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## Winter College on Optics and Energy

*8 - 19 February 2010*

# Physics of Solar Cells (II)

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## Physics of Solar Cells (II)

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# Objectives

- We want to understand how the performance characteristics of a p-n junction solar cell depend upon the properties of the material
- Photocurrent generation results from the absorption of light and the competition between charge transport and recombination.
- Power generation also depends on the competition between the photocurrent and the diode or dark current
- We will
  - find expressions for these physical quantities
  - present a simplified model of a p-n junction device
  - study how performance characteristics are related to the properties of materials
- This understanding leads to design rules for solar cells.

# Outline

1. Semiconductor basics and device equations
2. Simplification of the p-n junction
3. Calculation of photocurrent
4. Dark current and diode equation
5. Factors limiting performance and cell design
6. Photovoltaic materials

# Outline

1. **Semiconductor basics and device equations**
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# Charge carrier density and Fermi levels

At equilibrium:

$$np = n_i^{\,2} = N_C N_V e^{-E_g/kT}$$

$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = n_i e^{(E_i - E_F)/kT}$$

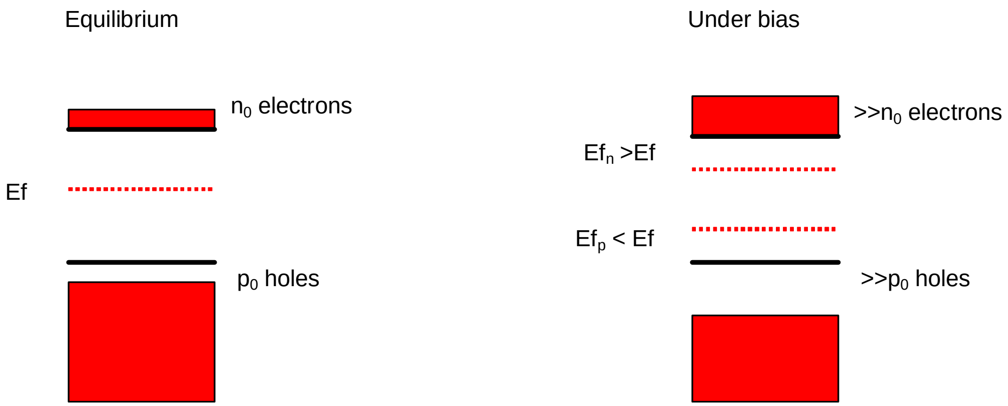
At bias V:

$$np = n_i^{\,2} e^{qV/kT}$$

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

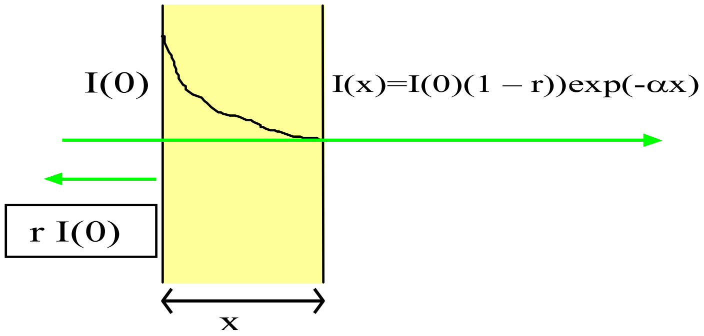
$$p = n_i e^{(E_i - E_{Fp})/kT}$$

quasi Fermi levels $E_{Fn}$ and $E_{Fp}$ are separated



# Photogeneration

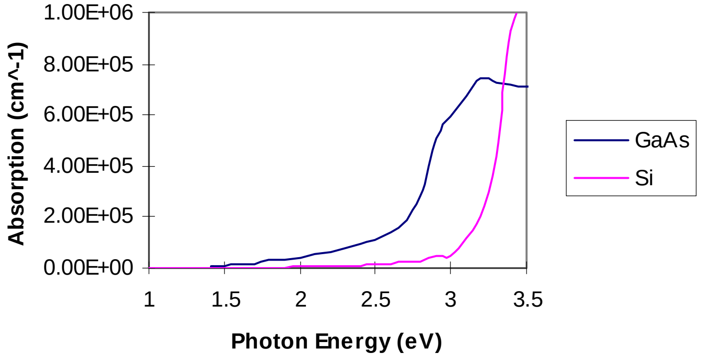
Attenuation of light intensity:



Electron-hole pair *generation rate*

$$G(E,x) = \alpha(E) b_s(E)[1 - r(E)]\exp\left(-\int_0^x \alpha(E)dx'\right)$$

Absorption spectrum α(E)



# Recombination

*Non-radiative* recombination (Shockley-Read Hall)

$$R_{nr} = \frac{np - n_i^2}{\tau_n(p+p_t)+\tau_p(n+n_t)}$$

*When p >> n*

$$R_{nr} \approx (n-n_0)/\tau_n$$

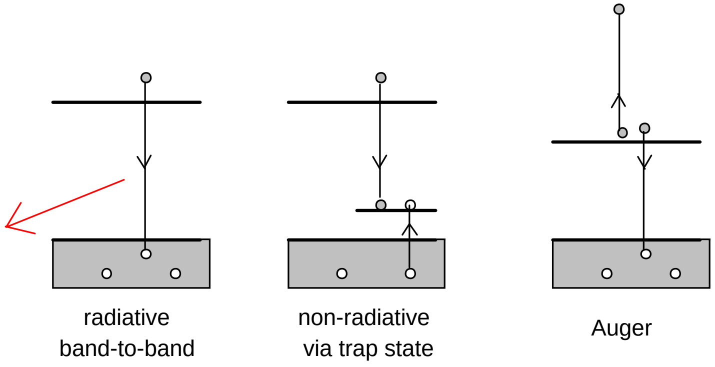
*or n >> p*

$$R_{nr} \approx (p-p_0)/\tau_p$$

*i.e. minority carriers dominate*

*Radiative* recombination $R_{rad} = R_{th}(e^{qV/kT}-1)$

*Auger* recombination $R \propto n^2 p$



# Charge transport

*Current:*

*electrons:* $J_n = eD_n \frac{dn}{dx} + en\mu_n F$ ⇨ $J_n = en\mu_n \frac{dE_{F_n}}{dx}$

*holes:* $J_p = -eD_p \frac{dp}{dx} + ep\mu_p F$ ⇨ $J_p = ep\mu_p \frac{dE_{F_p}}{dx}$

*Continuity:* $-\frac{1}{e}\frac{dJ_n}{dx} = G - R$ $\frac{1}{e}\frac{dJ_p}{dx} = G - R$

*Poisson's equation:*

$$\frac{d^2\phi_i}{dx^2} = \frac{e}{\varepsilon_s}\left(N_a - N_d + n - p\right)$$

⇨ *set of 3 differential equations, for n, p and* $\phi_i$.

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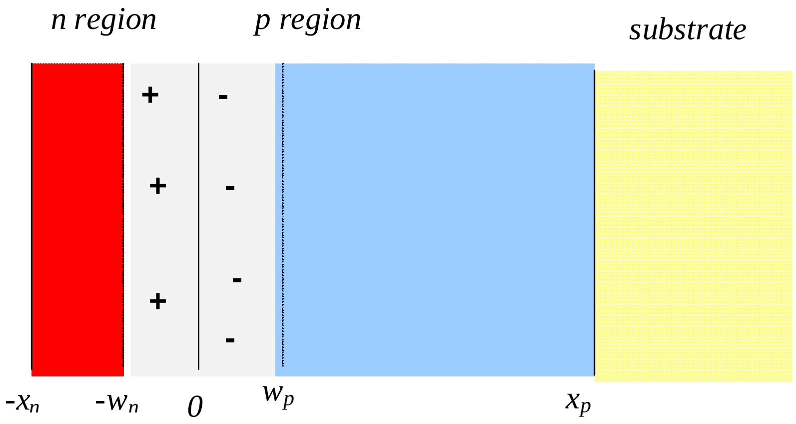
# *p-n* junction as a solar cell

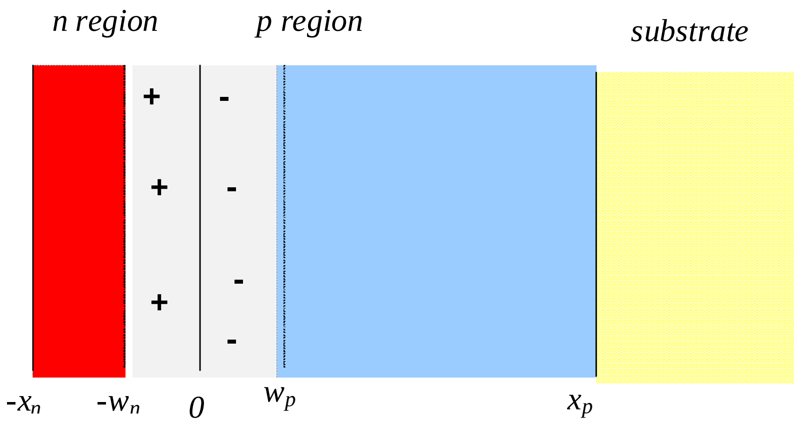
Analyse making two simplifications:

- depletion approximation
- net current = short circuit photocurrent - junction dark current.

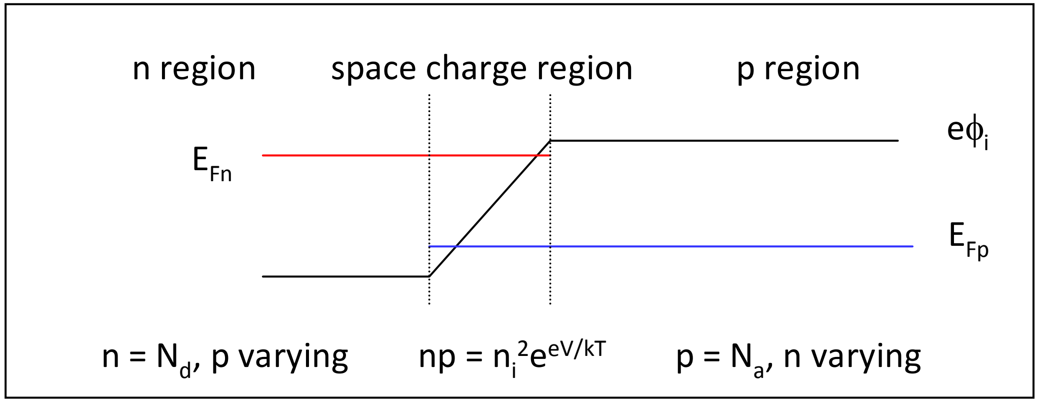


# Depletion approximation

- *Space charge regions* $w_p$ + $w_n$ completely free of carriers:
- surrounding n and p layers completely *neutral*



Fermi levels and intrinsic potential in depletion approximation:



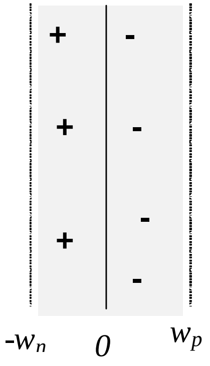
$n = N_d$, p varying

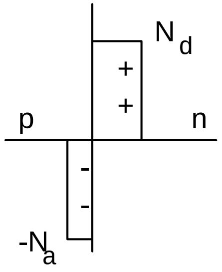
$np = n_i^2 e^{eV/kT}$

$p = N_a$, n varying

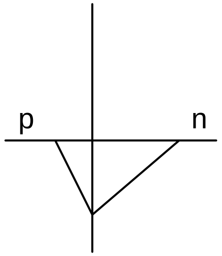
# Width of space charge region

- Calculate width of space charge regions from doping density :

