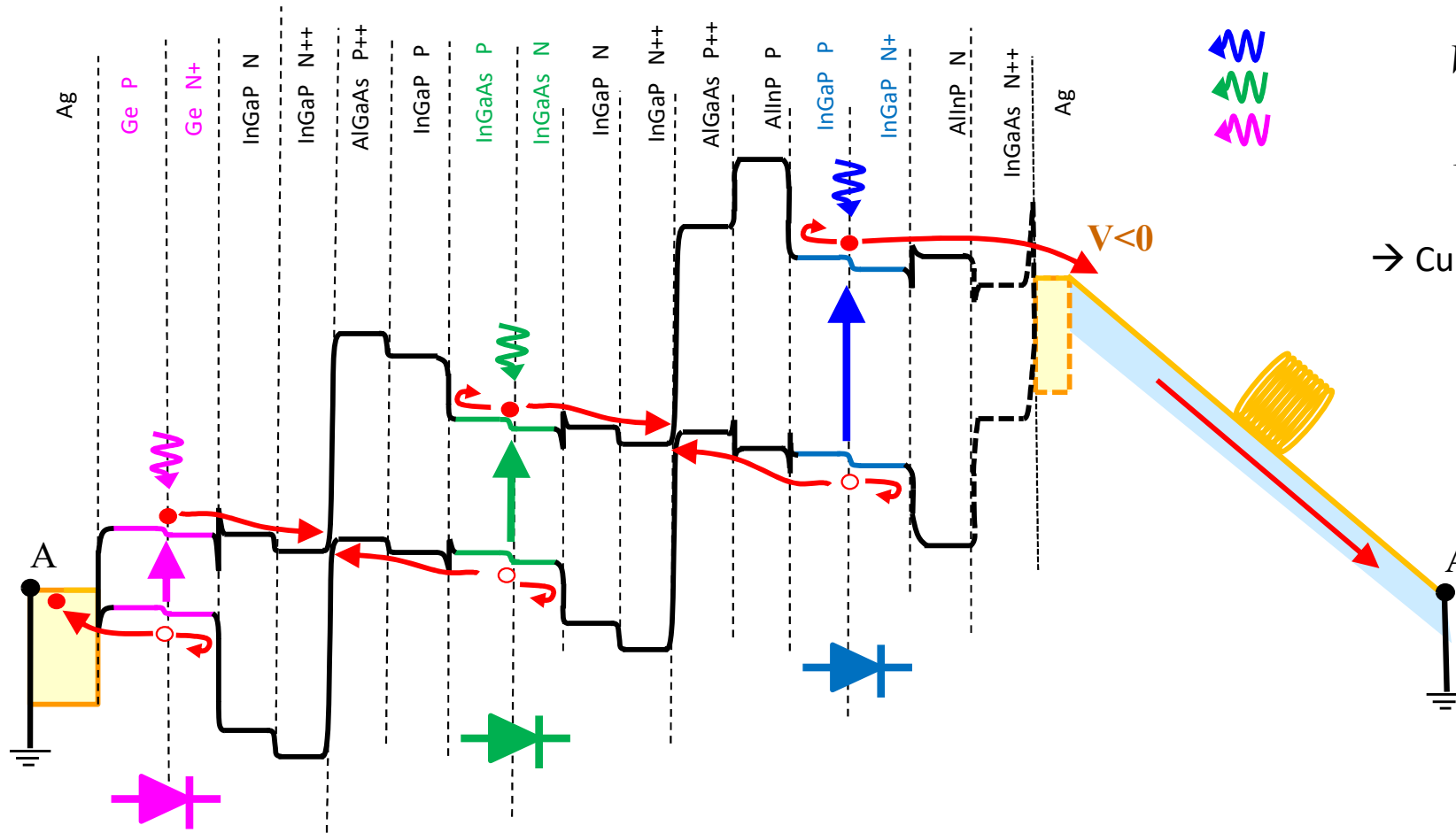
[https://en.wikipedia.org/wiki/Multi-junction\\_solar\\_cell](https://en.wikipedia.org/wiki/Multi-junction_solar_cell)

