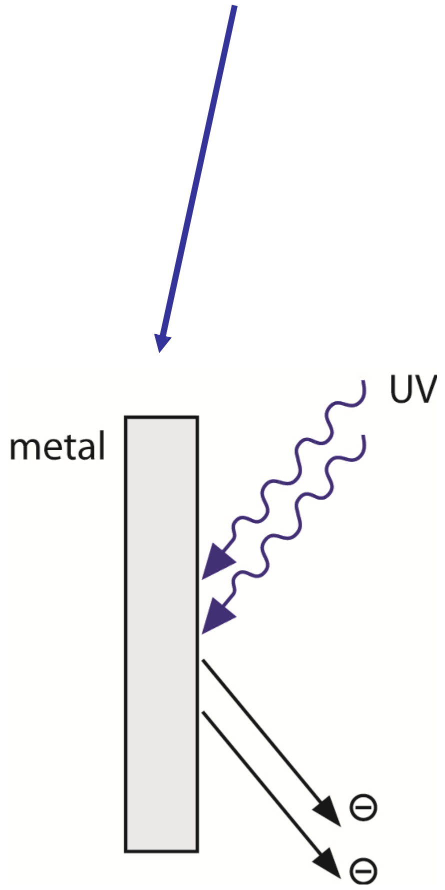
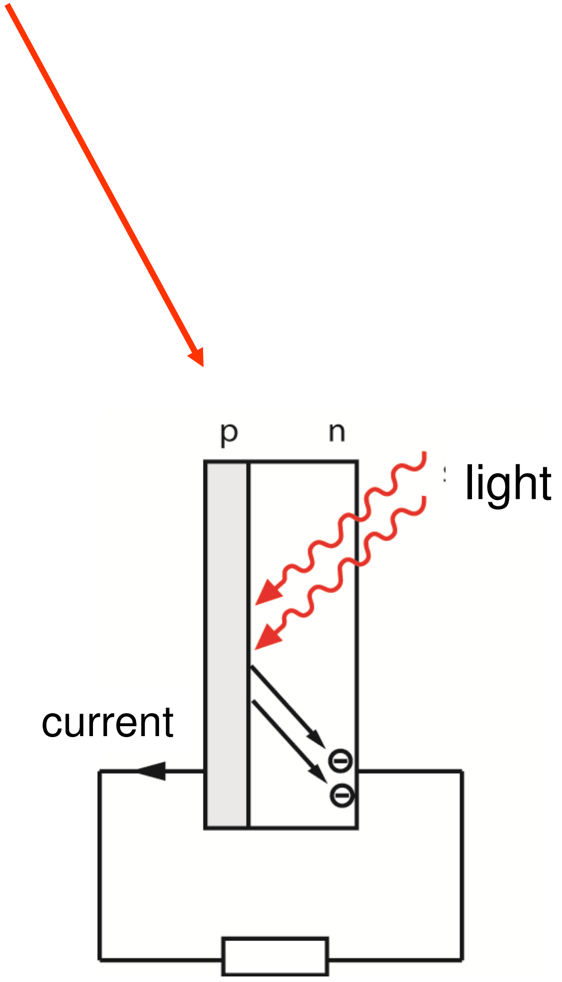
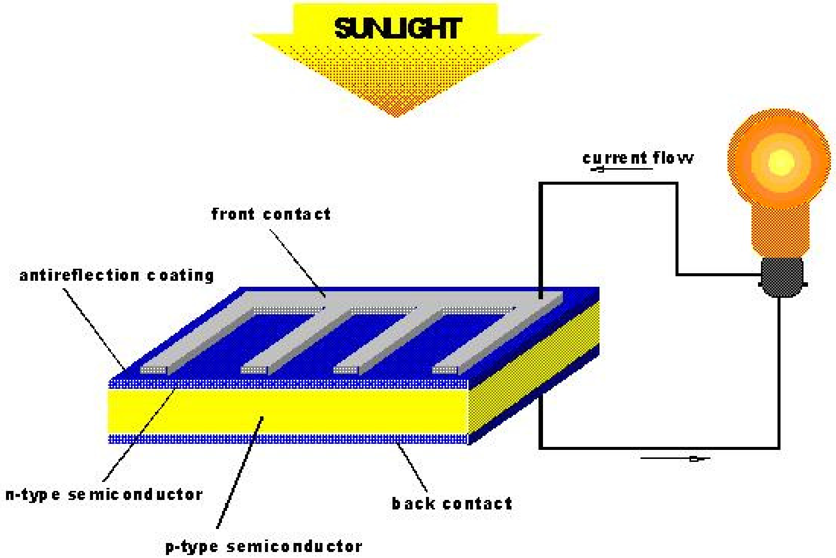
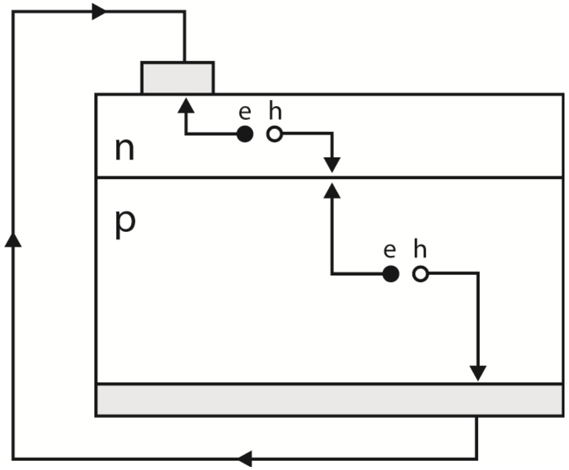
External and internal photovoltaic effect