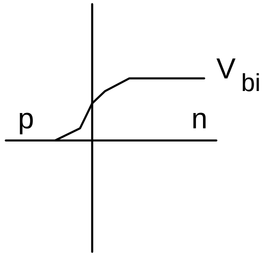




space charge



electric field



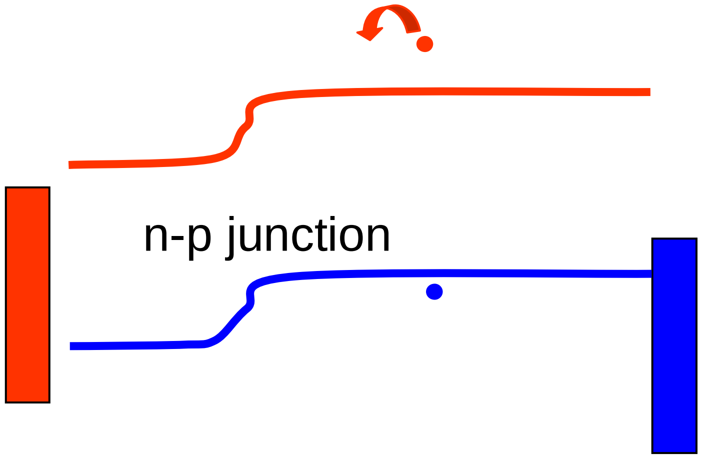
potential

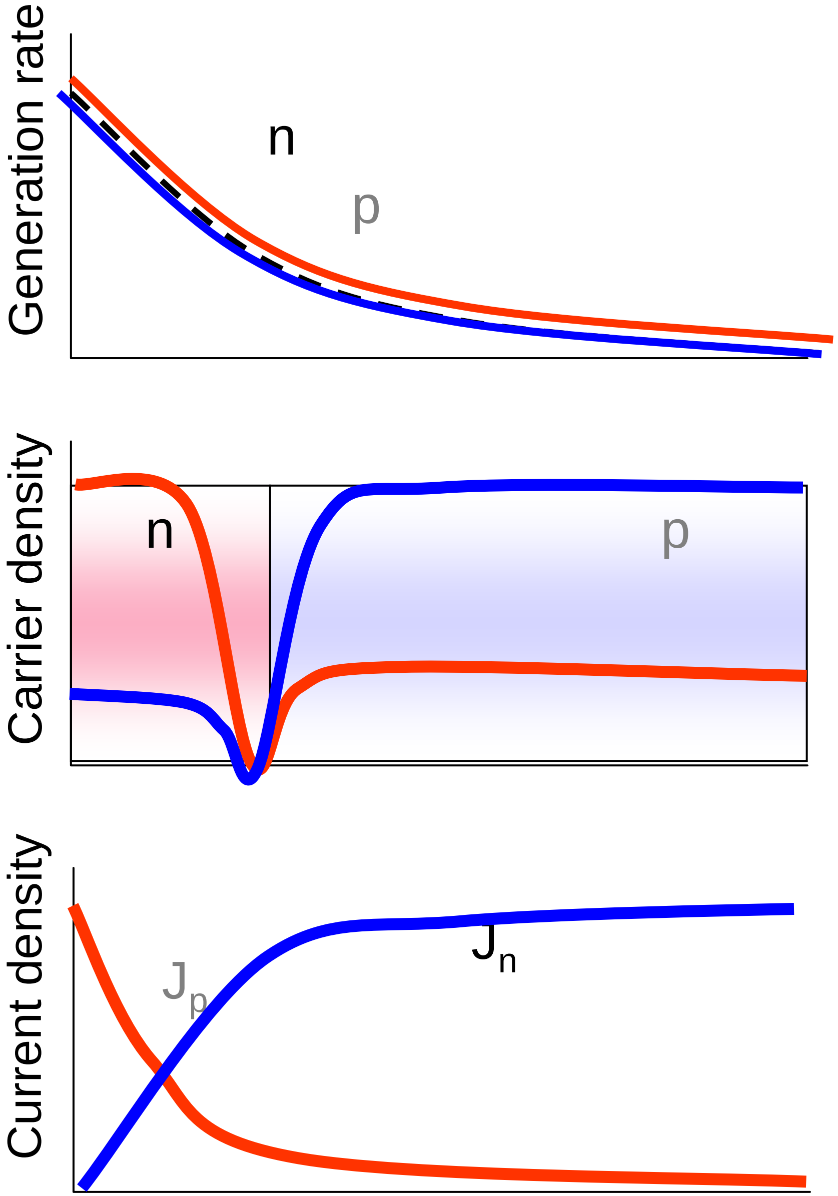
Find $$W_{scr} = w_p + w_n = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)V_{bi}}$$ *where* $$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_d N_a}{n_i^{\,2}}\right)$$

For asymmetric n+ - p junction $$W_{scr} \approx w_p = \sqrt{\frac{2\varepsilon_s}{qN_a}V_{bi}}$$

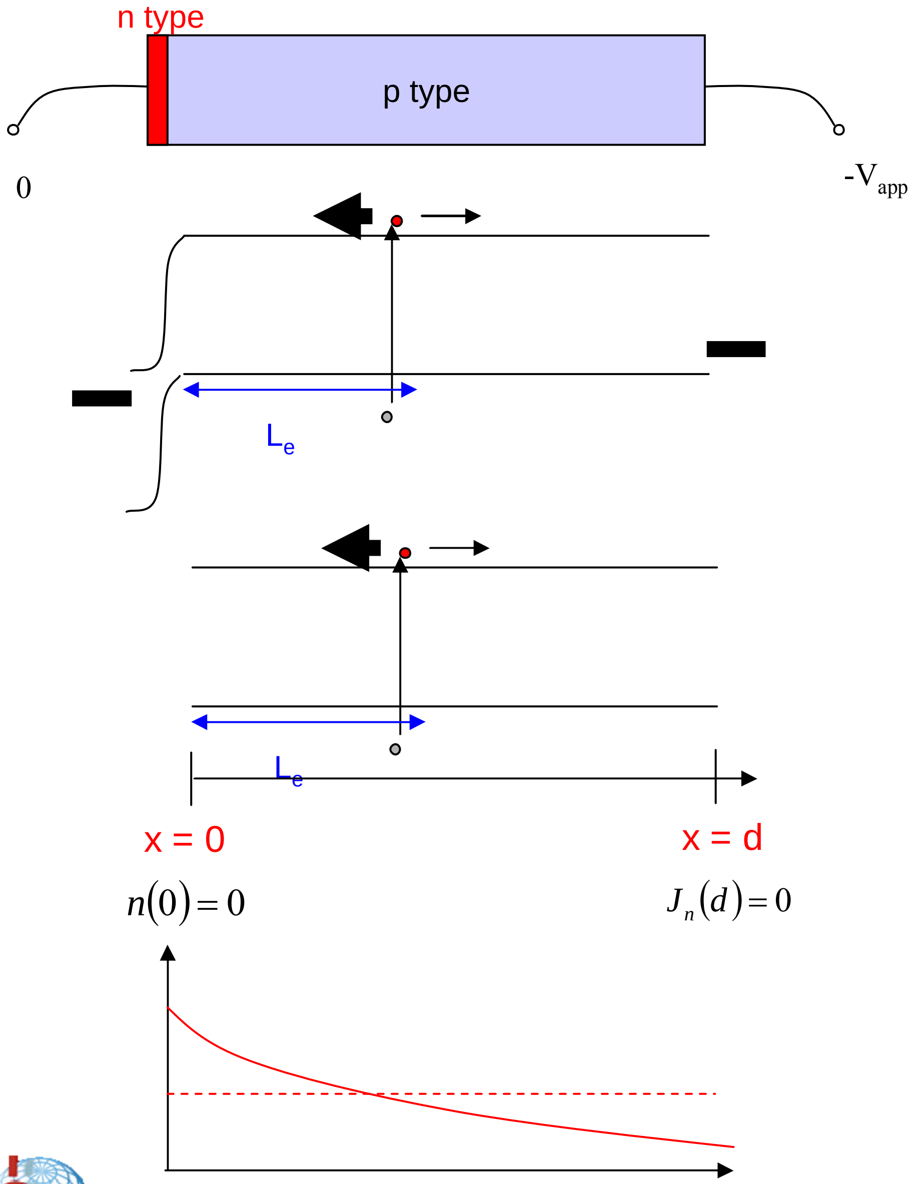
In silicon, $W_{scr} \ll x_p$

# Overview


n-p junction


Generation rate
n
p
Carrier density
n
p
Current density
$J_p$
$J_n$

# Calculation of photocurrent at short circuit



- Assumptions
  - Neglect photocurrent from thin emitter
  - Neglect photocurrent from space charge region
  - All electrons reaching p-n junction are collected
  - No current exits through base
  - No drift
  - Generation rate is uniform
  - electrons diffuse with coeff $D_n$
  - electrons relax with lifetime $\tau_n$

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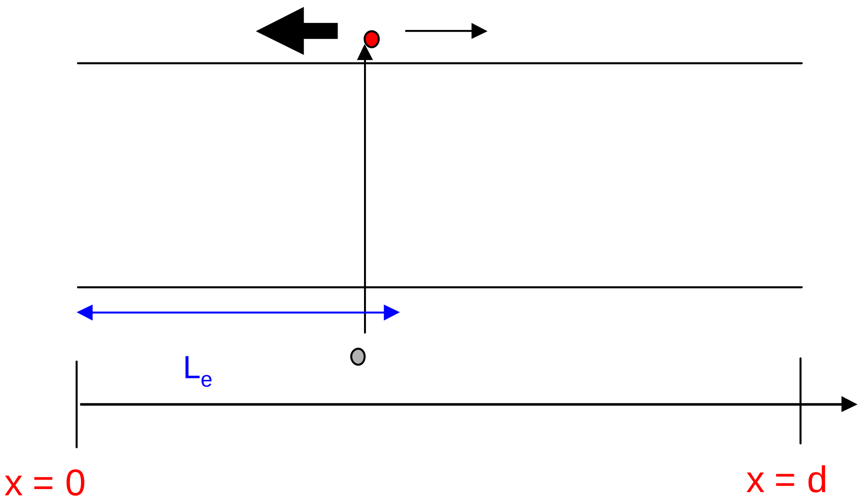
# Calculation of photocurrent at short circuit



$$n(0) = 0 \qquad J_n(d) = 0$$

Continuity equation for electrons $$\frac{1}{e}\frac{dJ_n}{dx}+G-R=0$$

electron diffusion current: $$J_n=eD_e\frac{dn}{dx}$$

electron relaxation rate: $$R=\frac{n}{\tau_e}$$

electron generation rate: $$G\approx\frac{1}{d}\frac{(1-r)I_0}{E}\int_0^d \alpha e^{-\alpha x}dx=\frac{1}{d}(1-r)\left(1-e^{-\alpha d}\right)\frac{I_0}{E}$$

$$\Rightarrow\quad D_e\frac{d^2n}{dx^2}-\frac{n}{\tau_e}=-G$$

Second order inhomogeneous differential equation.
Solution = complementary function + particular integral

$$n=\underbrace{Ae^{x/L_e}+Be^{-x/L_e}}_{\text{complementary function}}+\underbrace{G\tau_e}_{\text{particular integral}}$$

$$n = Ae^{x/L_e} + Be^{-x/L_e} + G\tau_e \qquad \Rightarrow \qquad J_n = eD_e\frac{dn}{dx} = \frac{eD_e}{L_e}\left(Ae^{x/L_e} - Be^{-x/L_e}\right)$$

Apply boundary conditions:

$$J_n(d) = 0 \qquad \Rightarrow \qquad B = Ae^{2d/L_e}$$

$$n(0) = 0 \qquad \Rightarrow \qquad A = \frac{-G\tau_e}{\left(1 + e^{2d/L_e}\right)}$$

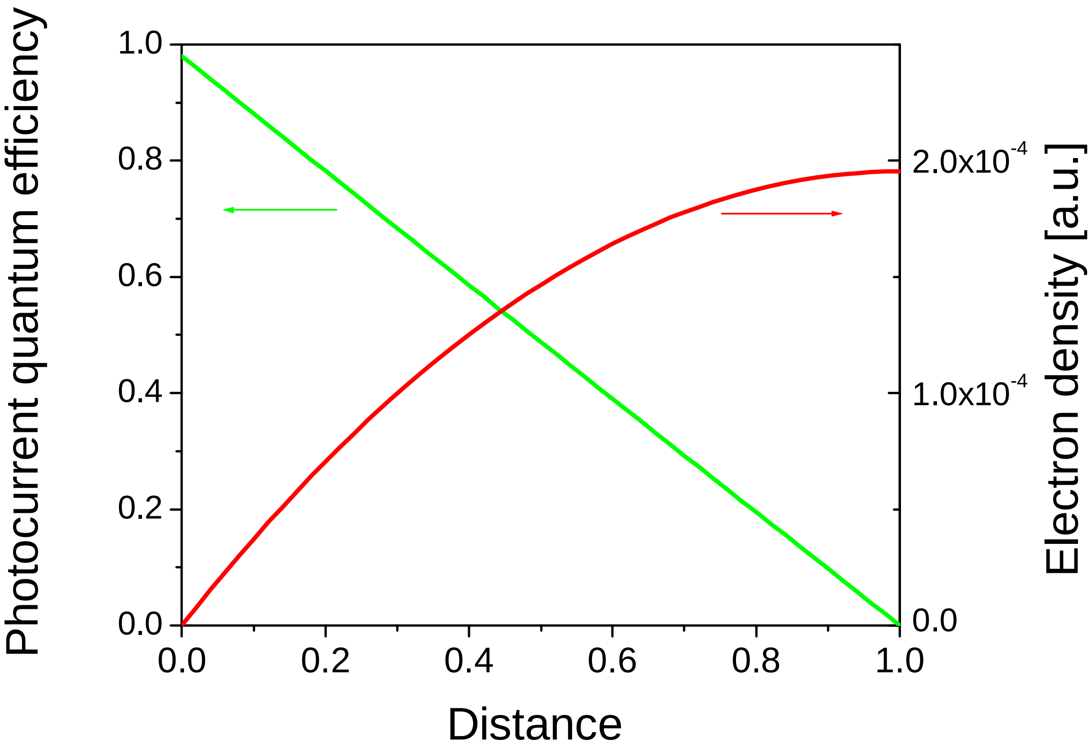
$$A = \frac{-G\tau_e e^{-d/L_e}}{2\cosh(d/L_e)} \qquad B = \frac{-G\tau_e e^{d/L_e}}{2\cosh(d/L_e)}$$

$$n = G\tau_e - \frac{G\tau_e e^{(x-d)/L_e}}{2\cosh(d/L_e)} - \frac{G\tau_e e^{-(x-d)/L_e}}{2\cosh(d/L_e)} = G\tau_e\left\{1 - \frac{\cosh((x-d)/L_e)}{\cosh(d/L_e)}\right\}$$