<https://www.youtube.com/watch?v=2U8BxI5RmLc>

# Multi-junctions solar cells: with illumination

BACK

FRONT



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

$$I = \min [I_{bleu}, I_{vert}, I_{rouge}]$$

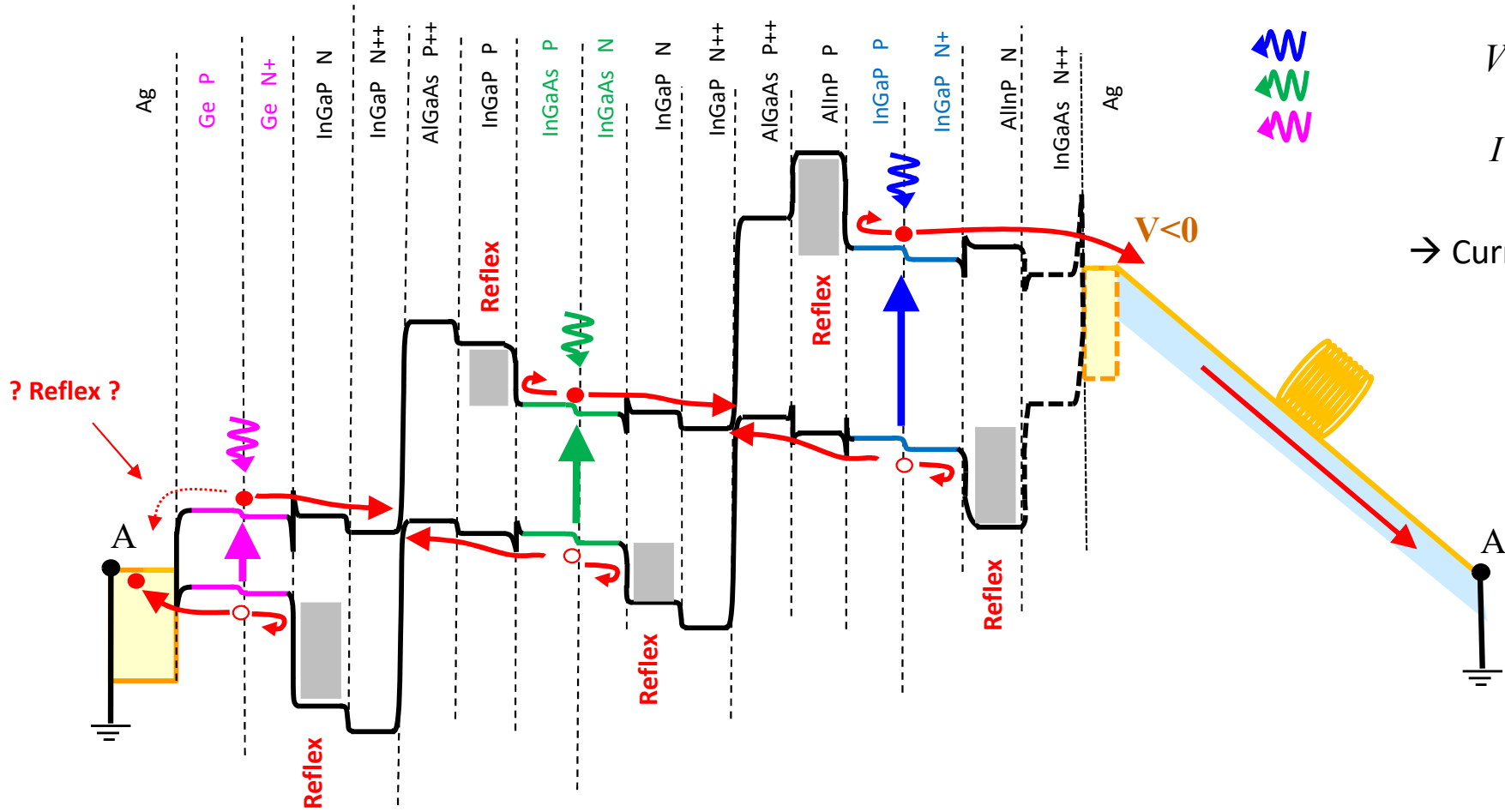
→ Current matching required