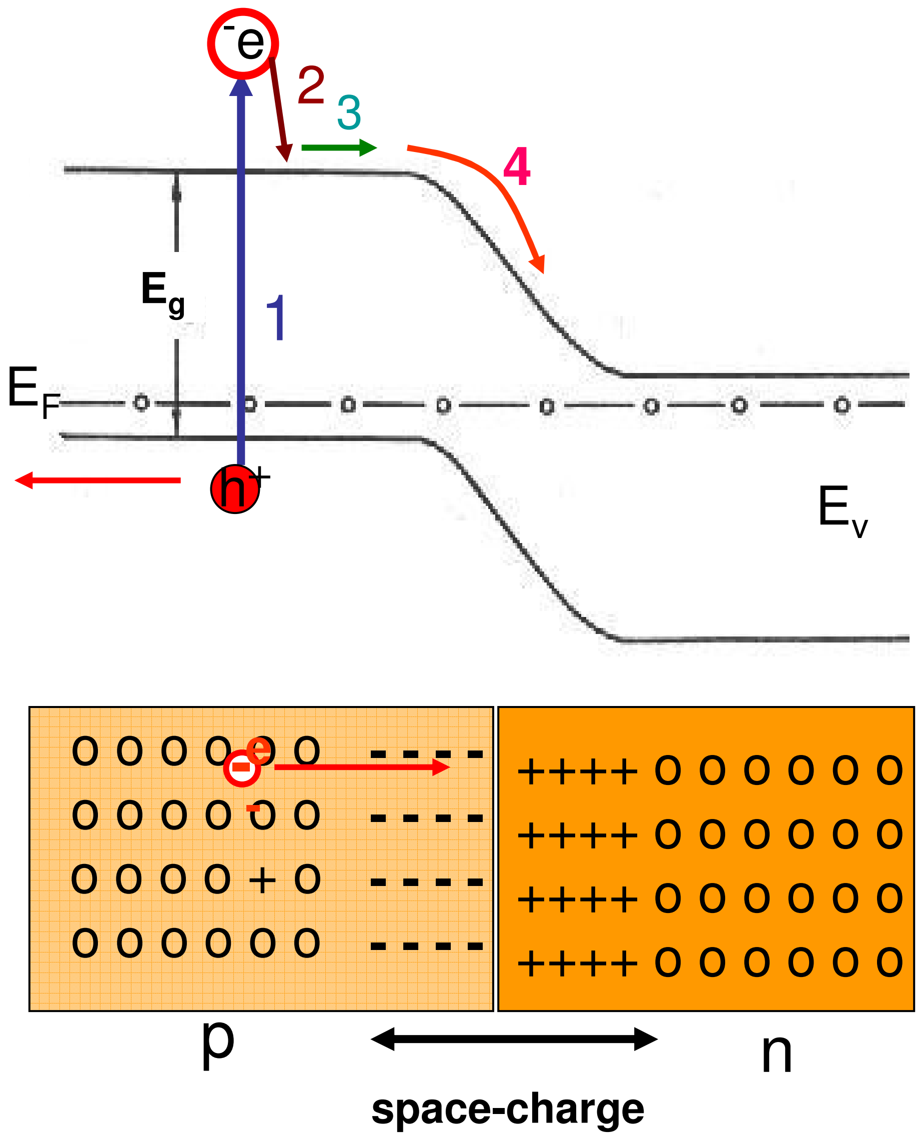


Basic pn cell design





Photovoltaic effect in pn junction



1. absorption
2. **thermalisation**
3. **diffusion**
4. drift

important parameters:
o band gap $\mathbf{E_g}$
o doping level
o absorption coefficient α
o lifetime of carriers τ
o diffusion length $\mathbf{L_d}$
o mobility μ

Current-voltage characteristics under illumination

I-V in the dark

$$I_{dark} = J_o\left(\exp\left\{\frac{eV}{Ak_BT}\right\} - 1\right)$$

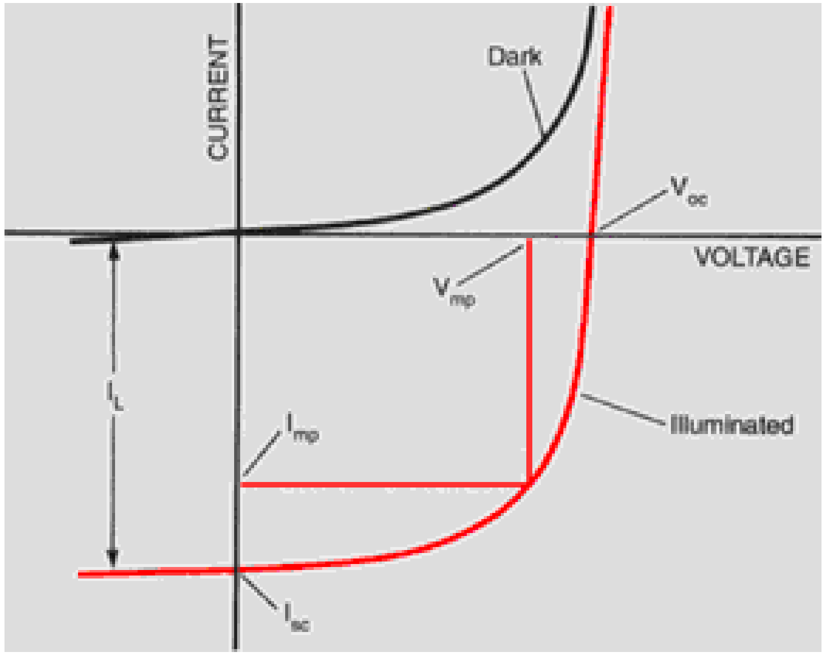
$$J_o = J_{oo}\exp\left\{\frac{-E_a}{k_BT}\right\}$$

I-V under illumination

***superposition principle*:**

$$\mathbf{I_{ill} = I_{dark} - I_{sc}}$$

$$\mathbf{I_{ill} = I_o\left(\exp\left\{\frac{eV}{Ak_BT}\right\} - 1\right) - I_{sc}}$$



A – ideality factor, 1<A<2

Efficiency

$$\eta = \frac{\mathbf{I_{mp} V_{mp}}}{\mathbf{P_{in}}} = \frac{\mathbf{I_{sc} V_{oc} FF}}{\mathbf{P_{in}}}$$

I_{sc} – short circuit current:

more absorbed photons - larger I_{sc}

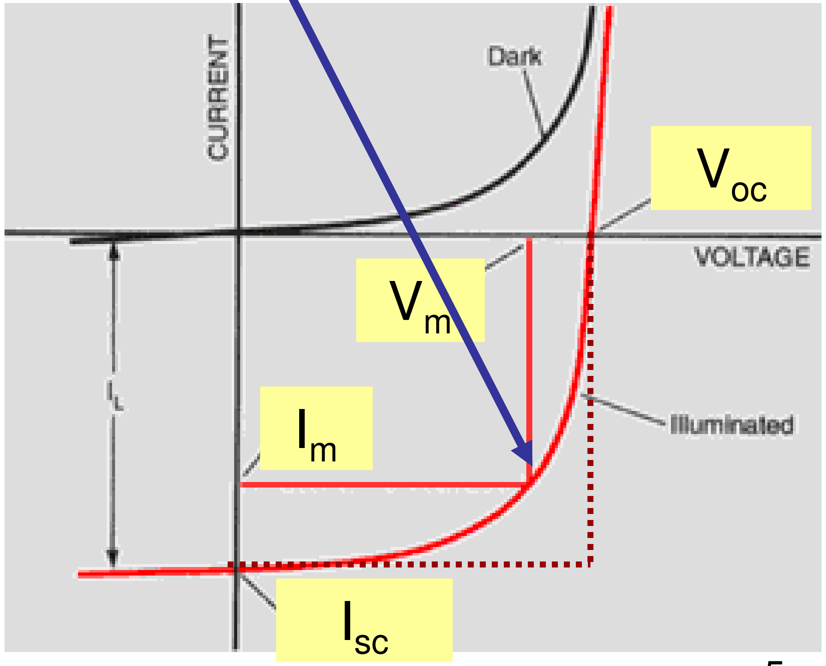
V_{oc} – open circuit voltage

larger bandgap - higher V_{oc}

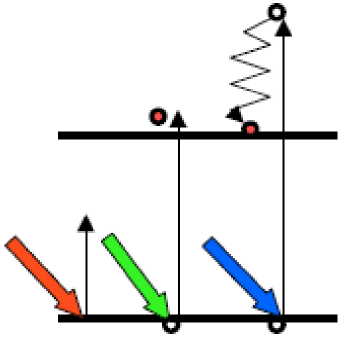
FF – fill factor

$$\mathbf{FF} = \frac{\mathbf{I_{mp} V_{mp}}}{\mathbf{I_{sc} V_{oc}}}$$

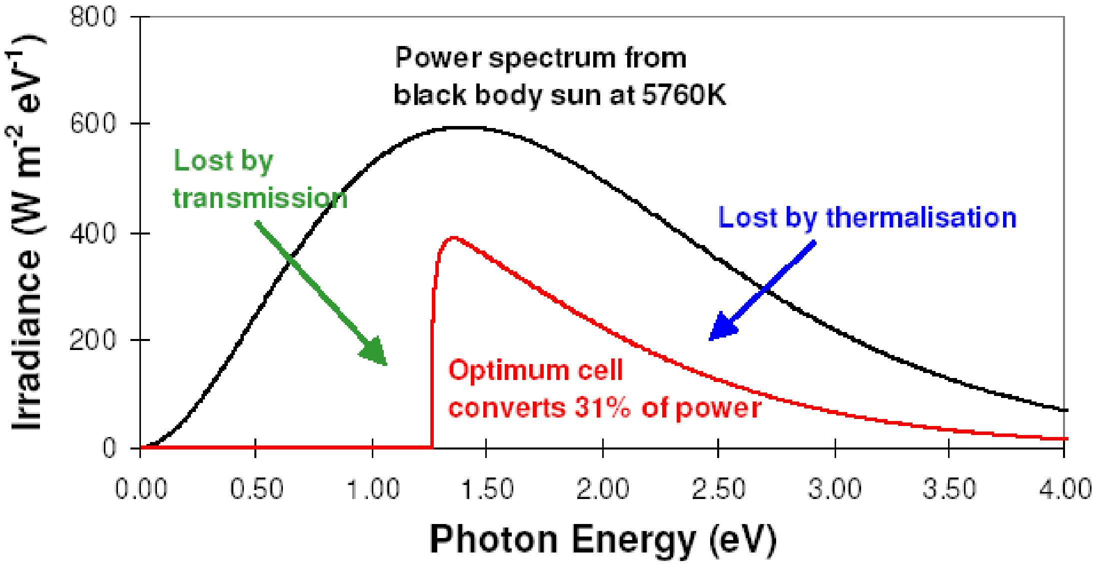
maximum power $I_m V_m$



Photogeneration and thermalisation

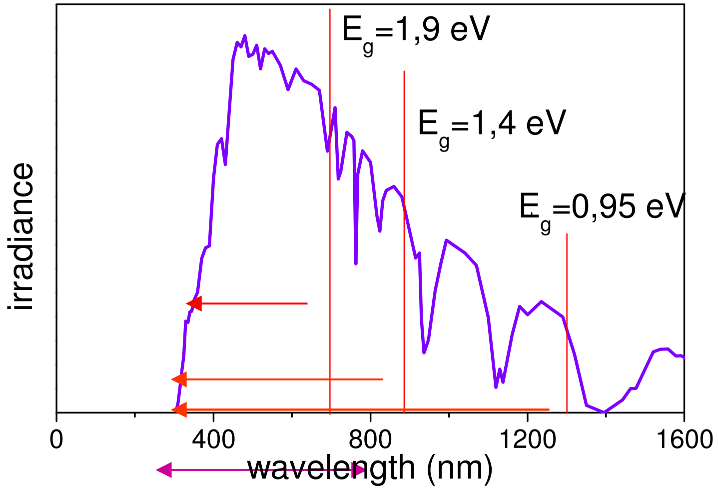


Single band gap

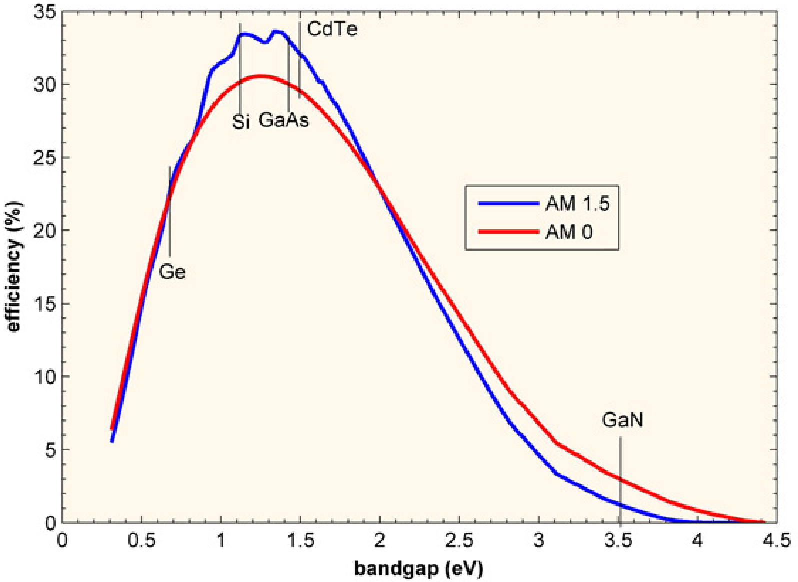


Efficiency – dependence on E_g

solar spectrum AM1,5 (1 kW/m²)

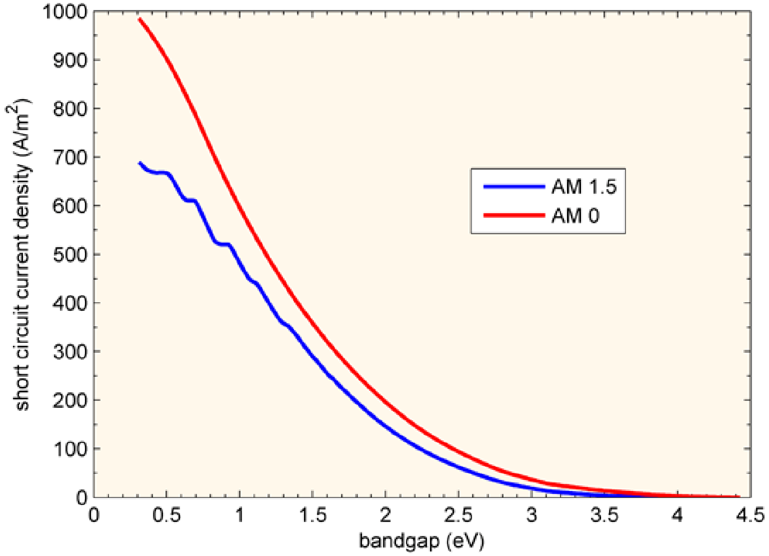


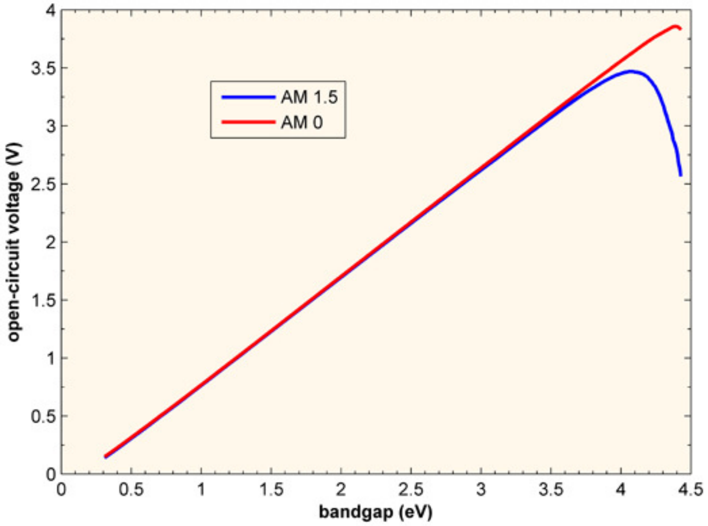
Maximum efficiency
E_g = 1,4 -1,5 eV



max. possible efficiency for single junction (only radiative recombination, only thermalization losses, no other losses)