$$J_n = eD_eG\tau_e\frac{1}{L}\frac{\sinh((d-x)/L_e)}{\cosh(d/L_e)} = eGL_e\frac{\sinh((d-x)/L_e)}{\cosh(d/L_e)}$$

$$\boxed{J_{ph} = J_n(0) = eGL_e\tanh(d/L_e)}$$

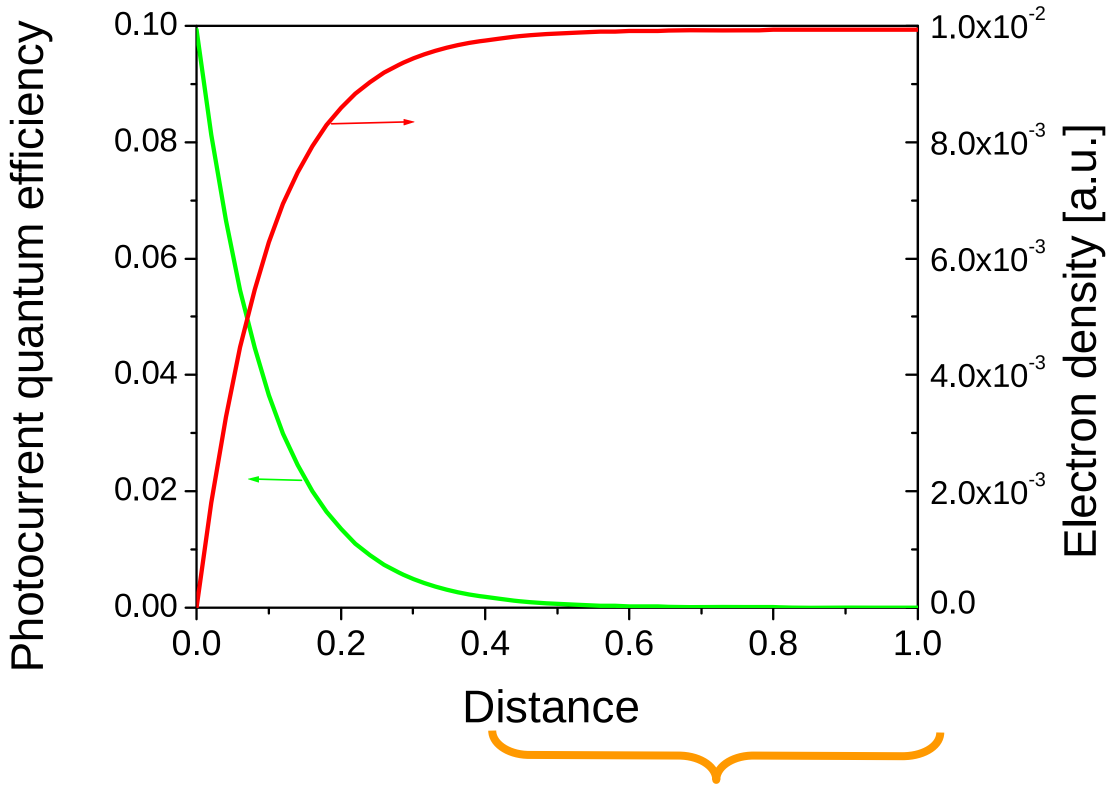
# $d = 1\ \mu m$, $L = 5\ \mu m$, $\alpha = 5\ \mu m^{-1}$



High absorption, long diffusion length:

- all photons absorbed
- all electrons reach external circuit
- QE ~ 1

$d = 1\ \mu m$, $L = 0.1\ \mu m$, $\alpha = 5\ \mu m^{-1}$

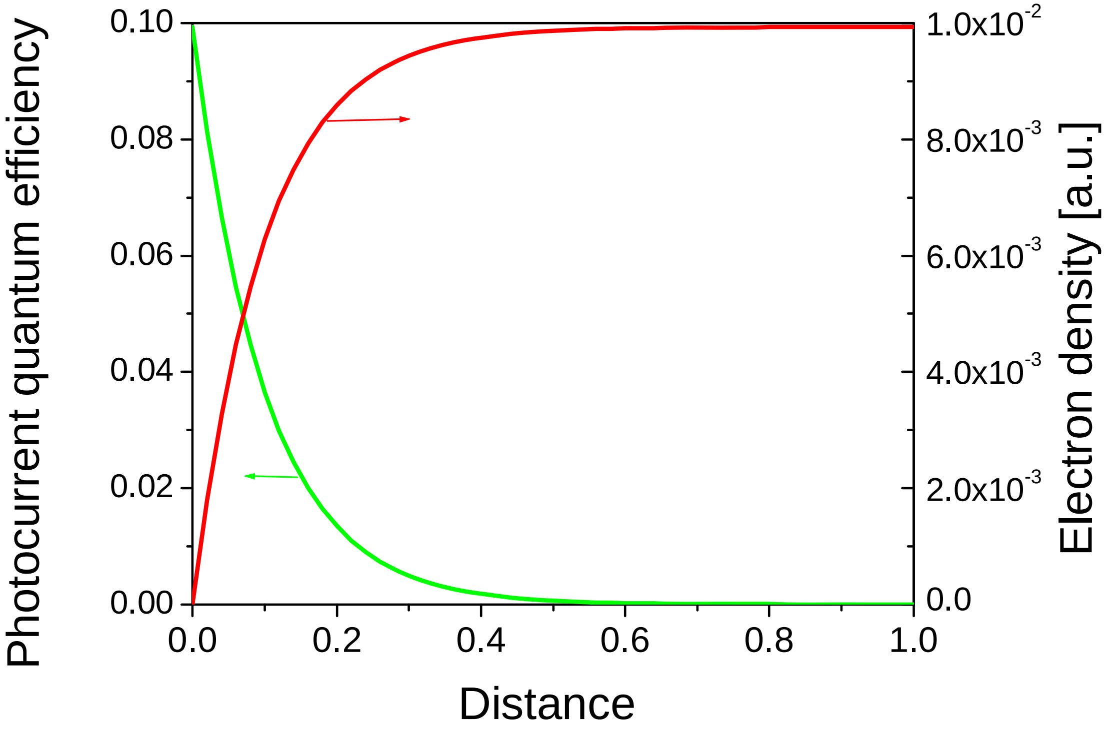


dJ/dx ~ 0

G = R

No useful photon absorption

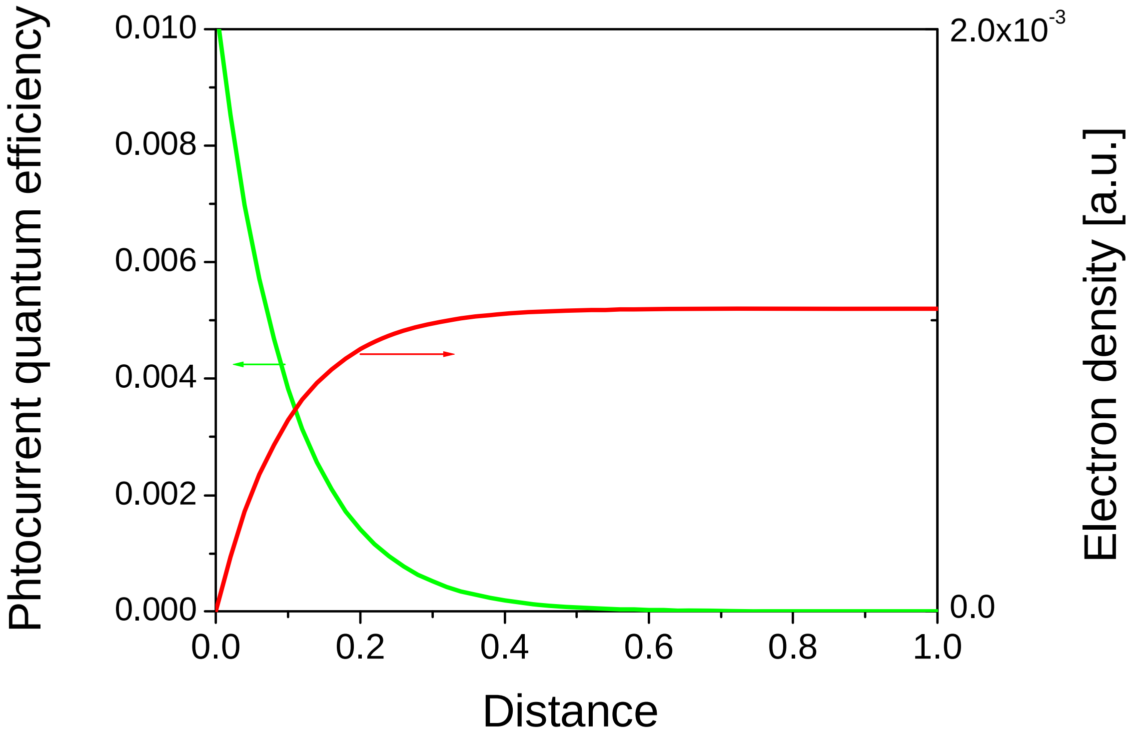
# d = 1 μm, L = 0.1 μm, α = 5 $\mu m^{-1}$



High absorption, short diffusion length:

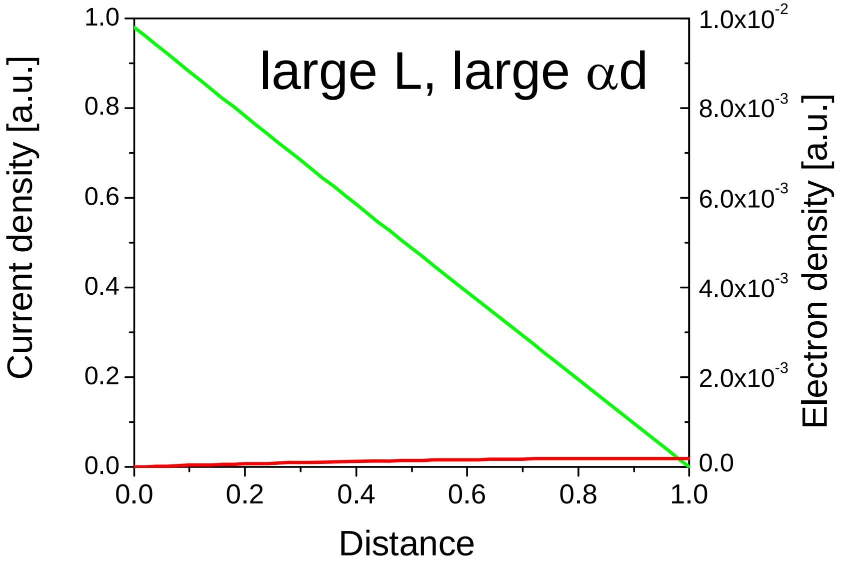
- all photons absorbed
- only ~ L/d of electrons reach external circuit
- QE ~ L/d

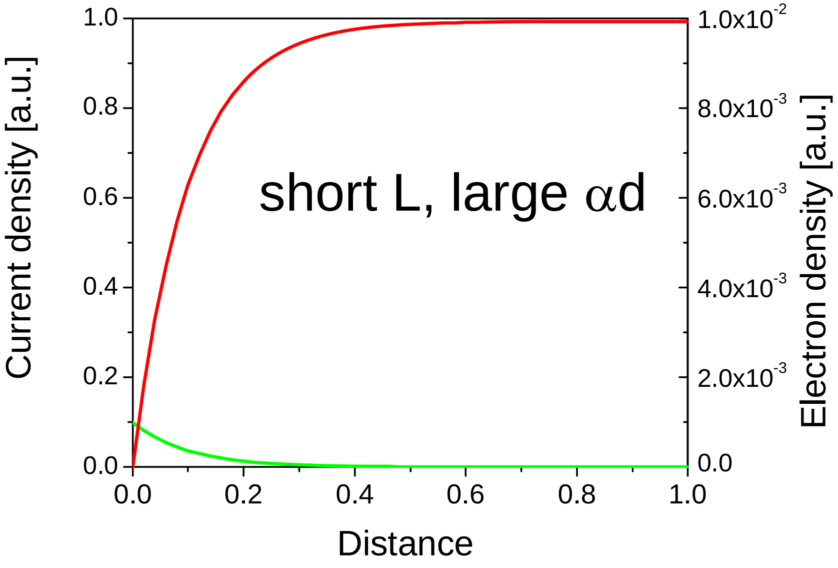
# $d = 1\ \mu m$, $L = 0.1\ \mu m$, $\alpha = 0.1\ \mu m^{-1}$



High absorption, short diffusion length:

- only $(1 - e^{-\alpha d})$ of photons absorbed
- only ~ L/d of electrons reach external circuit
- QE ~ $(1 - e^{-\alpha d}) * L/d$