# Multi-junctions solar cells: with illumination

BACK

FRONT



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

$$I = \min [I_{bleu}, I_{vert}, I_{rouge}]$$

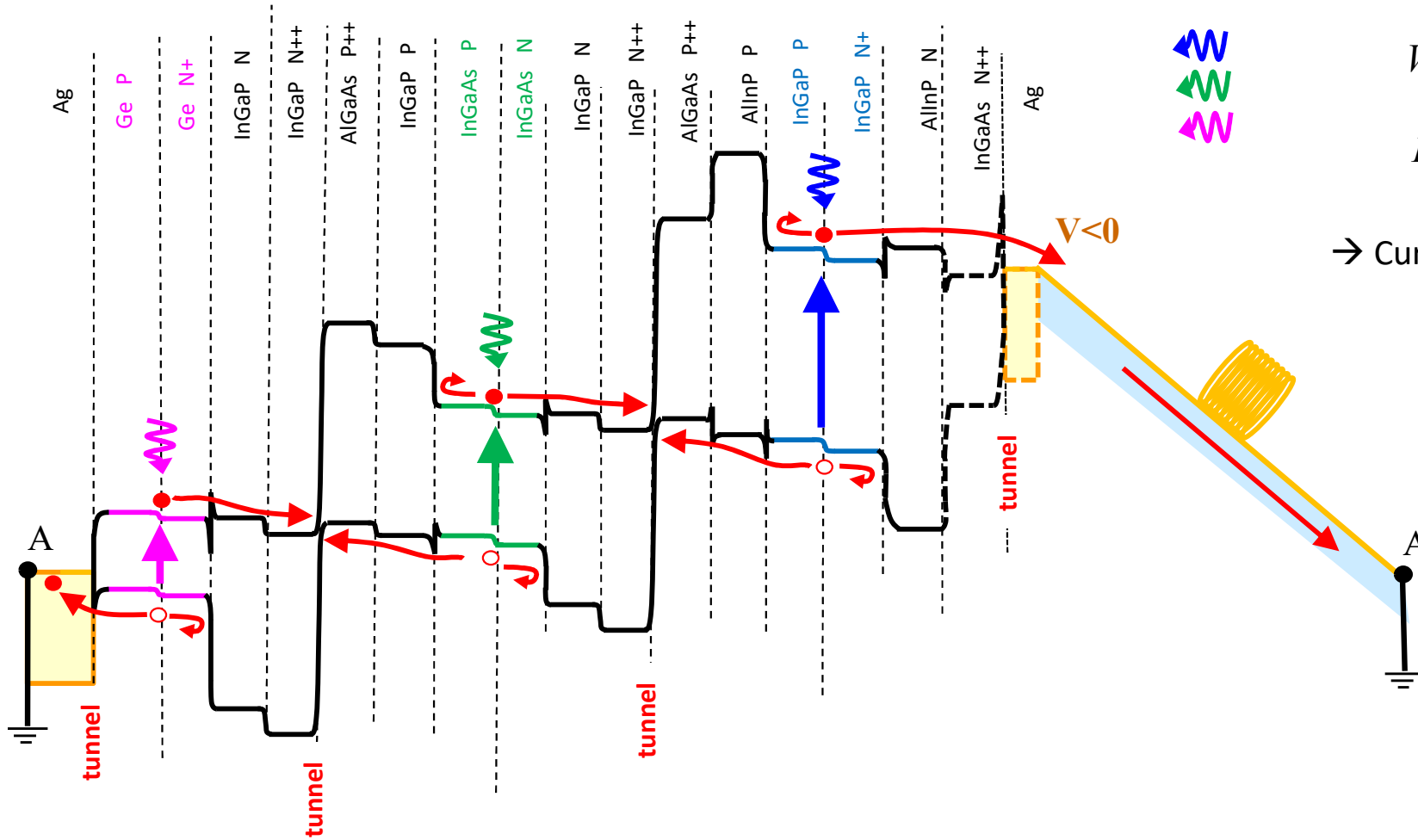
→ Current matching required



# Multi-junctions solar cells: with illumination

BACK

FRONT



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