Maximum efficiency



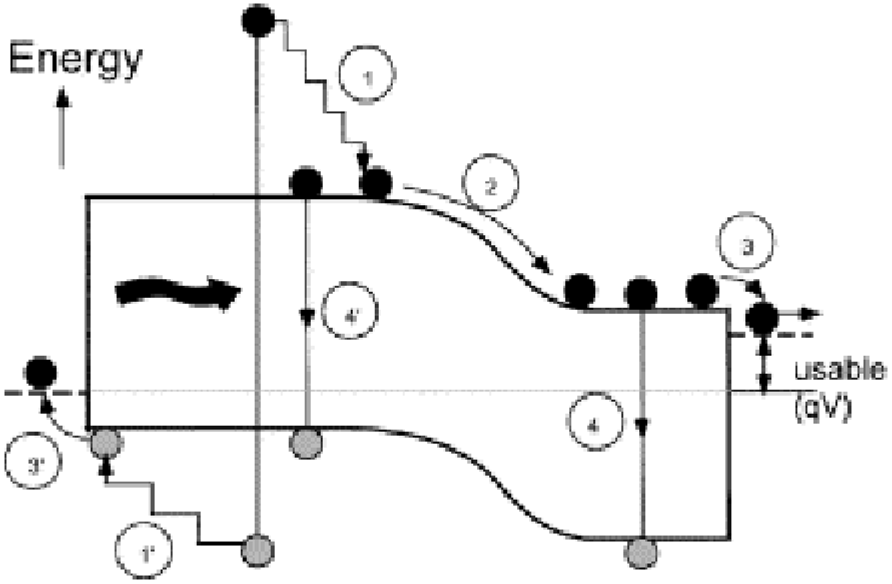


Isc ⇧ when Eg ⇩

Voc ⇧ when Eg ⇧

η_{max} : $E_g \cong$ 1.5 eV

Energy losses in the cell

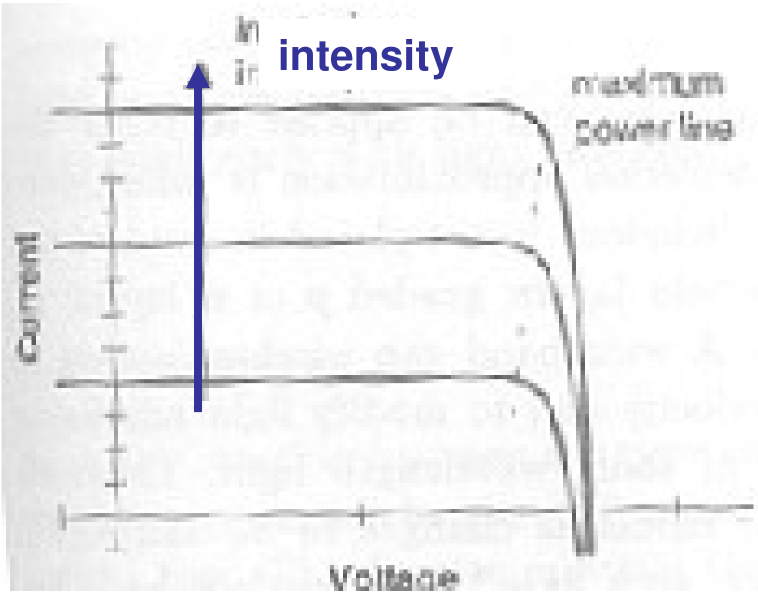


(1) thermalisation loss;
(2) junction loss;
(3) contact loss;
(4) recombination loss.

Effect of light intensity

$$V_{oc} = \frac{Ak_BT}{e}\ln\left(\frac{I_{sc}}{I_o}+1\right) \approx \frac{Ak_BT}{e}\ln\left(\frac{I_{sc}}{I_o}\right)$$

I_{sc}~ Φ (light intensity)
V_{oc}~ln Φ



Effect of temperature

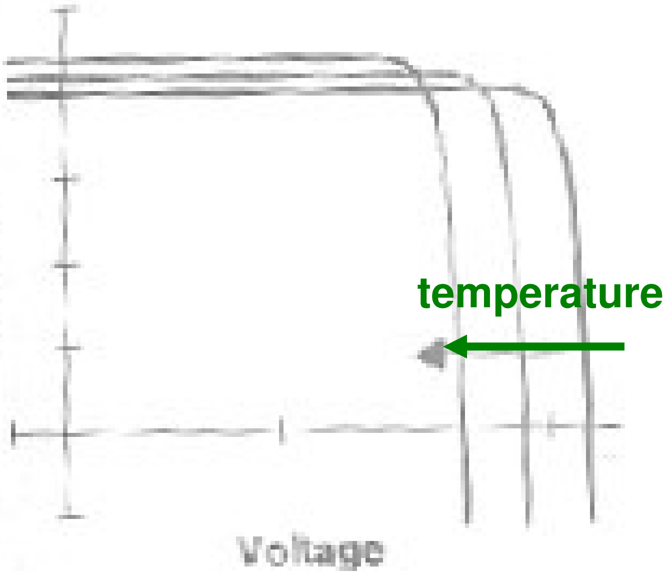
$$V_{oc} = \frac{Ak_BT}{e}\ln\left(\frac{I_{sc}}{I_o}\right) =$$

$$I_o = I_{oo}\exp\left\{\frac{-E_a}{k_BT}\right\}$$

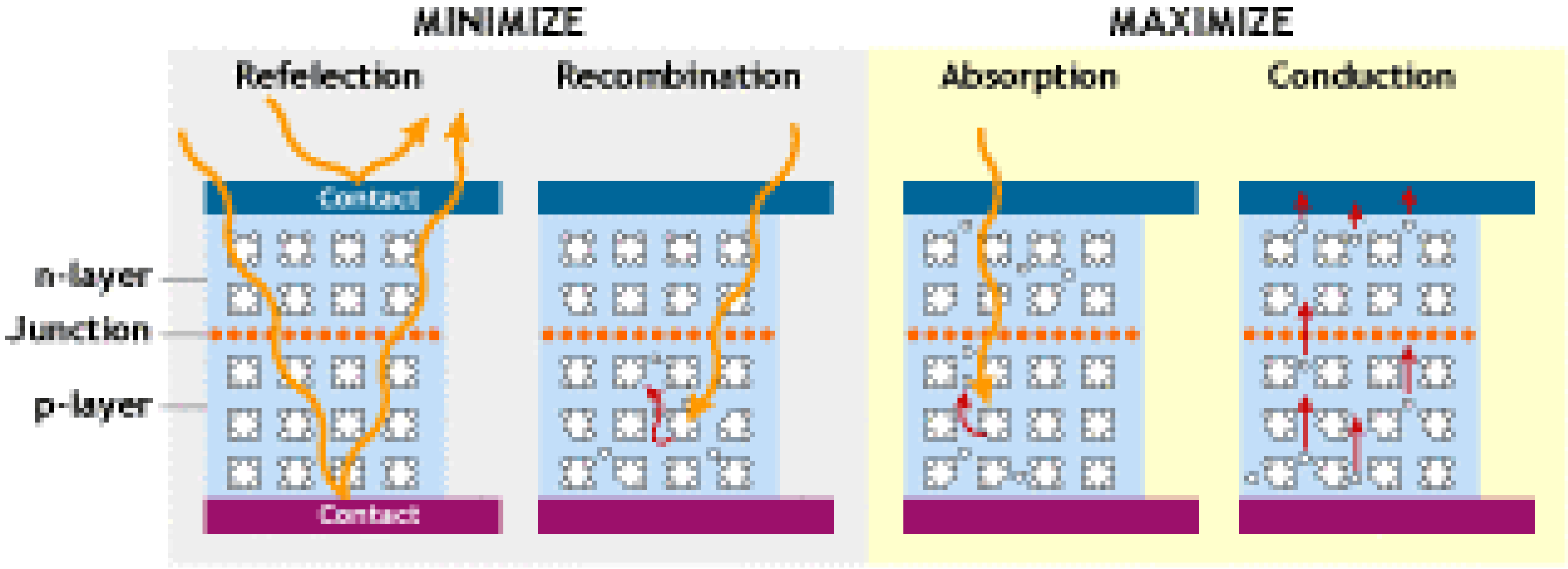
$$V_{oc} = \frac{AE_a}{e} - \frac{Ak_BT}{e}\ln\frac{I_{oo}}{I_{sc}}$$

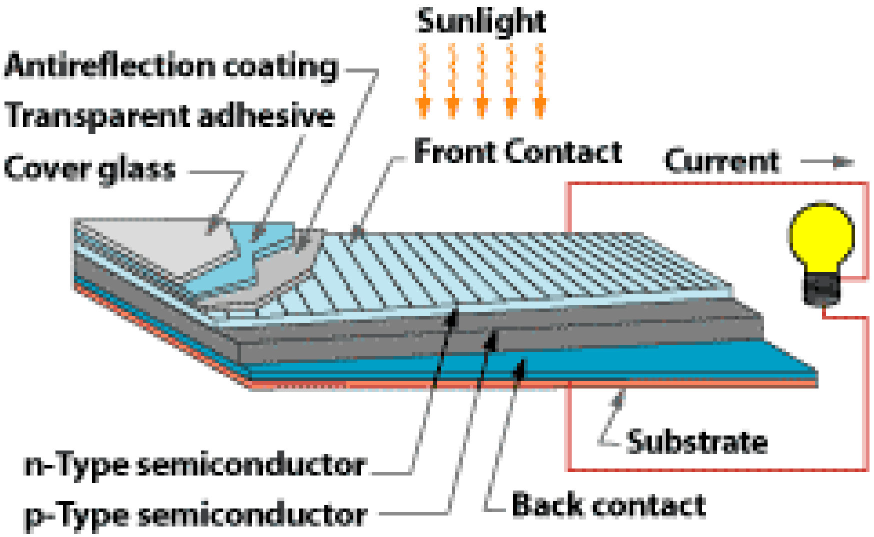
I_{sc} ~ const

for pn junction $E_a=E_g$, $A=1$,



Maximum efficiency if:



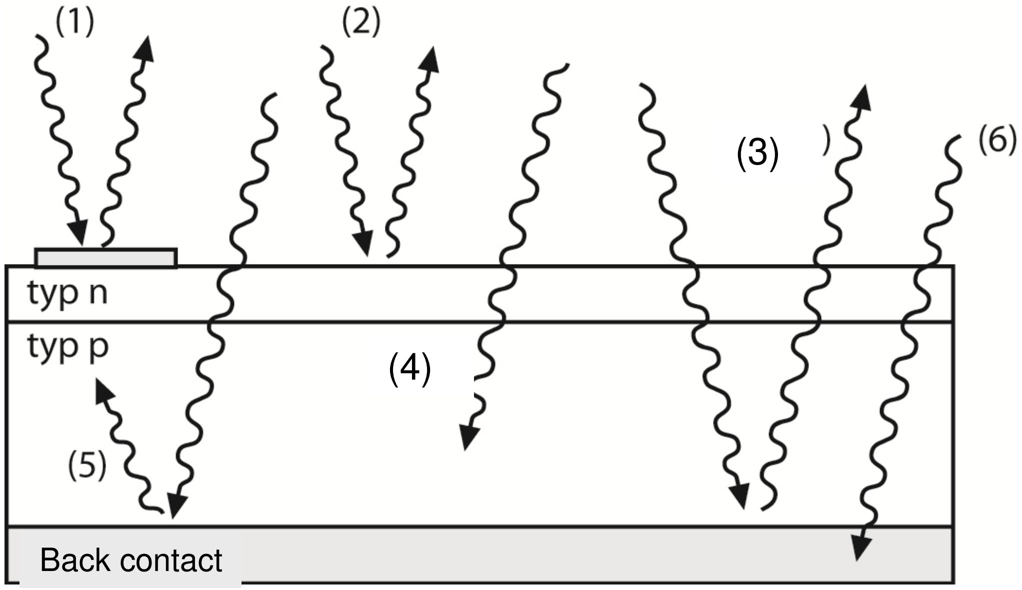


Light in a cell

1. reflection at top contact
2. reflection at cell surface
3. reflection from the rear
4. absorption
5. absorption after reflection at rear contact

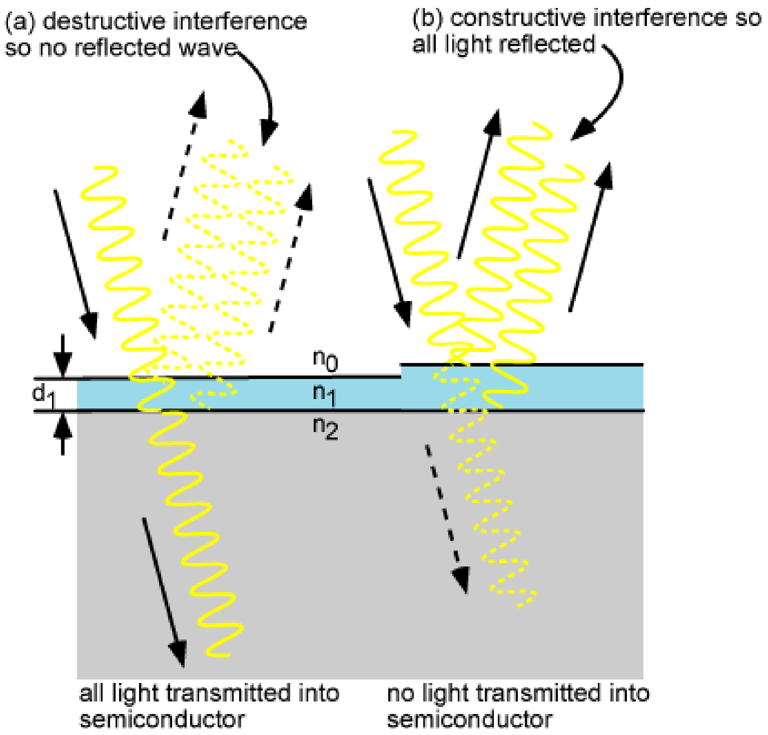
losses

desired processes



light management: increase desired processes, decrease losses

Anti-reflection coating



$$d_1 = \frac{\lambda_0}{4n_1}$$

quarter wavelength antireflection coating
- minimum reflection

$$n_1 = \sqrt{n_0 n_2}$$

optimal refractive index

Reflection losses

$$\Phi=\Phi o(1-R)\exp\{-\alpha(\lambda)\ x\}$$

losses: $R(\lambda)\phi_o(\lambda)\exp^{-\alpha(\lambda)x}$

where $R(\lambda)$ **- reflectivity of the Si**

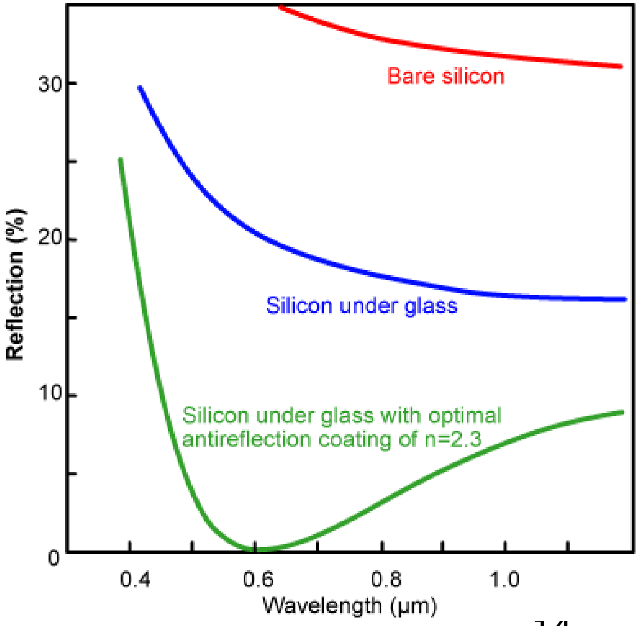
$\phi_o(\lambda)$ **- photons incident on the surface**

$\alpha(\lambda)$ **- absorption coefficient of Si**

•.

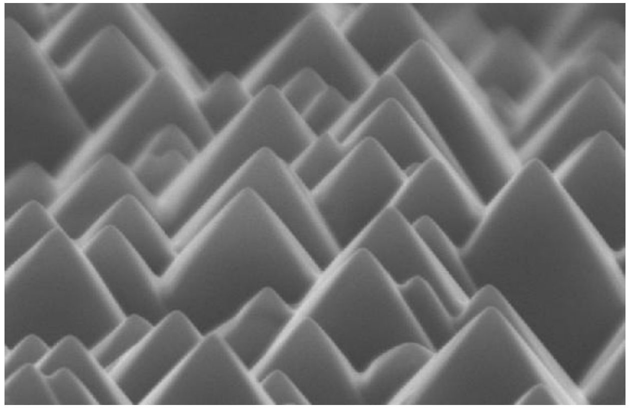
to reduce the top surface reflection

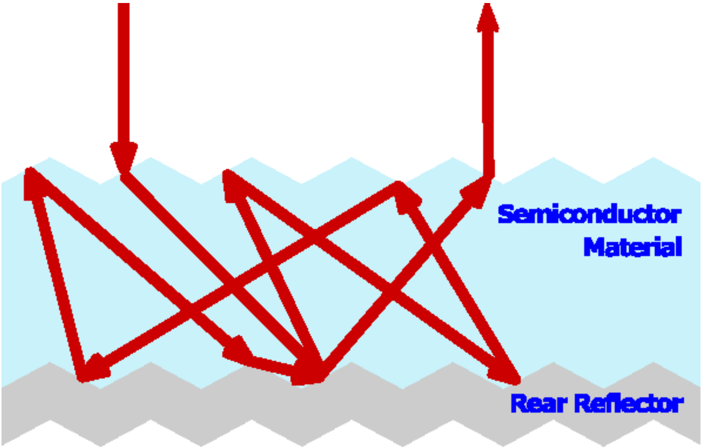
- using an antireflective coating (SiO, SiN, MgF, ZnO)
- making the surface rough
- optimize top fingers design
- texturing (isotropic etching of the top surface)