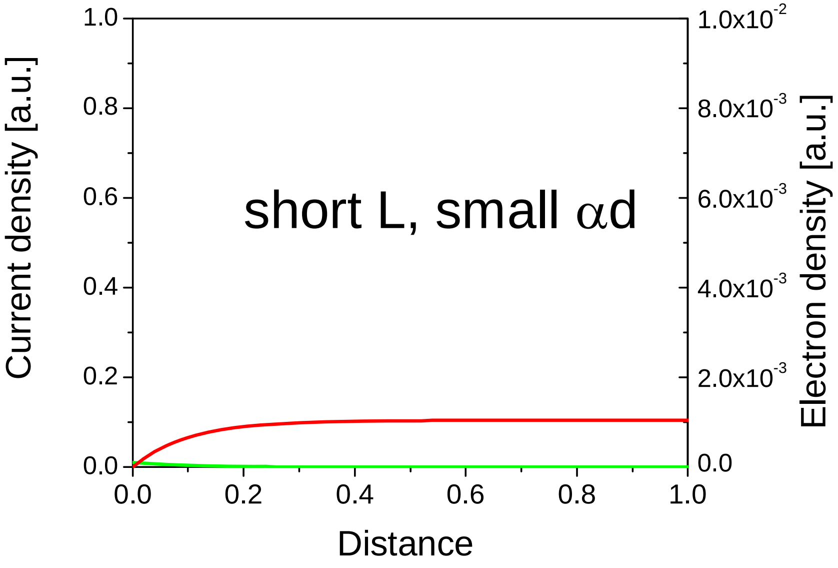




$$J_{ph} = e\ QE(E)\ I_0 / E$$

$$QE = (1 - r)(1 - e^{-\alpha d})\ L/d\ \tanh(d/L)$$

Internal QE



# Outline

1. **Semiconductor basics and device equations**
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# Calculation of photocurrent under bias

Modify boundary conditions:

$$J_n(d) = 0$$

$$n(0) = n_v = n_0\left(e^{eV/kT} - 1\right)$$

$$n(x) = Gt_n + \frac{(n_v - Gt_n)}{\cosh(d/L)}\cosh((x-d)/L)$$

$$\frac{1}{e}J_n(x) = \frac{(n_v - Gt_n)}{L\cosh(d/L)}\sinh((x-d)/L)$$

$$J(V) = J_n(0) = \underbrace{eGD_n t_n / L\tanh(d/L)}_{\substack{\text{Intensity dependent term} \\ J \propto G}} - \underbrace{eD_n n_v / L\tanh(d/L)}_{\substack{\text{Bias dependent term} \\ J \propto -\exp(eV/kT)}}$$

# Diode equation

J(V) is the sum of short circuit photocurrent and dark current:

$$J(V) = J_{\mathrm{sc}} - J_{\mathrm{dark}}(V)$$

For an ideal diode: $J(V) = J_{\mathrm{sc}} - J_0\,(\exp(eV/kT) - 1)$

In practice: $J(V) = J_{\mathrm{sc}} - J_0\,(\exp(eV/mkT) - 1)$

The non-ideality results from different recombination mechanisms.

$J_{\mathrm{dark}}$ is due to recombination in both neutral regions and space charge region.

In SCR, both n and p vary and R is non linear. Here

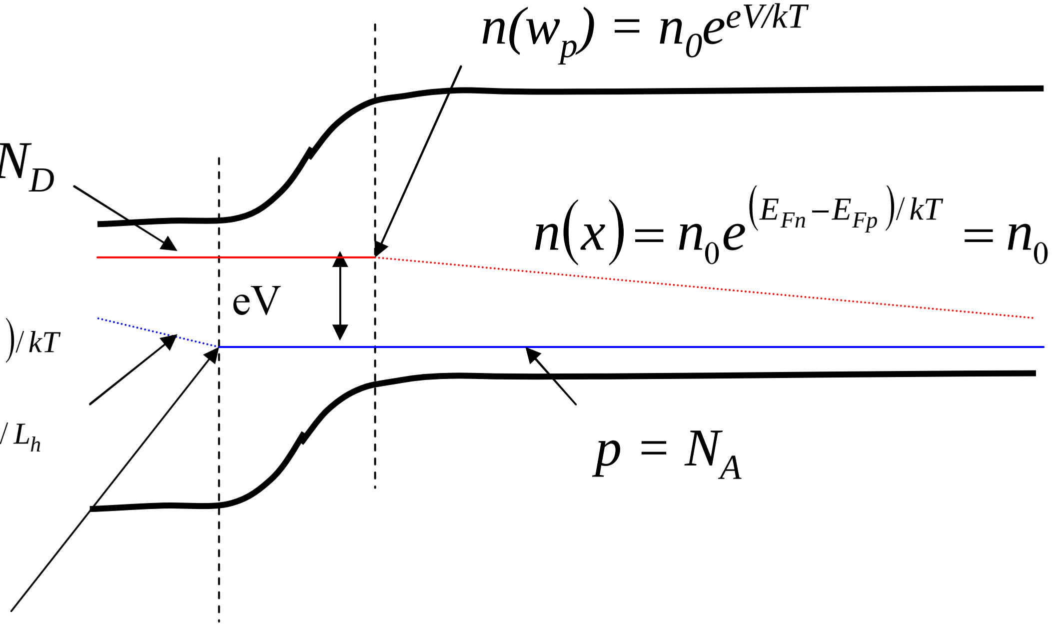
$$J_{\mathrm{dark}}(V) \approx - J_0\,(\exp(eV/2kT) - 1)$$

In practice, *m* is usually between 1 and 2.

# Contributions to dark current

$$n(w_p) = n_0 e^{eV/kT}$$

$$n = N_D$$



$$n(x) = n_0 e^{(E_{Fn}-E_{Fp})/kT} = n_0 e^{eV/kT} e^{-(x-w_p)/L_e}$$

$$p(x) = p_0 e^{(E_{Fn}-E_{Fp})/kT}$$
$$= p_0 e^{eV/kT} e^{-(w_n-x)/L_h}$$

$$p = N_A$$

$$p(w_n) = p_0 e^{eV/kT}$$

$$np = n_i^2\, e^{eV/kT}$$

$$J_{dark} = J_{n,dark} + J_{p,dark} + J_{DZ,dark} = e \int\limits_{\substack{neutral\\ n-region}} R\,dx + \int\limits_{\substack{neutral\\ p-region}} R\,dx + \int\limits_{DZ} R\,dx$$

$$R = \frac{p - p_0}{\tau_h} \qquad R = \frac{n - n_0}{\tau_e} \qquad R = \sum R_i(n, p)$$

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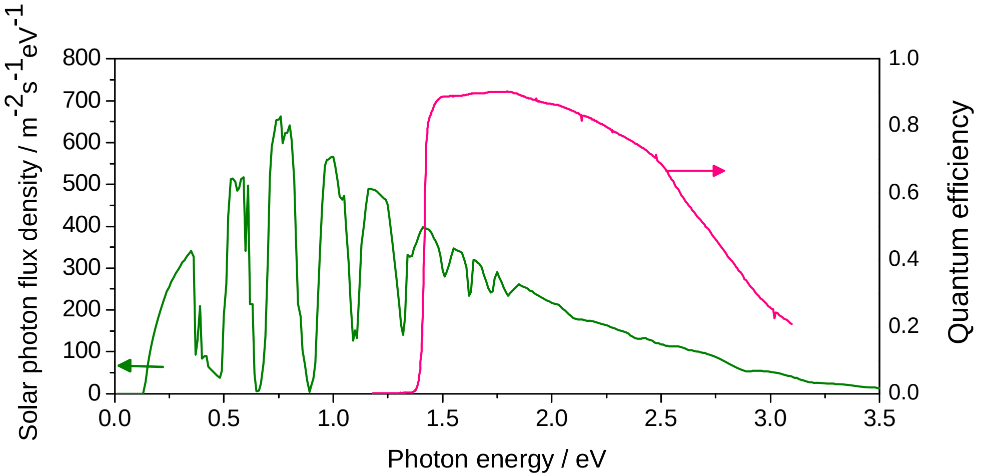
# Factors limiting performance

Short circuit current density $J_{SC}$ :

$$J_{SC} = e\int QE(E)b_{in}(E)dE$$

$$QE(E) = (1-r)(1-e^{-\alpha d})\eta$$



To increase $J_{SC}$ we need to:

| | |
|---|---|
| increase spectral range of absorption | reduce band gap $E_g$ |
| increase $b_{in}$ | increase light intensity |
| increase internal QE $\eta$ | improve material quality to increase L |
| reduce reflectivity | anti-reflection coating |
| increase optical depth $\alpha d$ | increase thickness, use back mirror |

# Factors limiting performance

Open circuit voltage $V_{OC}$ :

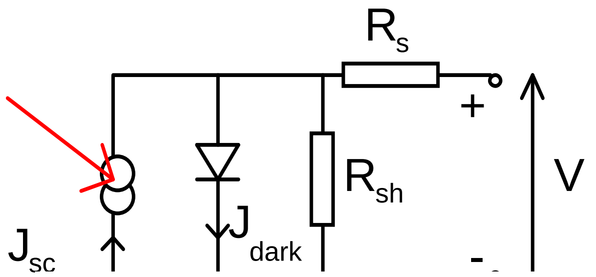
$$V_{OC} = \frac{mkT}{e}\ln\left(\frac{J_{SC}}{J_0}+1\right) \approx \frac{mkT}{e}\ln\left(\frac{J_{SC}}{J_0}\right)$$

$$J_0\,(\exp(eV/mkT) - 1) = e \int\limits_{\substack{neutral\\ n-region}} Rdx + \int\limits_{\substack{neutral\\ p-region}} Rdx + \int\limits_{DZ} Rdx$$

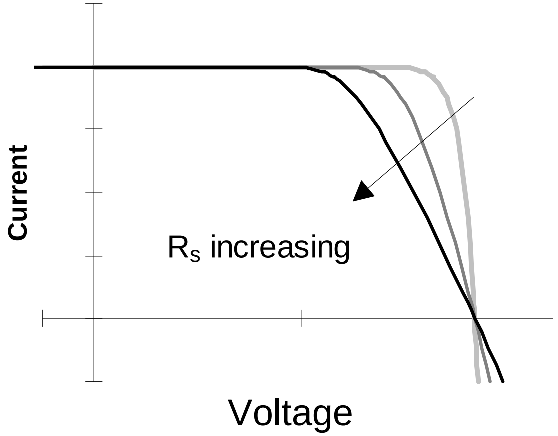
To increase $V_{OC}$ (at a given $J_{sc}$) we need to decrease $J_0$:

| | |
|---|---|
| decrease intrinsic carrier density | increase band gap $E_g$ |
| reduce minority carrier density in neutral regions | increase doping levels |
| increase minority carrier lifetime in doped regions | improve material quality to increase L |
| reduce R in depletion region (SCR) | reduce defect density in space charge region |

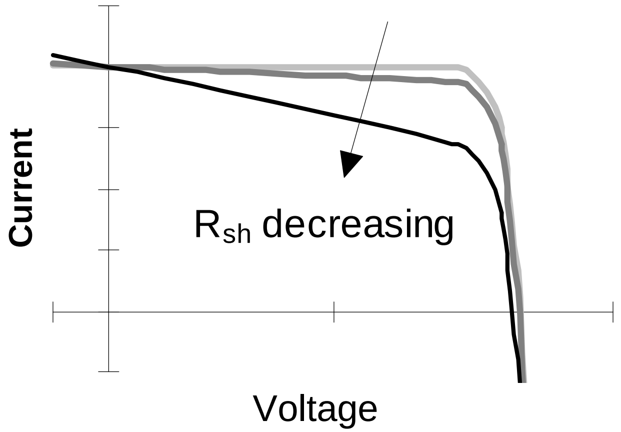
# Factors limiting performance



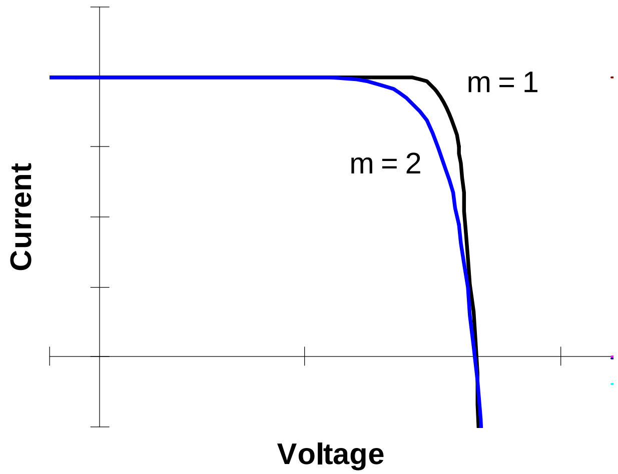
Fill factor FF:



Series resistance



Shunt resistance

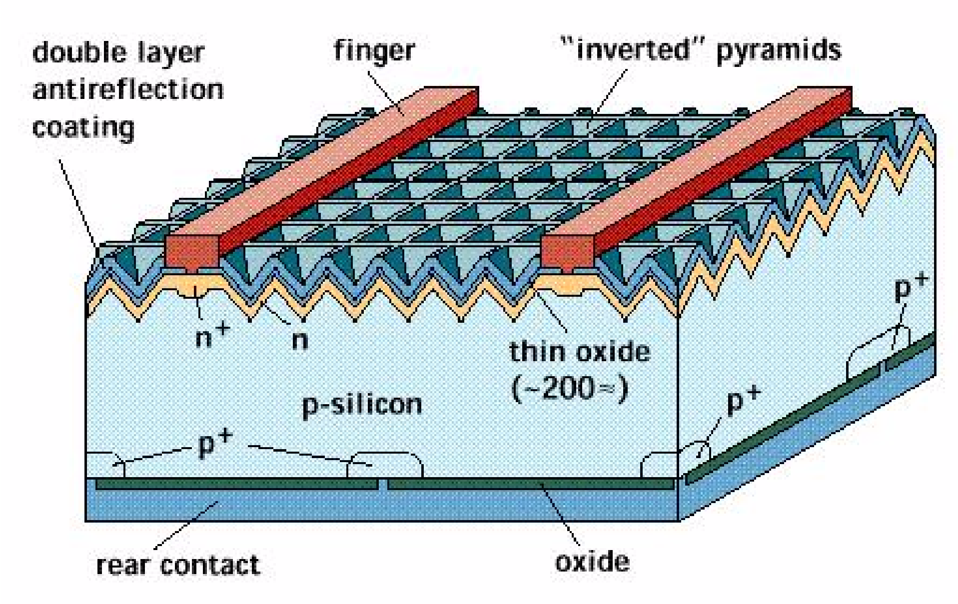


Ideality factor

To increase FF we need to:

| | |
|---|---|
| reduce recombination through traps | reduce trap density in DZ |
| decrease series resistance | increase doping levels, increase contact cross section or density |
| increase shunt resistance | improve edge quality, thickness, passivate grain boundaries |

# Solar cell design



**24.4% efficient PERL cell (design: UNSW; Manufactured by BP Solar)**

| ***Problem*** | ***Solution*** |
|---|---|
| Reflection by surface and contacts | Antireflection coat, narrow metal fingers |
| Incomplete of light absorption | Textured surfaces, thick active layer |
| Fast charge recombination | High purity crystal, high quality junction, low doping in bulk of cell, surface passivation |
| Resistive losses | High doping near contacts, deep metal fingers |

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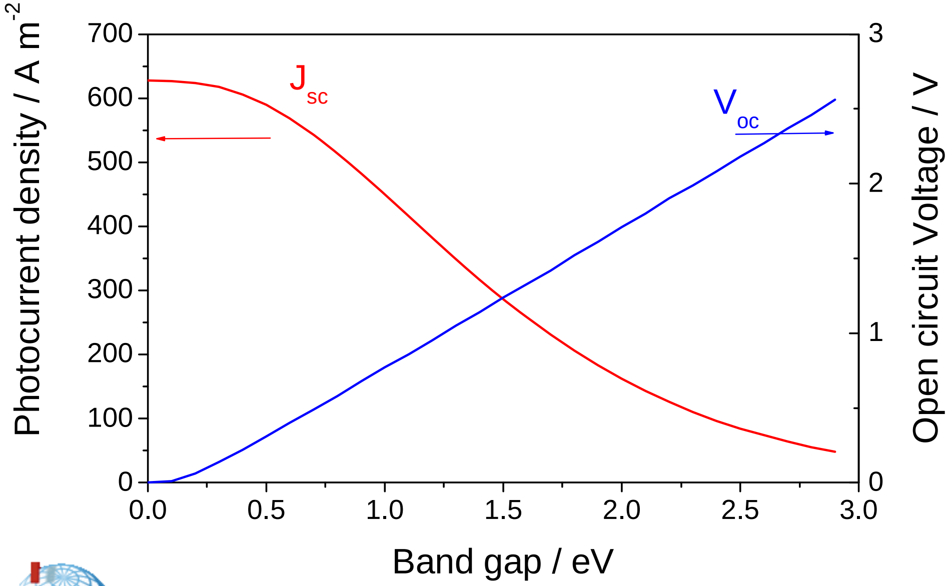
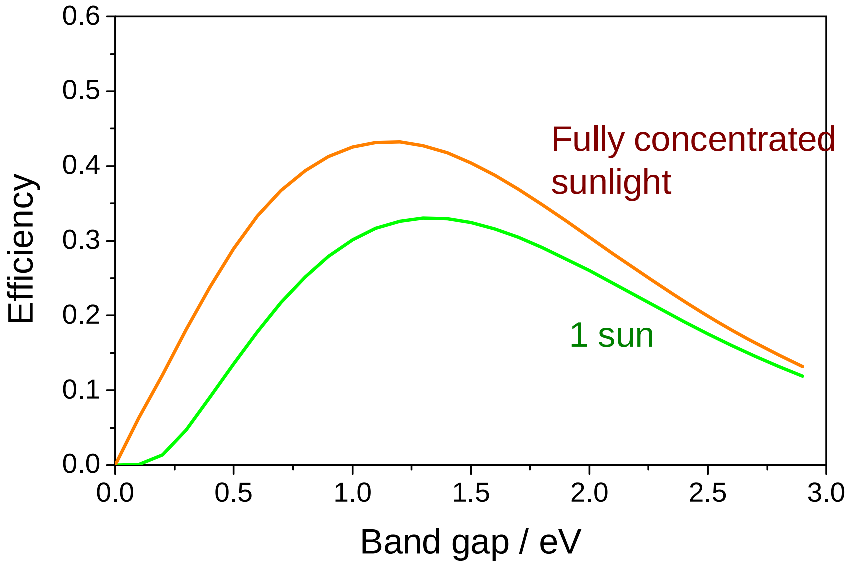
# Power conversion efficiency

- Expect Jsc to reduce as band gap Eg is increased
- Expect Voc to increase as band gap Eg is increased

- Theory predicts max efficiency of ~31% for standard solar spectrum at $E_g$ ~ 1.4 eV

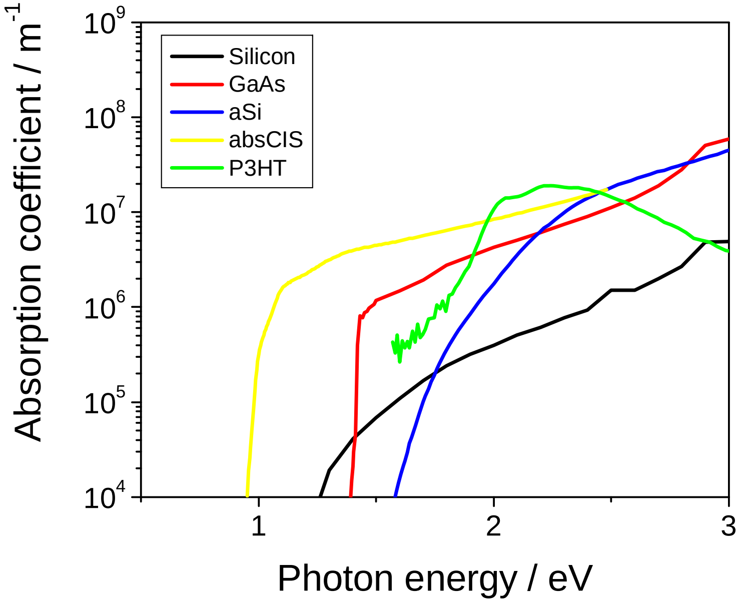
- In practice, material parameters also matter





# Photovoltaic materials

| **Material** | **Band gap (eV)** | **Max $J_{sc}$ (mA cm$^{-2}$)** | **Type of gap** | **Crystal size** |
|---|---|---|---|---|
| **Crystalline silicon (c-Si)** | 1.1 | 42 | indirect | >$10^{-3}$ m |
| **Crystalline GaAs** | 1.4 | 32 | direct | >$10^{-3}$ m |
| **Polycrystalline Si (p-Si)** | 1.1 | 42 | indirect | $10^{-4}$ m |
| **Amorphous Si (a-Si)** | ~1.7 | ~ 23 | ~ direct | amorphous |
| **CuInGaSe$_2$** | > 1.0 | < 45 | direct | $10^{-6}$ m |
| **Cd Te** | 1.4 | 42 | direct | $10^{-6}$ m |
| **P3HT / PCBM** | 2.0 | 16 | Direct (finite band width) | amorphous |