$$I = \min [I_{bleu}, I_{vert}, I_{rouge}]$$

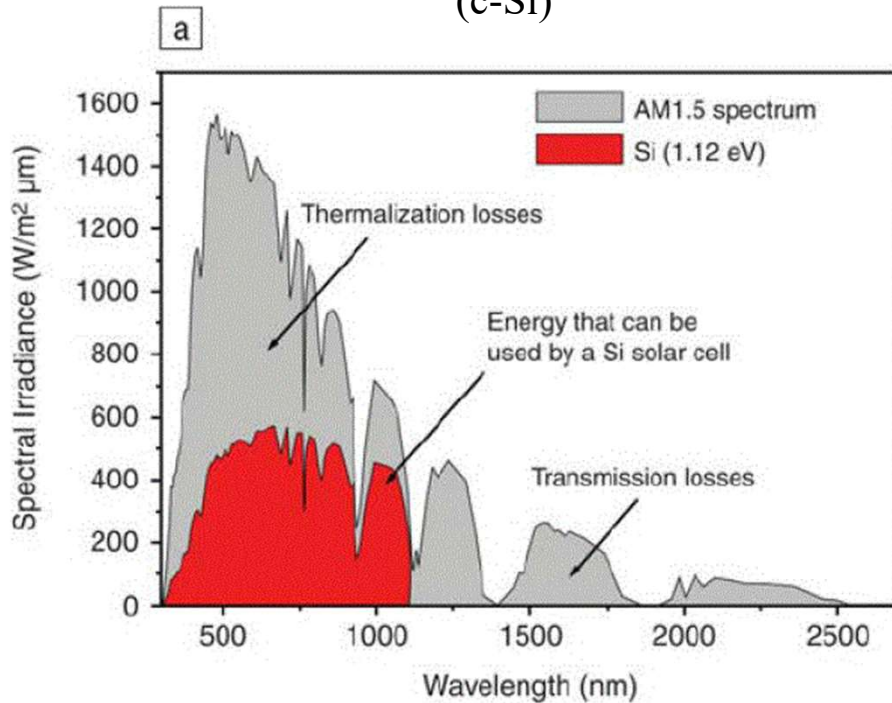
→ Current matching required



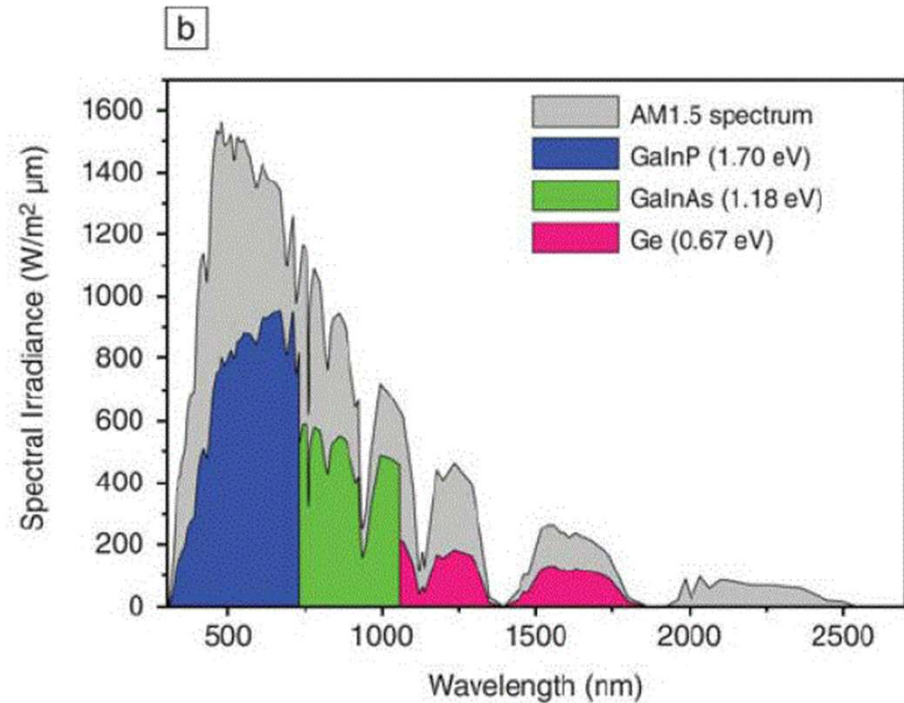
# Multi-junctions solar cells: spectral behavior

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

Single junction  
(c-Si)