Increase number of photons absorbed in the cell:

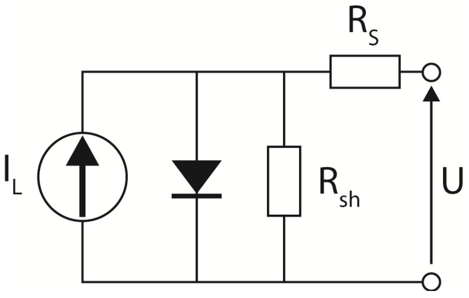
- reduce reflection
- increase photon path –light trapping (texture)
- optimize front electrode (buried contacts)

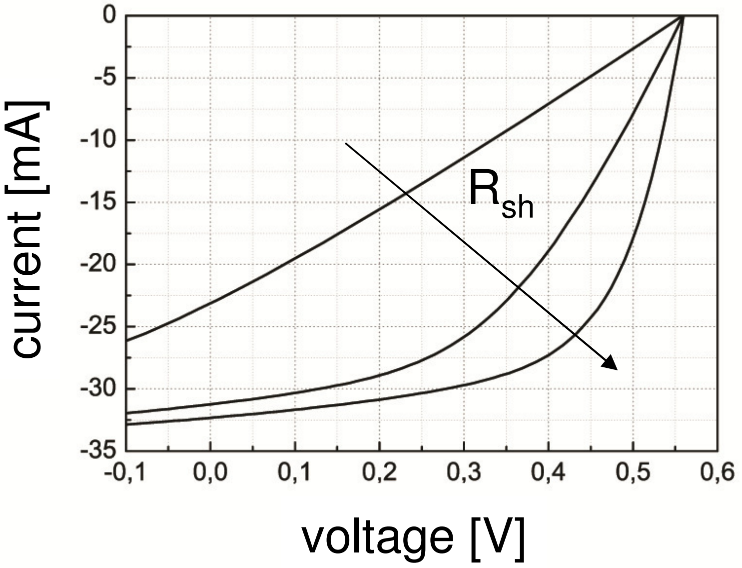


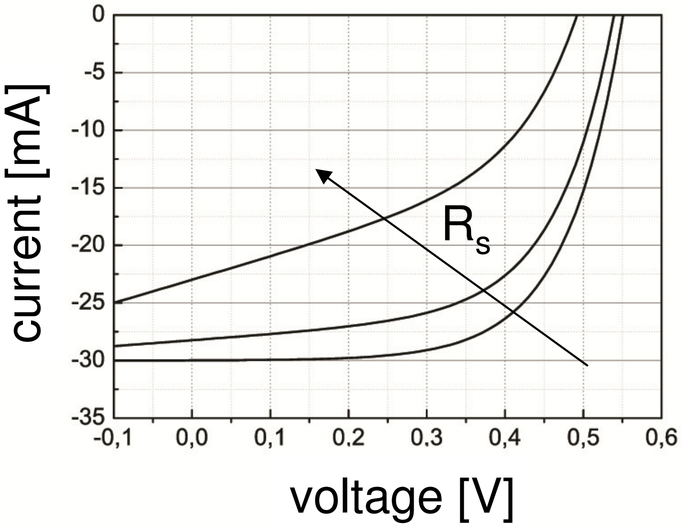


Front and rear surface texturing
can trap light for multiple passes
due to total internal reflection.

Resistive losses







shunt resistance
grains, edges, junction breakdown etc

series resistance
bulk absorber, contacts,
electrical connections, etc

Resistive losses

Series resistance consists of

✓ bulk resistance

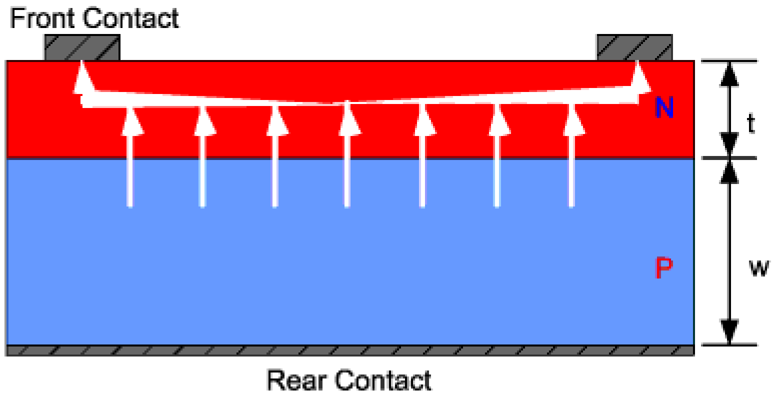
✓ emitter resistance

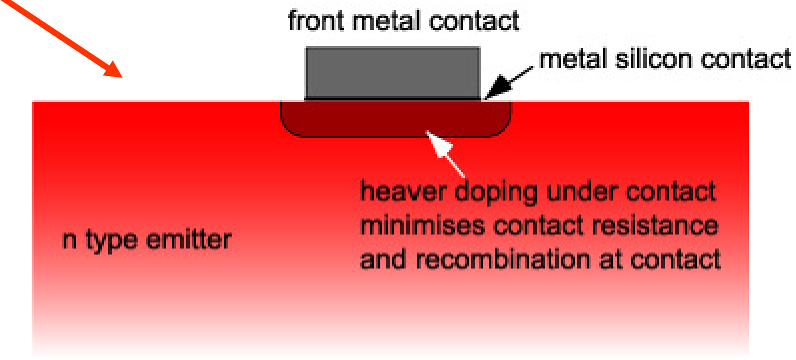
✓ metal-semiconductor contact resistance.

✓ fingers and bus bar resistance

optimum busbar width:

resistive loss = shadowing loss.





Effect of series and shunt resistance

effect on fill factor:

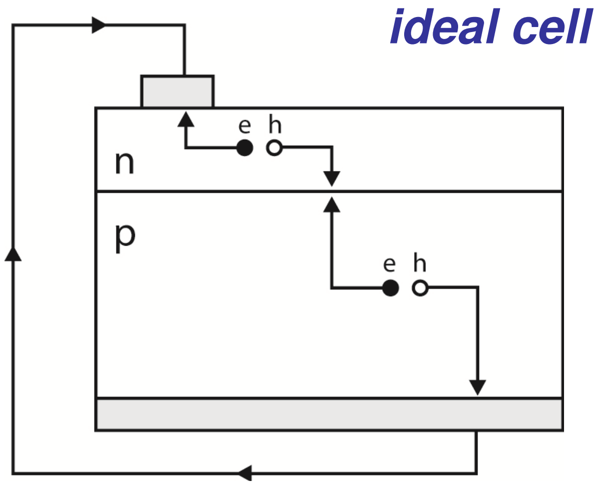
$FF=FF_0(1-r_s)$, $r_s=R_s/(V_{oc}/I_{sc})$