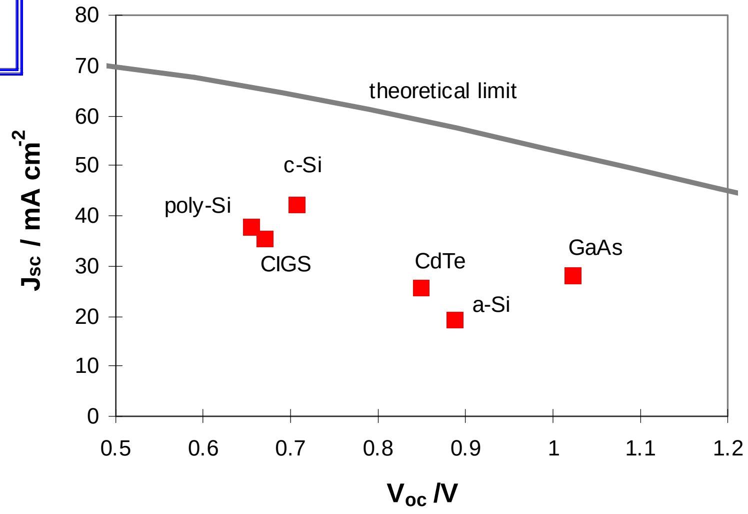


# Photovoltaic materials

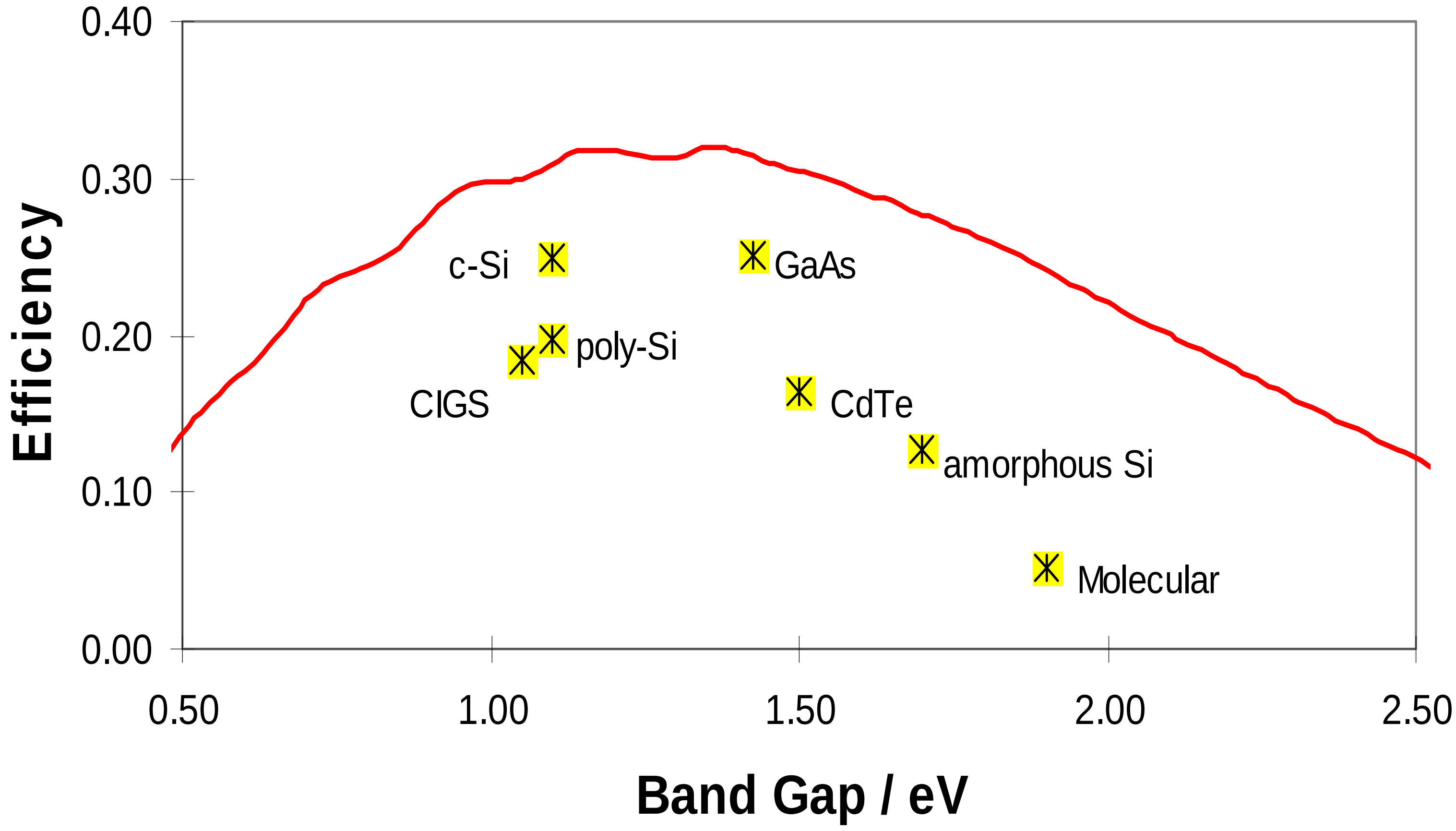
## Best cell performance parameters

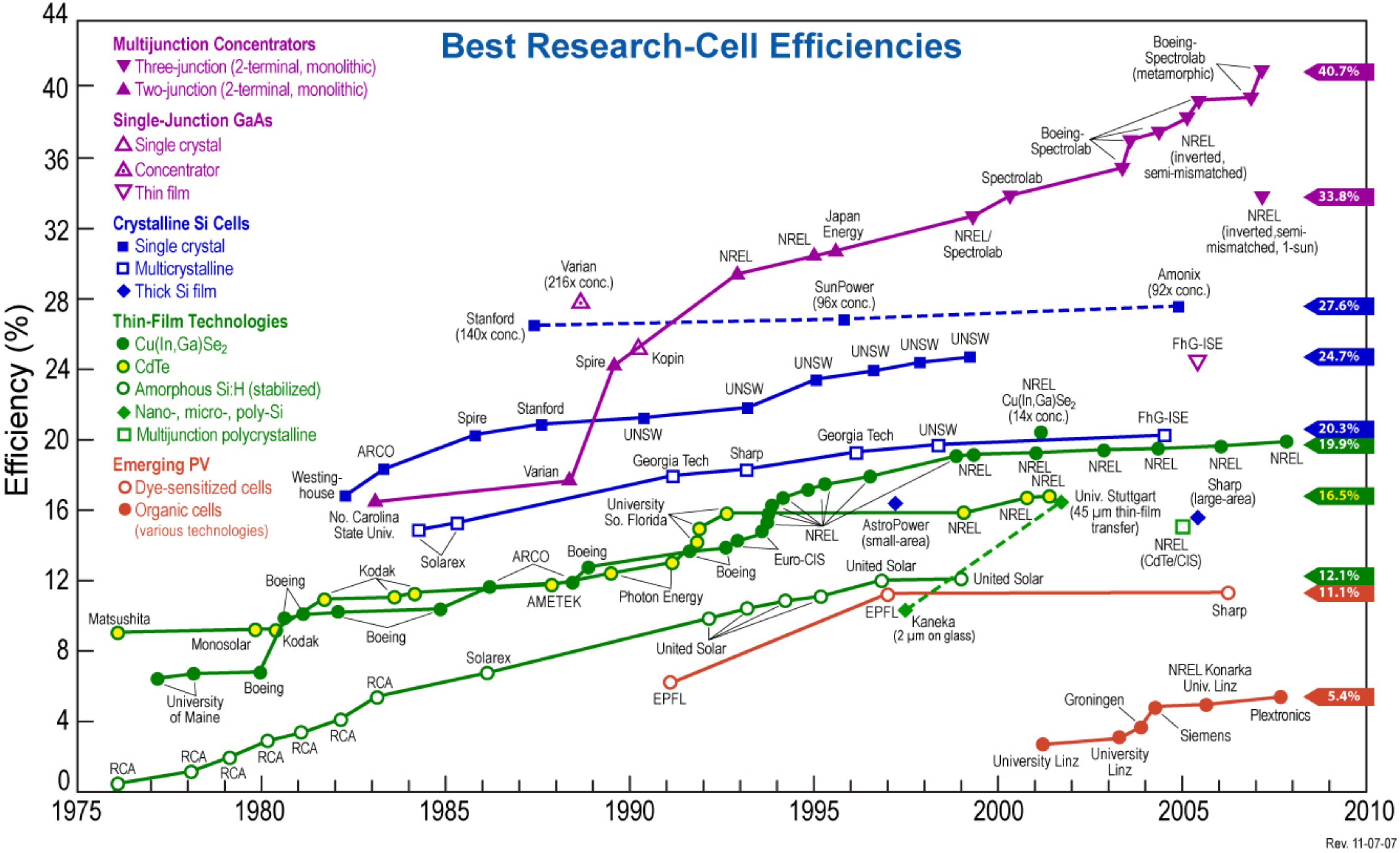
| **Cell Type** | **Area (cm$^2$)** | **$V_{oc}$ (V)** | **$J_{sc}$ (mA /cm$^2$)** | **FF (%)** | Efficiency (%) |
|---|---|---|---|---|---|
| c-Si | 4.0 | 0.696 | 42.0 | 83.6 | 24.9 |
| c-GaAs | 3.91 | 1.022 | 28.2 | 87.1 | 25.1 |
| poly-Si | 1.0 | 0.628 | 36.2 | 78.5 | 19.8 |
| a-Si | 1.0 | 0.887 | 19.4 | 74.1 | 12.7 |
| $CuInGaSe_2$ | 1.04 | 0.669 | 35.7 | 77.0 | 18.4 |
| Cd Te | 1.131 | 0.848 | 25.9 | 74.5 | 16.4 |
| P3HT / PCBM | 0.1 | ~0.6 | ~11 | ~70 | 5.4 |

- $J_{SC}$ decreases as band gap $E_g$ is increased
- $V_{OC}$ increases as band gap $E_g$ is increased
- PCE should have an optimum at some $E_g$



# Actual versus ideal PV performance





http://en.wikipedia.org/wiki/Image:PVeff%28rev110707%29d.jpg

# Summary of Lecture 2

- Photocurrent generation results from the absorption of light and the competition between charge transport and recombination.

- Power generation results from competition between photocurrent and dark current

- Photocurrent can be calculated for a simplified model of a p-n junction
  - it depends on cell optical depth and minority charge carrier diffusion length

- Dark current is due to recombination and depends on band gap and defect density

- Control of light harvesting, recombination and band gap lead to good solar cell design.

# 7.2 (cont.) Solar cell device physics

Dark current density $J_{dark}$ is made up of contributions from the two neutral doped regions and the depletion zone (DZ) :

$$J_{dark} = J_{n,dark} + J_{p,dark} + J_{DZ,dark}$$

By solving the continuity equation for holes in the n region with G = 0 we get :

$$J_{p,dark} = e n_i^2 \frac{D_h}{L_h N_D}\left(e^{eV/kT} - 1\right)$$

similarly for electrons in the p region with G = 0 :

$$J_{n,dark} = e n_i^2 \frac{D_e}{L_e N_A}\left(e^{eV/kT} - 1\right)$$

in each case it's assumed that only the Fermi level of the minority carries is moved by the applied V.

In the DZ, the dark current is due to recombination of electrons and holes with a net rate R. From the continuity equation with G=0 :

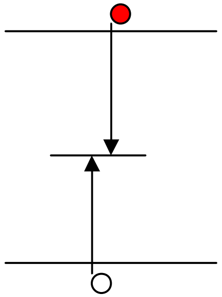
$$J_{DZ,dark} = e\int R\, dx$$

# 7.2 (cont.) Recombination mechanisms in DZ

Recombination in the DZ can occur by Shockley-Read-Hall recombination through trap states ($R_{SRH}$), by radiative recombination as well as by Auger and other methods.

$$R = R_{SRH} + R_{rad} + R_{Auger} + \ldots$$

SRH recombination involves the capture of an electron and a hole by a intra band gap state



$$R_{SRH} = \frac{np - n_i^2}{\tau_e(p + p_1) + \tau_h(n + n_1)} \approx \frac{np - n_i^2}{\tau_e p + \tau_h n}$$

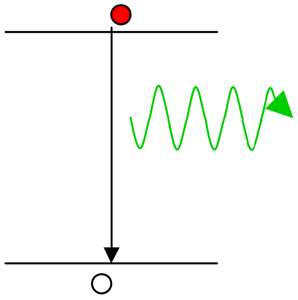
$R_{SRH}$ is maximised for mid gap traps and when n ≈ p. Then

$$R_{SRH} \approx \frac{np - n_i^2}{\langle\tau\rangle(n + p)} \approx \frac{n_i^2\left(e^{eV/kT} - 1\right)}{2\langle\tau\rangle n_i e^{eV/2kT}} \sim e^{eV/2kT}$$

$R_{SRH}$ gives rise to an ideality factor of ~ 2. This is often seen in direct gap semiconductor p-n junctions

# 7.2 (cont.) Recombination mechanisms in DZ

Radiative recombination involves the spontaneous emission of a photon as the electron relaxes to the valence band.



From lecture JN1 and PS5 we know that the spontaneous emission rate is proportional to the absorption coefficient, the photon density of states and occupation factor

$$W_{sp} = \frac{W_{abs}}{n_{ph}} f_{ph} g_{ph}$$

$$W_{sp} \propto \alpha(E) \frac{E^2}{e^{(E-eV)/kT} - 1} \quad \propto e^{eV/kT} \quad \propto np$$

To find the net $R_{rad}$ we subtract the rate at equilibrium, when $np = n_i^2$

$$R_{rad} = B_{rad}\left(np - n_i^2\right) \qquad \propto \left(e^{eV/kT} - 1\right)$$

$R_{rad}$ has an ideality factor of 1. This means that $R_{rad}$ becomes more important relative to $R_{SRH}$ as V is increased.

# 7.2 (cont.) Solar cell device physics

Integrating R over the DZ of width $W_{DZ}$ and summing contributions to $J_{dark}$ :

$$J_{dark} = J_{n,dark} + J_{p,dark} + J_{DZ,dark}$$

$$J_{dark} = en_i^2\left(\frac{D_e}{L_e N_A} + \frac{D_h}{L_h N_D}\right)\left(e^{eV/kT} - 1\right) + B_{SRH} n_i W_{DZ}\left(e^{eV/2kT} - 1\right) + B_{rad} n_i^2 W_{DZ}\left(e^{eV/kT} - 1\right)$$

The net dark current has the form :

$$J_{dark} = J_0\left(e^{eV/mkT} - 1\right)$$

where the ideality factor m is typically between 1 and 2.

# Factors limiting performance

Open circuit voltage $V_{OC}$ :

$$V_{OC} = \frac{mkT}{e}\ln\left(\frac{J_{SC}}{J_0}+1\right) \approx \frac{mkT}{e}\ln\left(\frac{J_{SC}}{J_0}\right)$$

$$J_0\left(e^{eV/mkT}-1\right) \approx en_i^2\left(\frac{D_e}{L_eN_A}+\frac{D_h}{L_hN_D}\right)\left(e^{eV/kT}-1\right)+B_{SRH}n_iW_{DZ}\left(e^{eV/2kT}-1\right)+B_{rad}n_i^2W_{DZ}\left(e^{eV/kT}-1\right)$$

$$J_{dark} = J_{n,dark} + J_{p,dark} + J_{DZ,dark} = e\int_{\substack{neutral\\n-region}} Rdx + \int_{\substack{neutral\\p-region}} Rdx + \int_{DZ} Rdx$$

$$J_0\,(\exp(eV/mkT) - 1) =$$

To increase $V_{OC}$ (at a given $J_{sc}$) we need to decrease $J_0$:

| | |
|---|---|
| decrease $n_i$ | increase band gap $E_g$ |
| increase $N_A$, $N_D$ | increase doping levels |
| increase $L_e$ $L_h$ | improve material quality to increase L |
| reduce $B_{SRH}$ | reduce trap density in space charge region |
| reduce $B_{rad}$ | reduce absorption $\alpha$ |

# Device physics of solar cells

- Physics governed by charge continuity

$$\boxed{\frac{1}{e}\frac{dJ}{dx}+G-R=0}$$

- Generation G = light absorption rate

$$G=\alpha b_{sun}e^{-\alpha x}$$

- Recombination R usually linear

$$R=Bnp\approx\frac{n}{\tau}$$

- Current density J Dominated by minority carrier diffusion.

$$J=qD\frac{dn}{dx}+qn\mu\varepsilon$$

- Differential equation for carrier density

$$D_n\frac{d^2n}{dx}-\frac{n}{t_n}=-G$$

- Boundary conditions

$$n(0)=n_0e^{V/kT}\qquad J_n(d)=0$$

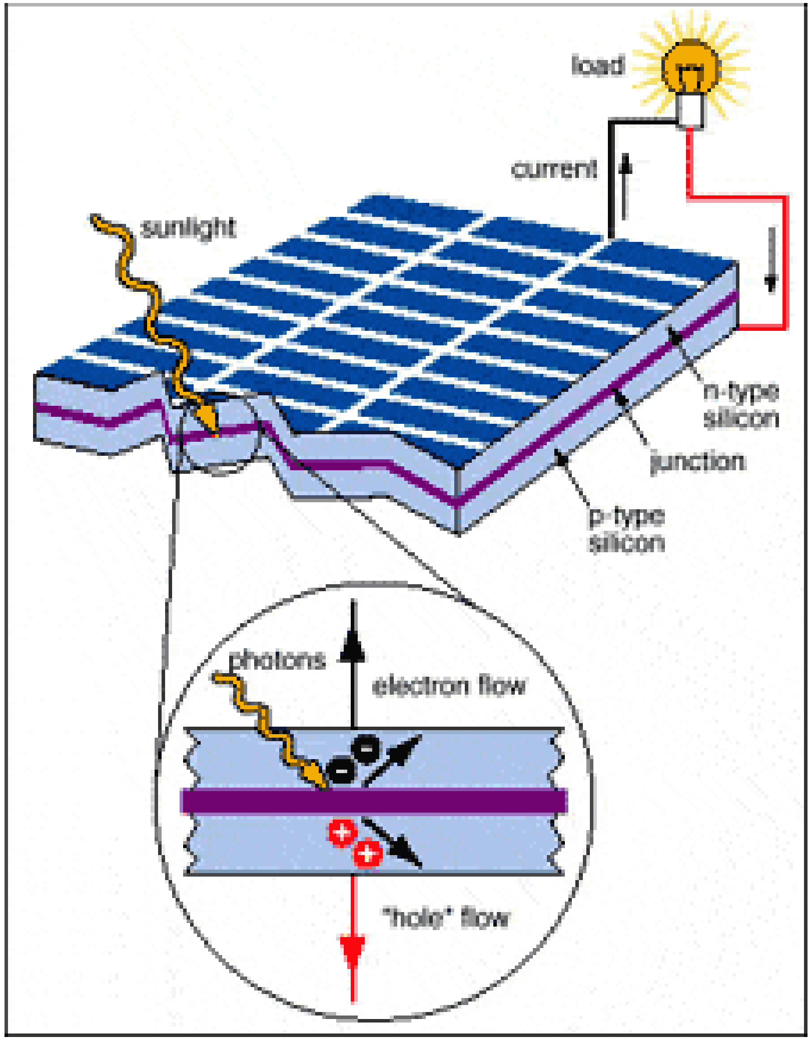
# Device physics of solar cells

- Result: diode equation for J-V

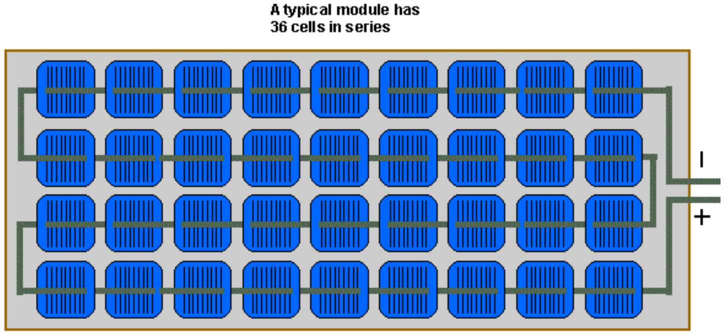
$$J = -J_{sc} + J_0\left(e^{qV/mkT} - 1\right)$$