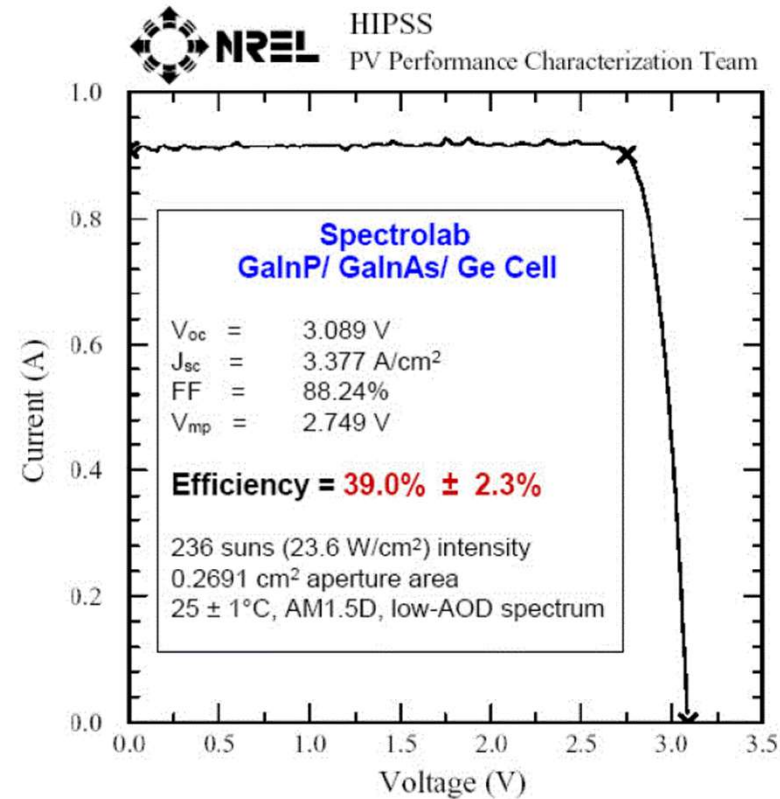
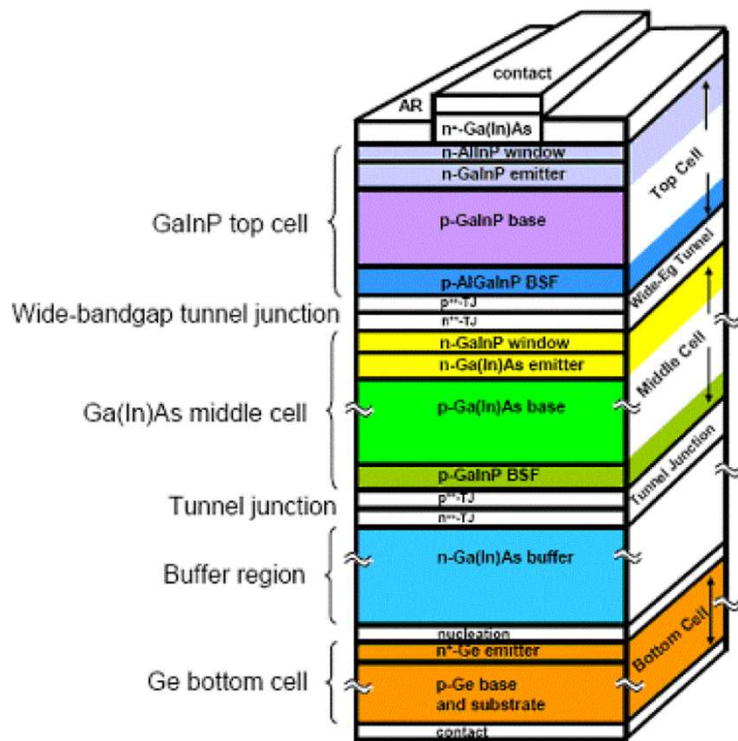