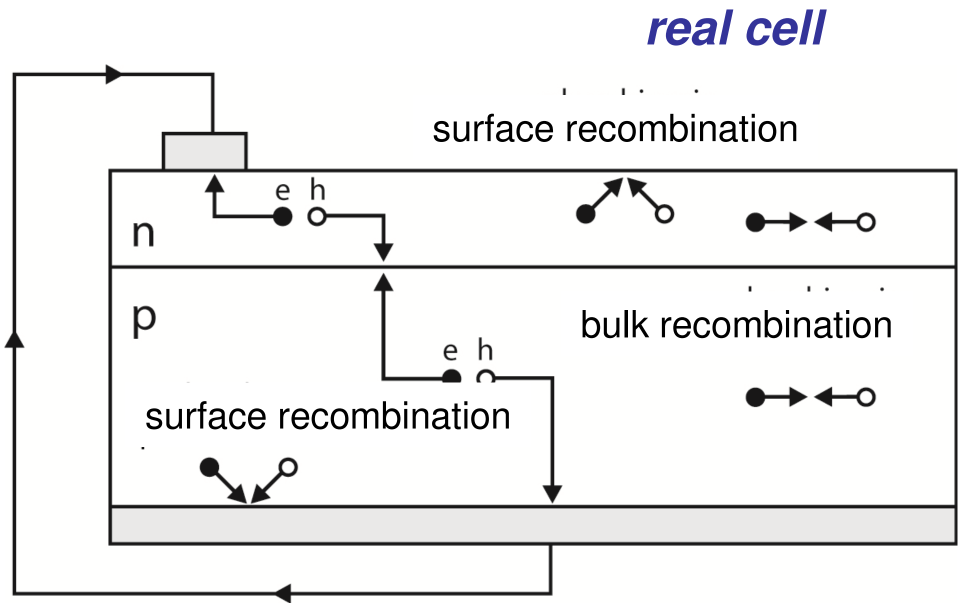
$FF=FF_0(1-1/r_{sh})$ $r_{sh}=R_{sh}/(V_{oc}/I_{sc})$

effect on illuminated current-voltage characteristics:

$$I_{ill}=I_o\left(\exp\left\{\frac{e(V-R_sI)}{Ak_BT}\right\}-1\right)+\frac{V-R_sI}{R_{sh}}-I_{sc}$$

Recombination losses contra collection

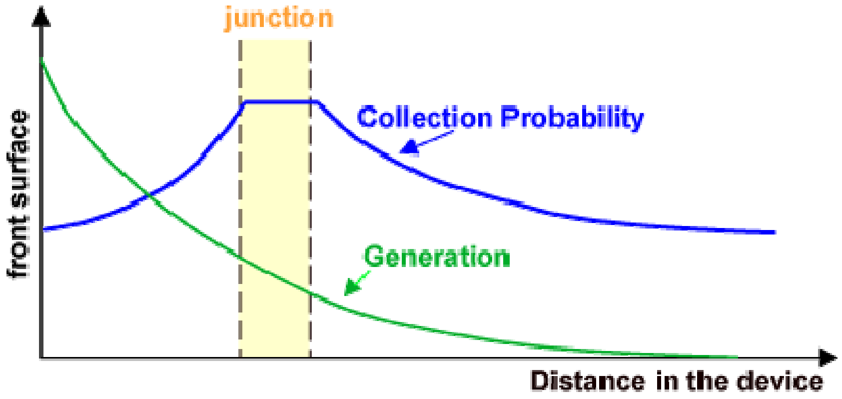




Type of recombination	Remedy
bulk recombination	high purity of bulk material
surface recombination	surface passivation (SiN, SiO)
recombination at metal –semi conductor contact	heavy doping of the contact region (BSF)

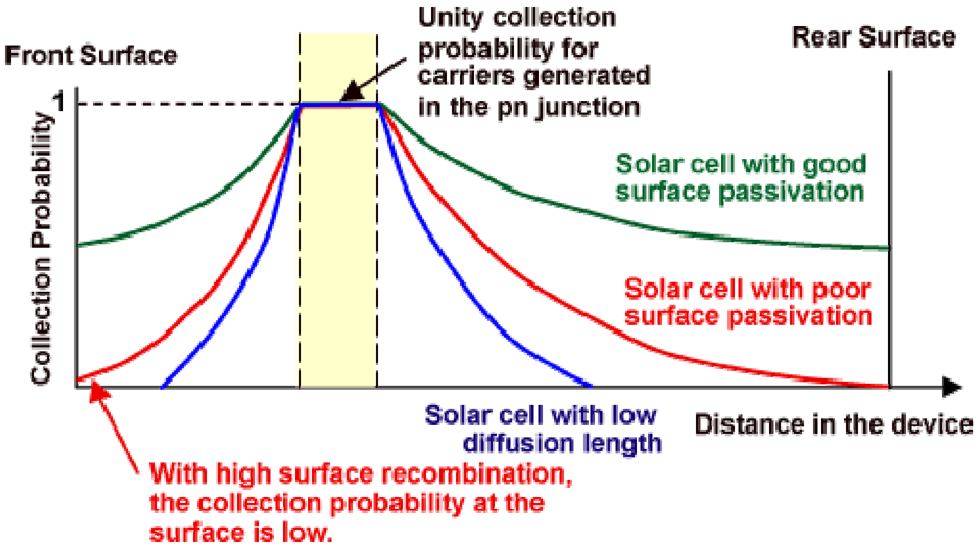
recombination losses – lifetime τ of photoexcited carriers

Collection probability of photogenerated carriers



W - thickness of the device;
$\alpha(\lambda)$ - absorption coefficient;
H_0 - number of photons at each wavelength

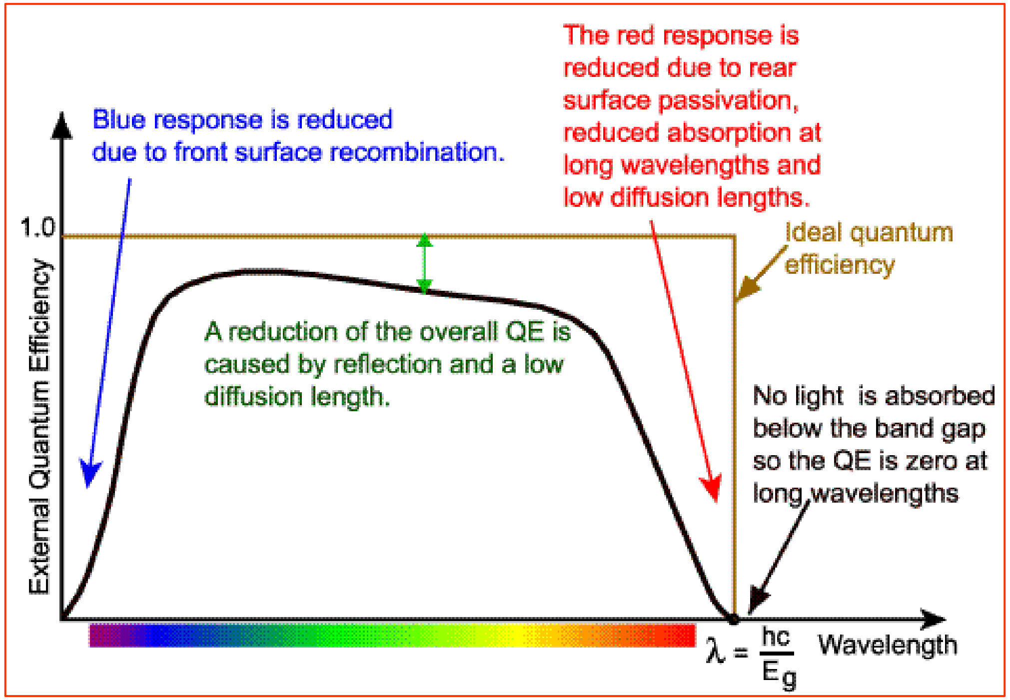
$$J_L = q\int_0^W \underbrace{G(x)}_{\text{generation rate}}\,\underbrace{CP(x)}_{\text{collection probability}}\,dx = q\int_0^W \left[\int \alpha(\lambda) H_0 \exp(-\alpha(\lambda)x)\, d\lambda\right] CP(x)\,dx$$