- Important parameters:
  - absorption coefficient $\alpha$, optical depth $\alpha d$, reflectivity
  - charge diffusion length $L = (D\tau)^{1/2}$
  - type of recombination (e.g. linear, bimolecular, via defect states)
  - parasitic resistances: series R and shunt R (leakage)

# From cells to systems



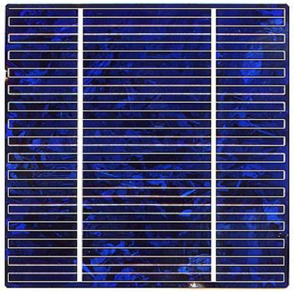
Light to power efficiency of best silicon solar cell ~ 25%



C-Si module efficiencies typically ~ 15%

# Photovoltaic systems: cell

Solar cell

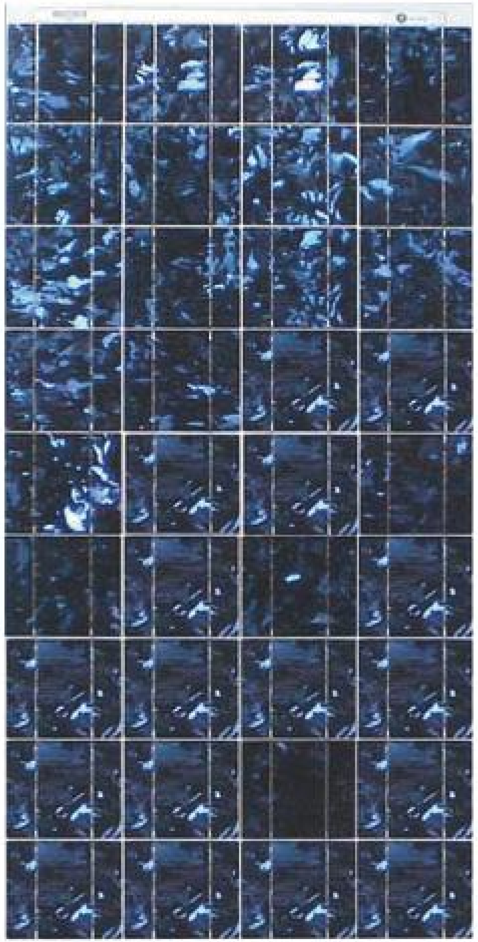


Efficiency 14.6%----Pmax 1.46W

- Area ~ 100 $cm^2$
- Current output in AM 1.5:
  I ~ 30 mA $cm^{-2}$ x 100 $cm^2$ = 3 A
- Voltage at maximum power point ~ 0.5 V
- Power conversion efficiency
  $\eta$ = 3A x 0.5 V / (100 $cm^2$ x 100 $mWcm^{-2}$) = 15%

# Photovoltaic systems: module

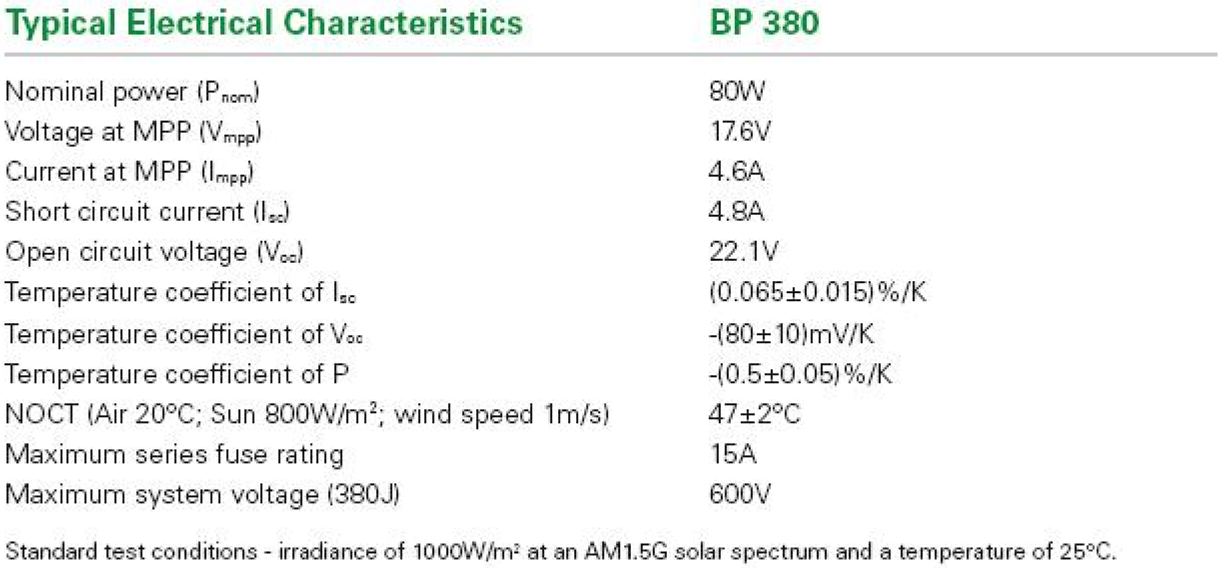
Solar module



BP 380J 80 $W_p$ module

36 x 150 $cm^2$ cells in series

Current output in AM 1.5:
$I \sim 30\ mA\ cm^{-2} \times 150\ cm^2 = 4.5\ A$

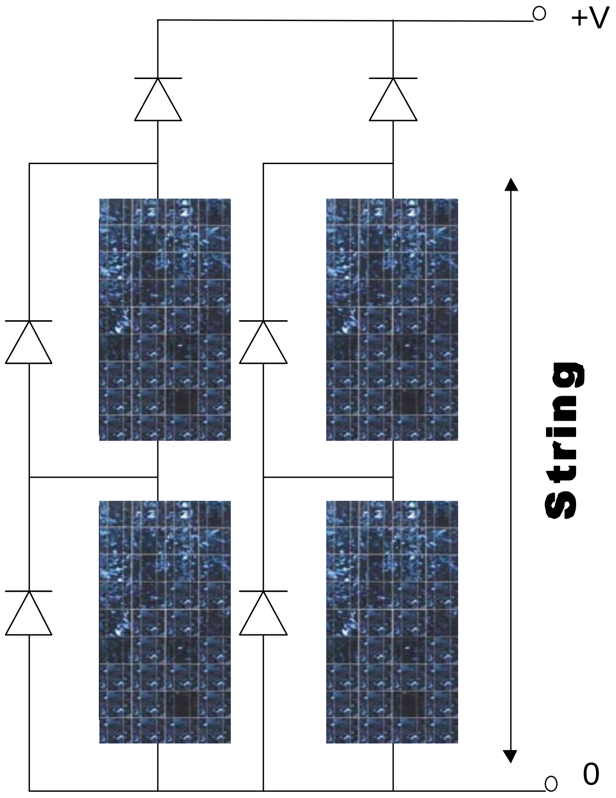


| **Typical Electrical Characteristics** | **BP 380** |
|---|---|
| Nominal power ($P_{nom}$) | 80W |
| Voltage at MPP ($V_{mpp}$) | 17.6V |
| Current at MPP ($I_{mpp}$) | 4.6A |
| Short circuit current ($I_{sc}$) | 4.8A |
| Open circuit voltage ($V_{oc}$) | 22.1V |
| Temperature coefficient of $I_{sc}$ | (0.065±0.015)%/K |
| Temperature coefficient of $V_{oc}$ | -(80±10)mV/K |
| Temperature coefficient of P | -(0.5±0.05)%/K |
| NOCT (Air 20°C; Sun 800W/m²; wind speed 1m/s) | 47±2°C |
| Maximum series fuse rating | 15A |
| Maximum system voltage (380J) | 600V |

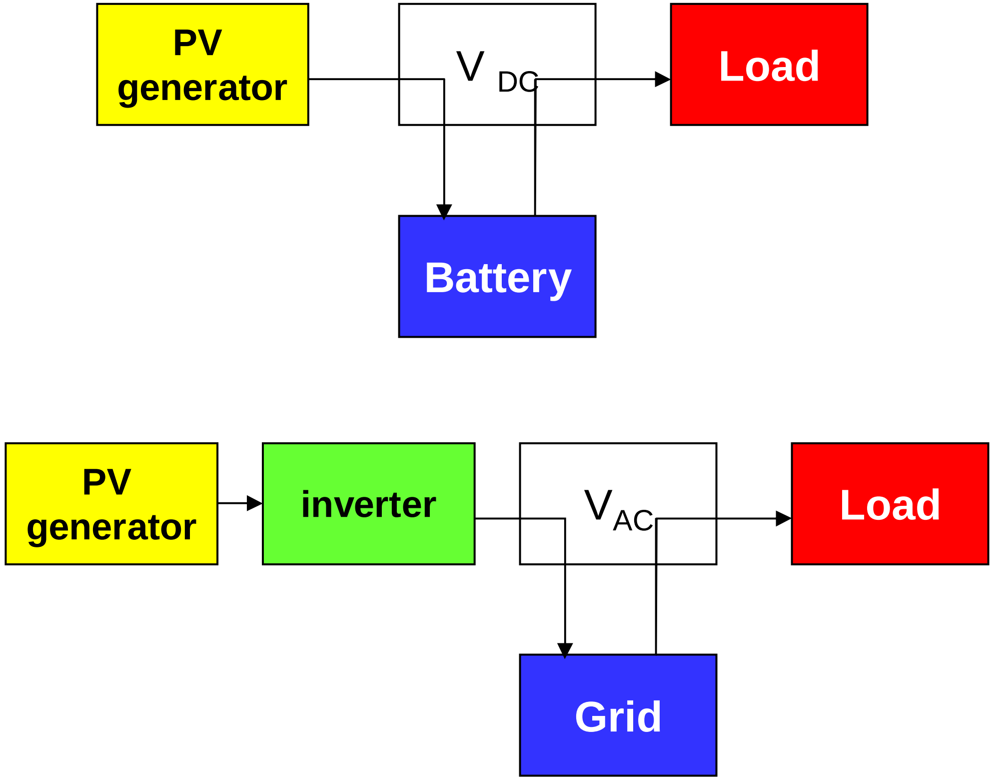
Standard test conditions - irradiance of 1000W/m² at an AM1.5G solar spectrum and a temperature of 25°C.