Triple junction



# Triple-junctions solar cells: spectral behavior

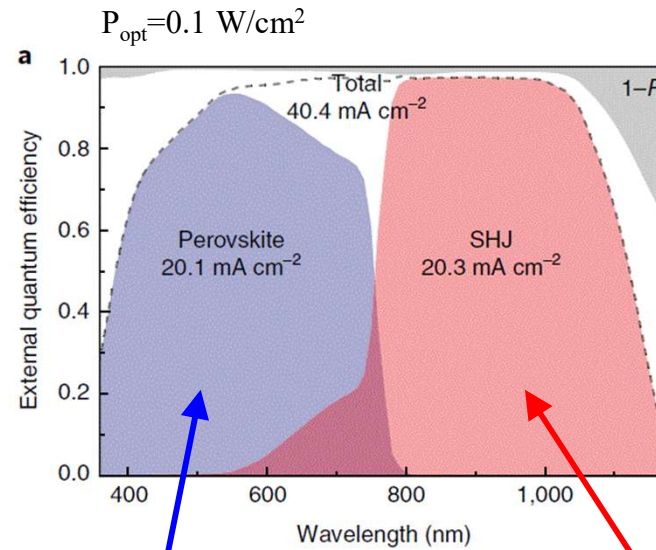
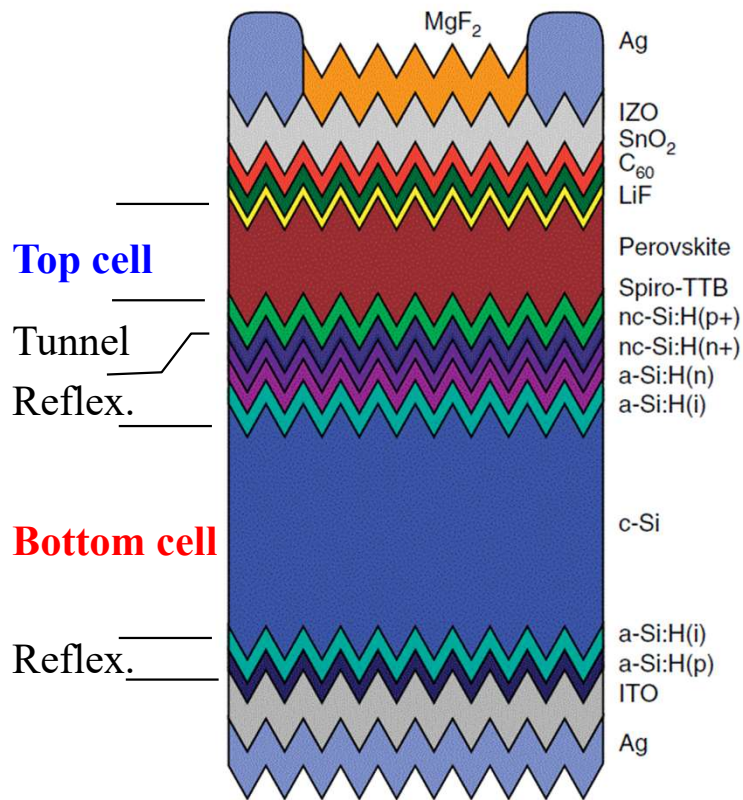
N.V.Yastrebova (2007). *High-efficiency multi-junction solar cells: current status and future potential*



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

# 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>



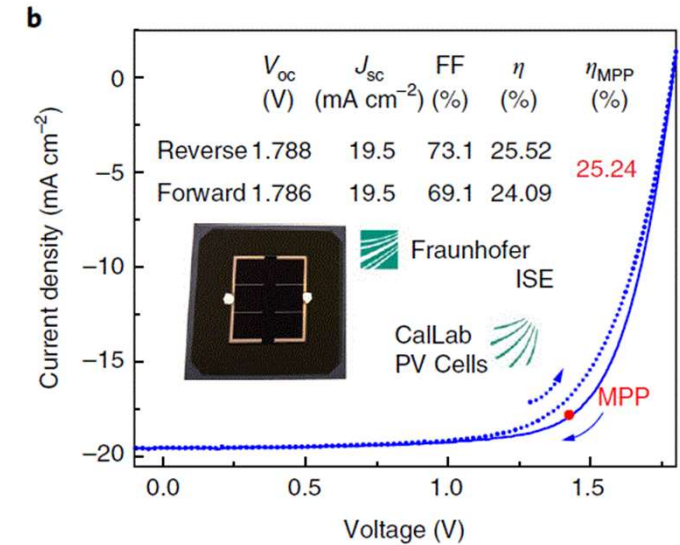
Top cell:  
Perovskite  
«visible light»

Bottom cell:  
Silicon Hetero-Junction  
«IR light»

20.1  
mA/cm<sup>2</sup>

Current  
matching

20.3  
mA/cm<sup>2</sup>



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

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

[https://en.wikipedia.org/wiki/Concentrator\\_photovoltaics](https://en.wikipedia.org/wiki/Concentrator_photovoltaics)