# Photovoltaic systems : system

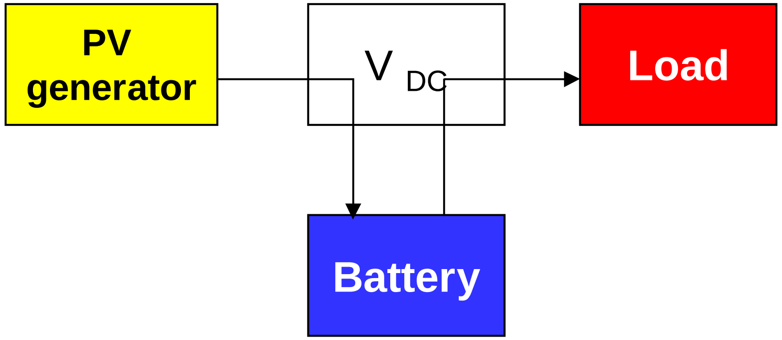
Solar PV system



Array of modules



Components of a PV system

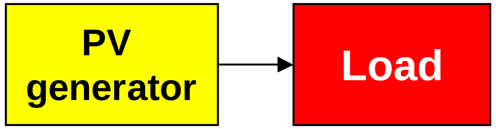


**PV generator**

V DC

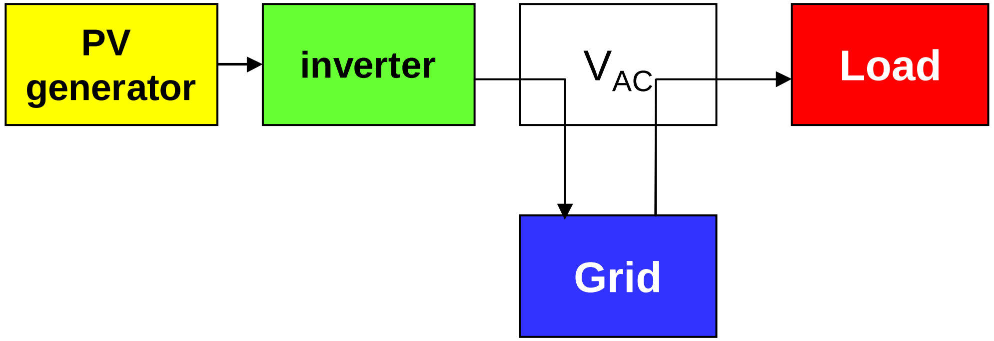
**Load**

**Battery**



**PV generator**

**Load**



**PV generator**

**inverter**

$V_{AC}$

**Load**

**Grid**

- The question of energy determines the whole project, from the structure's dimensions to the extreme weight constraints. At midday, each m$^2$ of land surface receives the equivalent of 1000 Watts, or 1.3 horsepower of light power. Over 24 hours, this averages out at just 250W/m$^2$. With 200m$^2$ of photovoltaic cells and a 12 % total efficiency of the propulsion chain, the plane's motors achieve no more than 8 HP or 6kW – roughly the amount of power the Wright brothers had a available to them in 1903 when they made their first powered flight.
- Only a machine of disproportionate dimensions (61 metre wingspan) and very light weight (1500 kg) will be able to fly sufficiently slowly (45 km/h) to operate off the available energy!.

# Summary of Lecture 20

- A PV cell is equivalent to a diode in parallel with a current generator

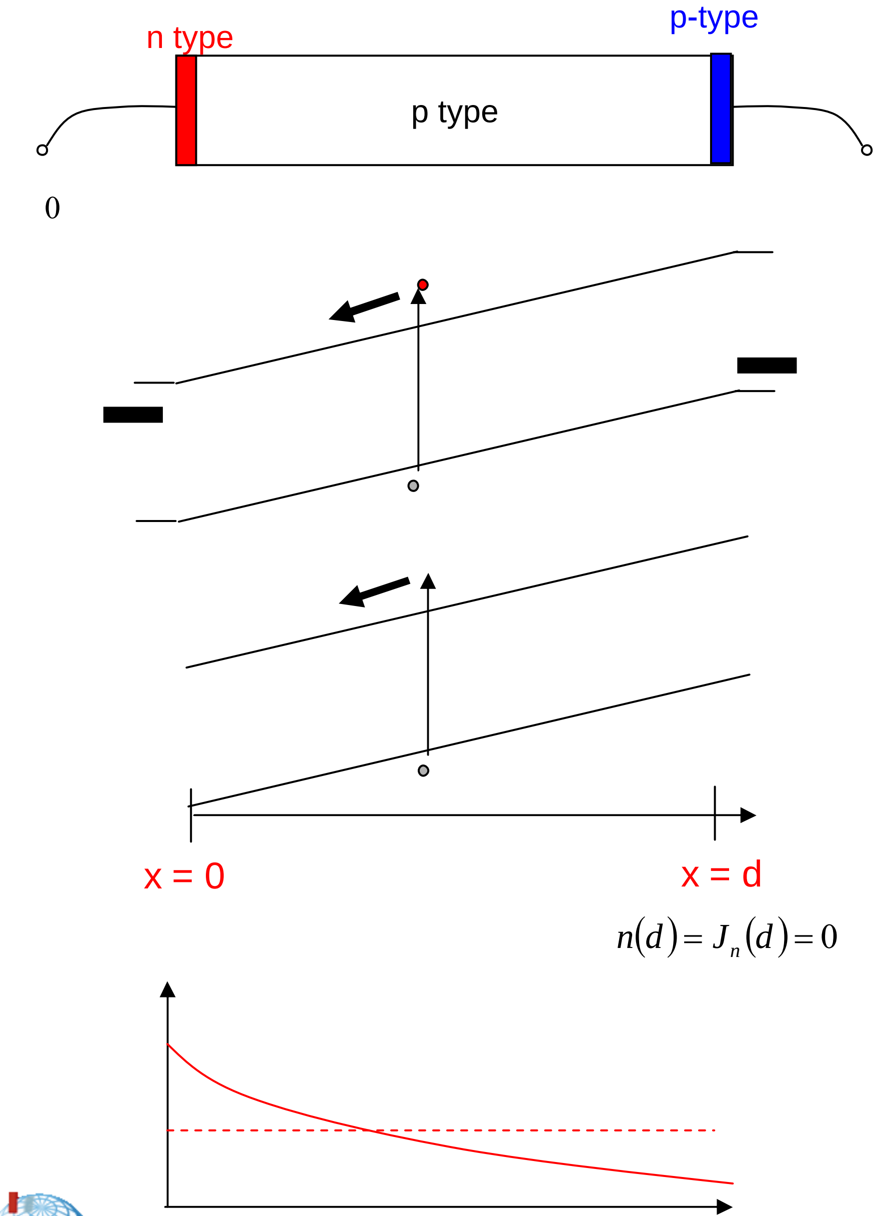
- Performance characteristics:
  - $J_{sc}$ (increases with reducing Eg or increasing X)
  - $V_{oc}$ (increases with increasing Eg, increases logarithmically with X)
  - FF (convenient indicator of operating point)

- Real materials limited by
  - incomplete light absorption
  - (non-radiative) charge relaxation
  - series resistance

- Thin film materials pursued for low cost (outweighs lower efficiency)

- PV systems designed for wide variety of applications: versatile, modular, decentralised

# Calculation of photodetector internal QE



$n(d) = J_n(d) = 0$

- Assumptions
  - Neglect photocurrent from thin emitter
  - All electrons reaching p-n junction are collected
  - No current exits through base
  - No diffusion
  - Generation rate is uniform
  - electrons drift with mobility $\mu_n$
  - electrons relax with lifetime $\tau_n$

Continuity equation for electrons

$$\frac{1}{e}\frac{dJ_n}{dx}+G-R=0$$

electron drift current:

$$J_n = e\mu_e F n$$

electron relaxation rate:

$$R = \frac{n}{\tau_e}$$

electron generation rate:

$$G \approx \frac{1}{d}\frac{(1-r)I_0}{E}\int_0^d \alpha e^{-\alpha x}dx = \frac{1}{d}(1-r)\left(1-e^{-\alpha d}\right)\frac{I_0}{E}$$

$$\Rightarrow \quad \mu_e F\frac{dn}{dx}-\frac{n}{\tau_e}=-G$$

First order inhomogeneous differential equation.
Solution

$$n = Ce^{x/\mu_e F\tau_e}+G\tau_e$$

$$n = Ce^{x/\mu_e F\tau_e} + G\tau_e \qquad J_n = e\mu_e F\left(Ce^{x/\mu_e F\tau_e} + G\tau_e\right)$$

Apply boundary conditions: $J_n(d) = 0 \quad \Rightarrow \quad C = G\tau_e e^{-d/\mu_e F\tau_e}$

$$n(x) = G\tau_e\left(1 - e^{-(d-x)/\mu_e F\tau_e}\right)$$

$$J_n(x) = e\mu_e F G\tau_e\left(1 - e^{-(d-x)/\mu_e F\tau_e}\right)$$

In limit of large μτF: $J_n(x) = eG(d - x)$

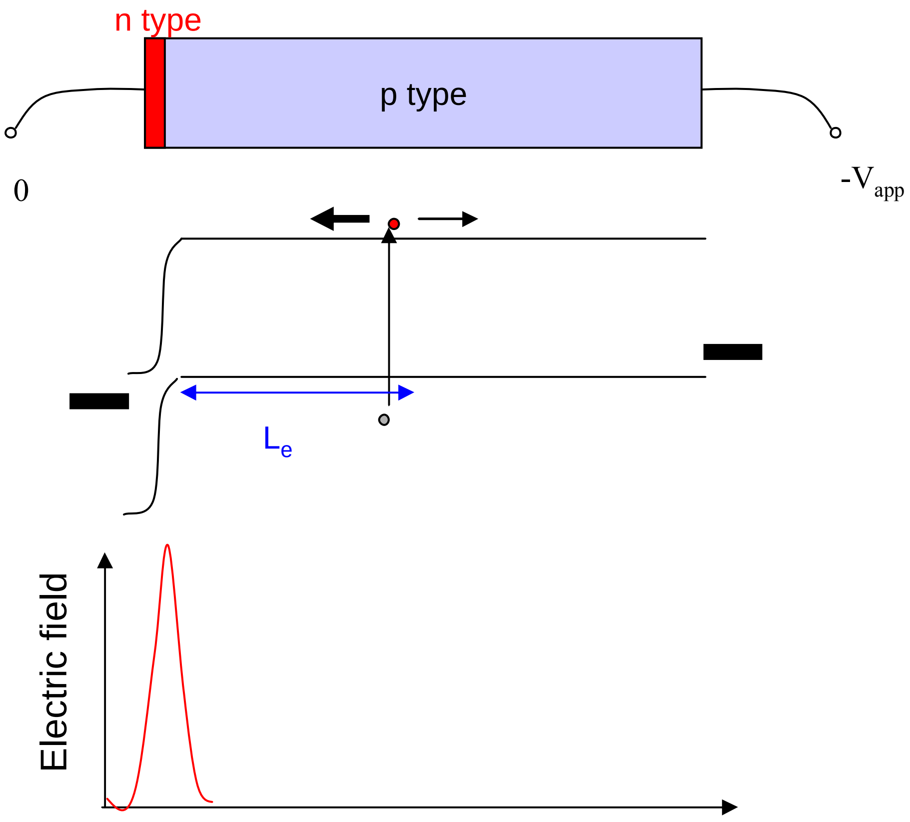
$$\boxed{J_{ph} = J_n(0) = eGd}$$

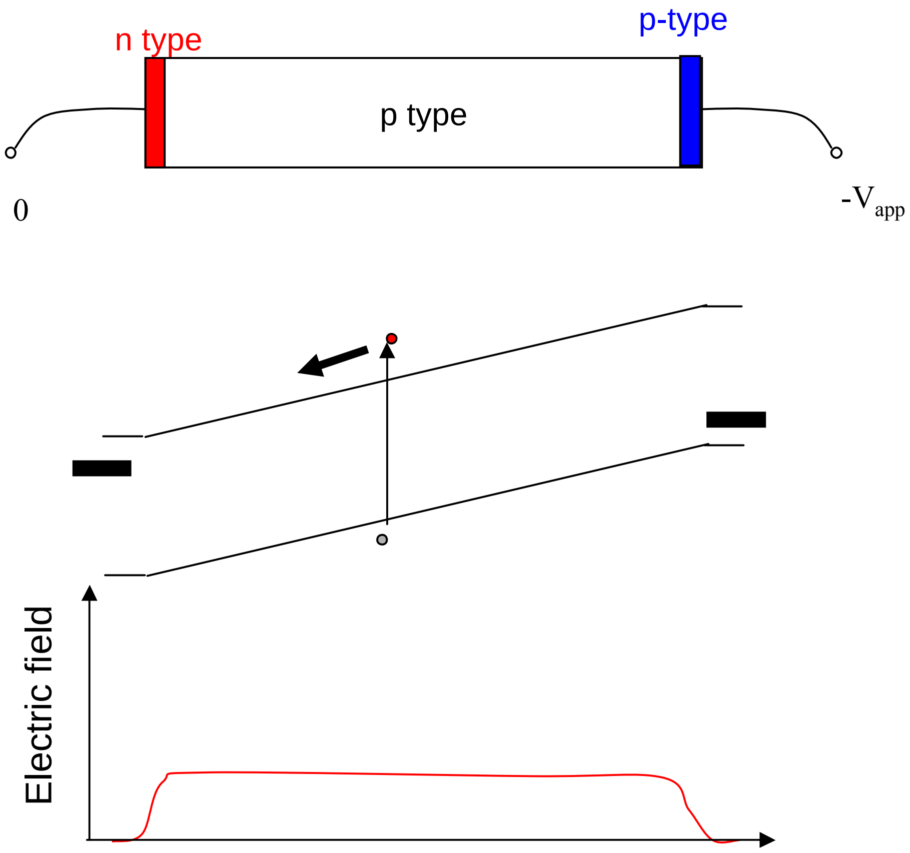
$J_{ph}$ = e QE(E) $I_{in}$ / E

QE = (1 – r)(1 – $e^{-\alpha d}$) η

η = 1

# p-n versus p-i-n device structures





$$\boxed{J_{ph} = J_n(0) = eGL_e \tanh\left(d / L_e\right)}$$

$$\boxed{J_{ph} = J_n(0) = eGd}$$

Maximise $J_{ph}$ when L >> d
Response time $t_r \sim d^2/D_e$

Maximise $J_{ph}$ when $\mu\tau F >> d$
Response time $t_r \sim d/\mu F$