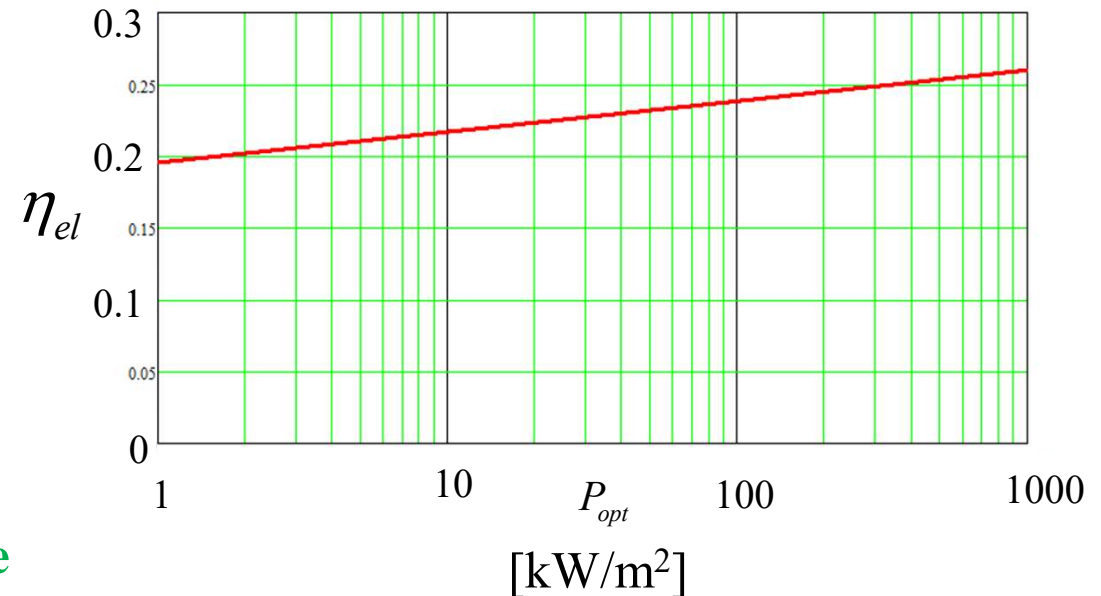
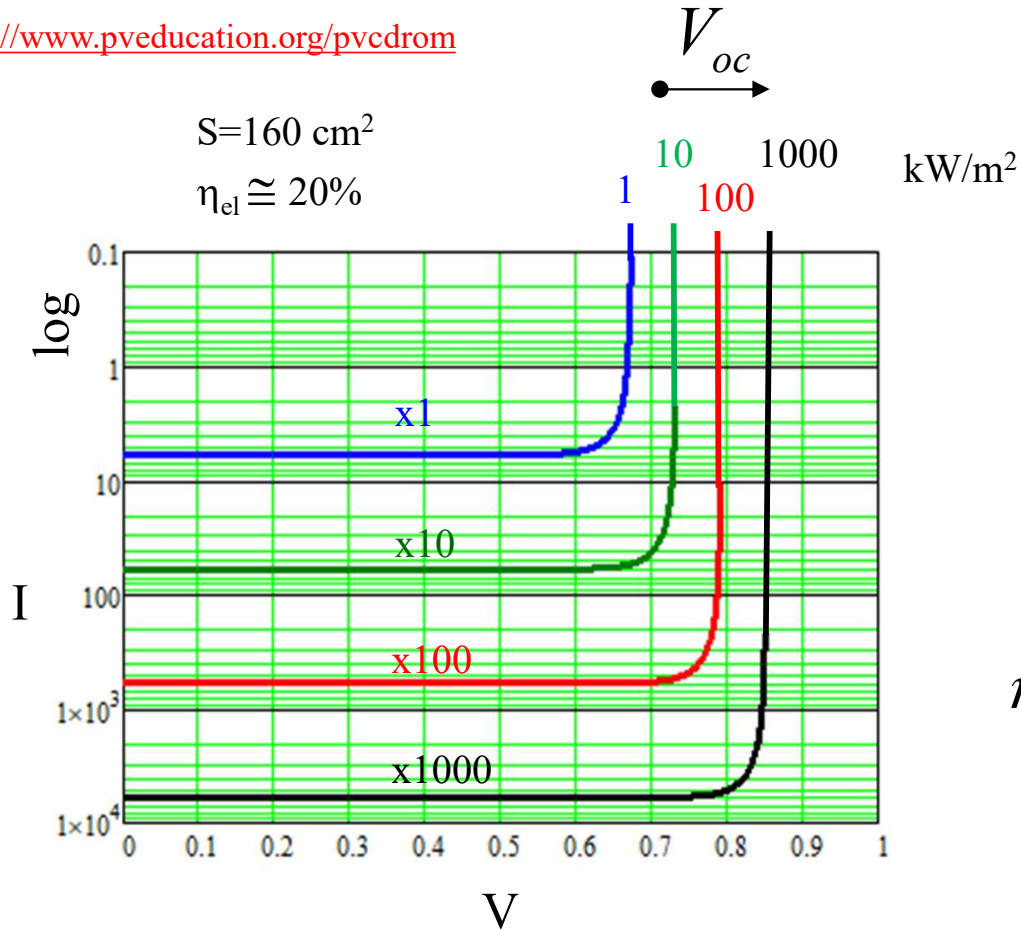
<https://www.pveducation.org/pvcdrom>

Augmentation de la puissance optique

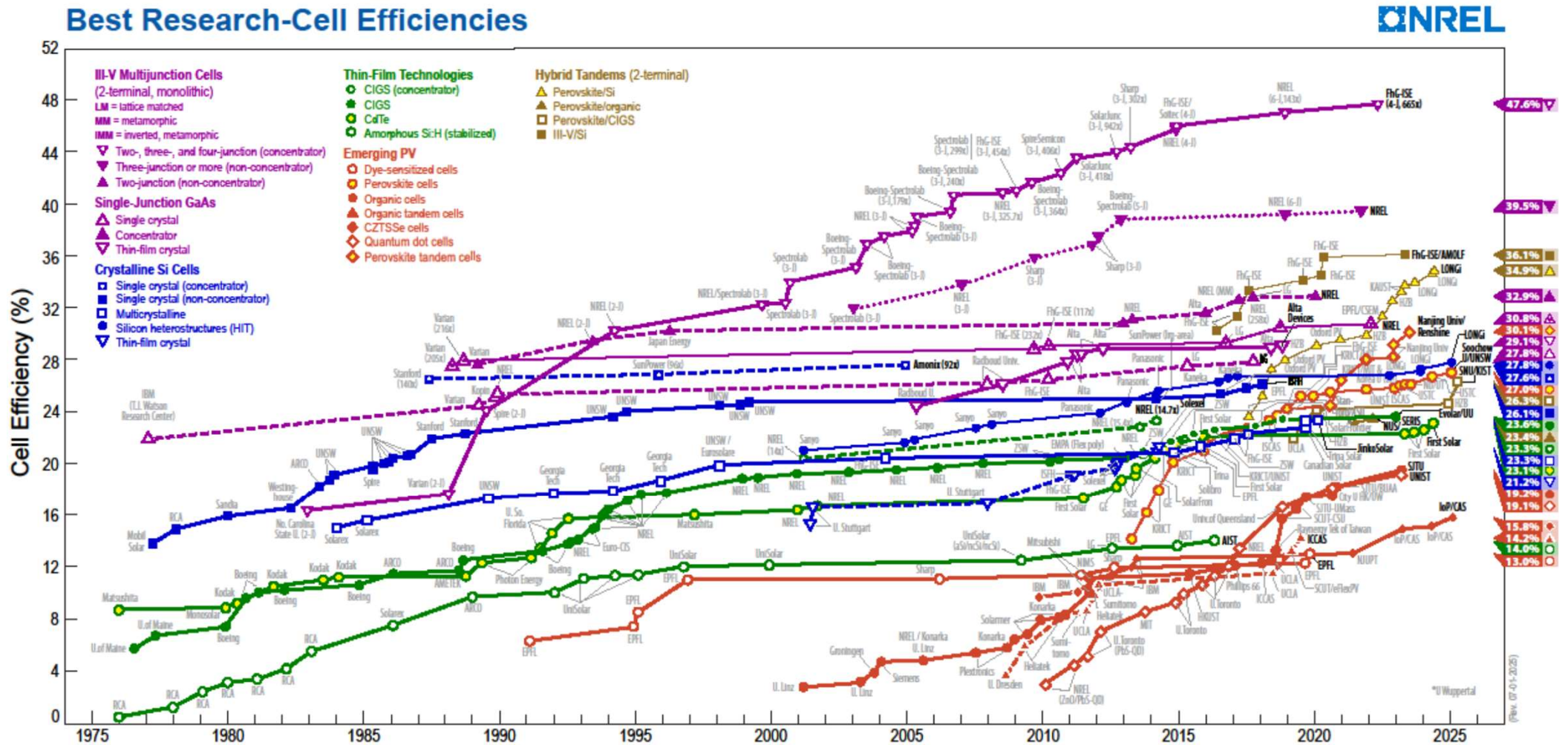


Augmentation de la tension récoltée

$$V_{oc} \cong \frac{kT}{q} \text{Ln} \left( \frac{I_L}{I_s} \right) \quad \text{et} \quad \eta \approx V_{oc} \Rightarrow \frac{\Delta \eta}{\eta_0} \cong \frac{kT}{qV_{oc}^0} \cdot \text{Ln} \left( \frac{P_{opt,1}}{P_{opt,0}} \right)$$



**Avec un concentrateur de lumière, l'efficiéce de la cellule solaire augmente**



<https://www.nrel.gov/pv/cell-efficiency>

## **Deuxième test à blanc**

Envoyé par email et sur Moodle

Correction mardi prochain 11 nov.