Quantum efficiency

Ideal case:QE=1 **$QE= 1-\exp\{-\alpha W(U)\}/(1+\alpha L_D)$**

W - depletion width
L_D - diffusion length



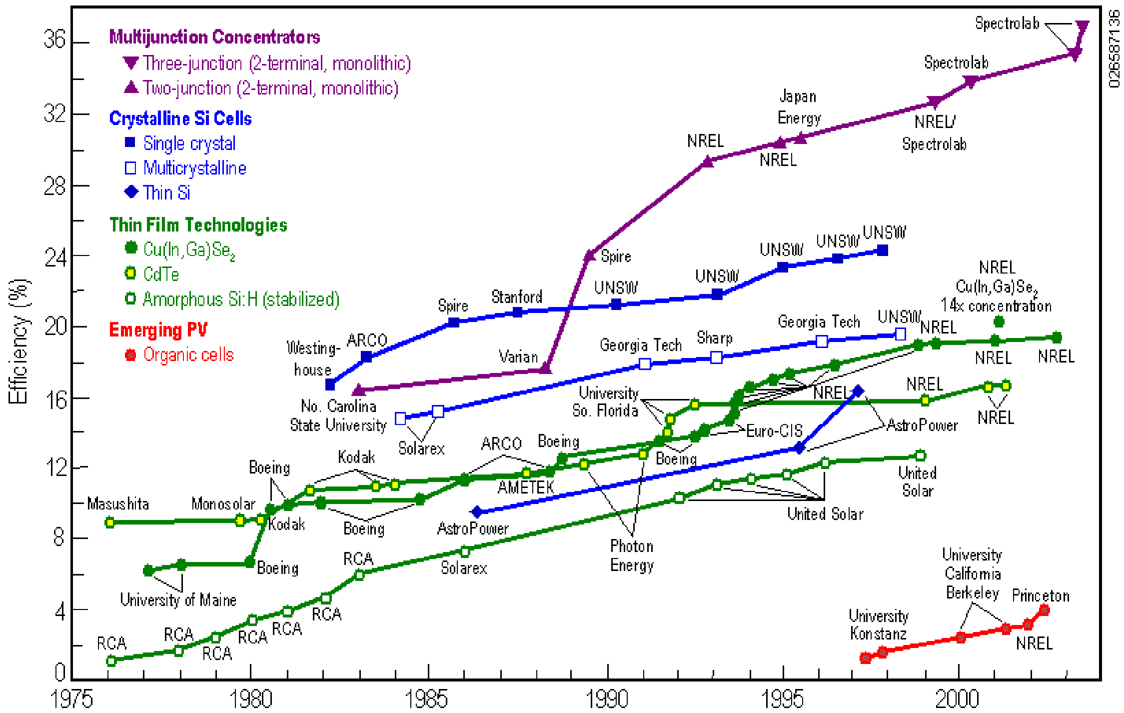
Efficiency losses in a standard c-Si cell

η = 16.6%

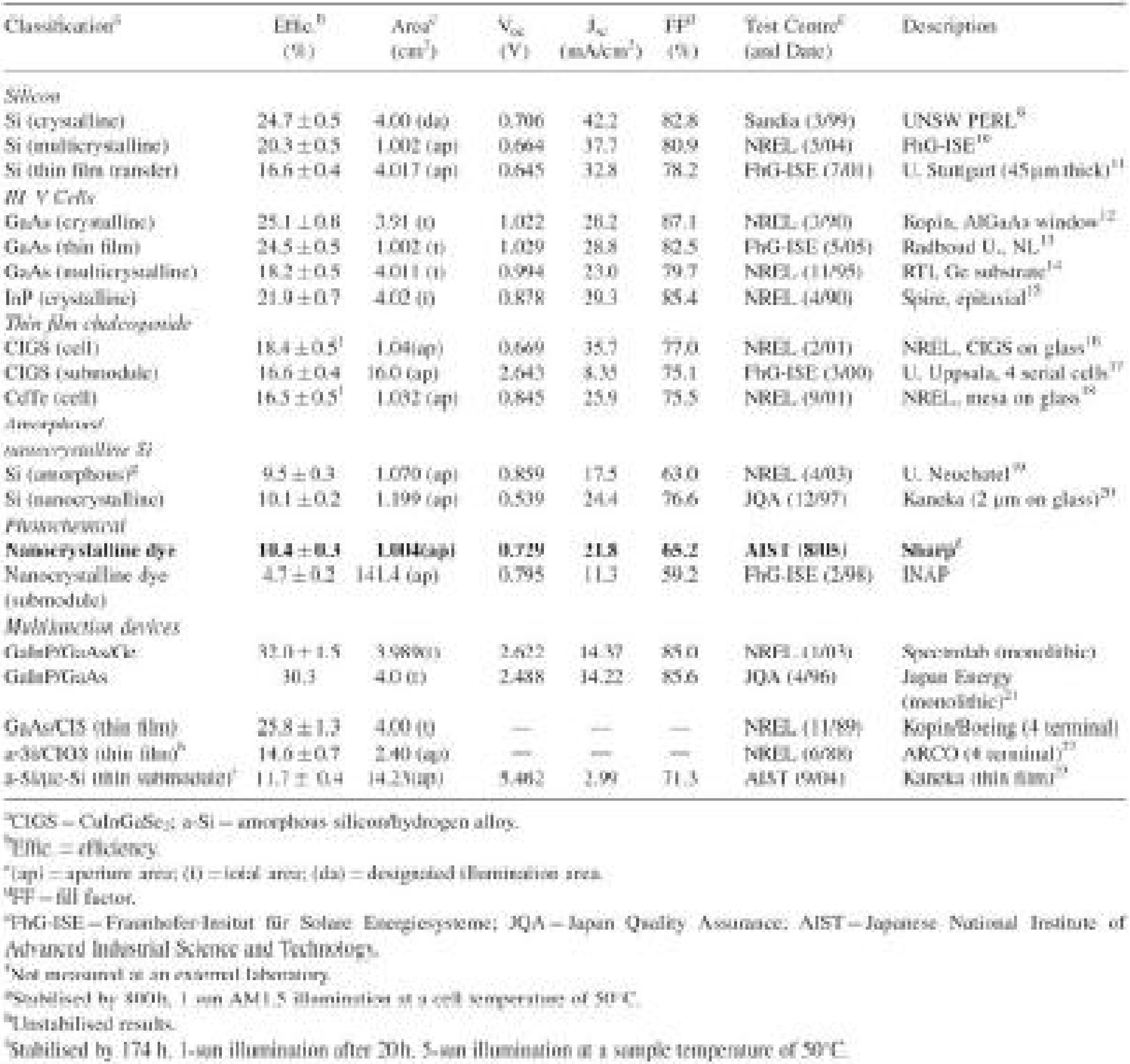
grid coverage	4%
reflection loss	3%
$h\nu < E_g$	18.8%
$h\nu > E_g$	29.2%
collection loss (0.9)	4.5%
$qV_{oc} < Eg$	19.2%
FF=0.78	4.7%

Best Research-Cell Efficiencies

www.nrel.gov/ncpv/thin_film/docs/kaz_best_research_cells.ppt



	Eff. (%)	*Voc (V)*	*Jsc (mA/cm^2)*	*FF (%)*
Si-c	**24.7**	**0.706**	**42.2**	**82.8**
Si-μc	**19.8**	**0.654**	**38.1**	**79.5**
InP-c	**21.9**	**0.878**	**29.3**	**85.4**
a-Si (module)	**12.0**	**12.5**	**1.3**	**73.5**
GaAs (thin film)	**23.3**	**1.011**	**27.6**	**83.8**
CIGS	**18.4**	**0.669**	**35.7**	**77.0**
CIGS (module)	**16.6**	**2.643**	**8.35**	**75.1**
CdTe (cell)	**16.4**	**0.848**	**25.9**	**74.5**
CdTe (module)	**10.6**	**6.565**	**2.26**	**71.4**
Nanocr. dye	**6.5**	**0.769**	**13.4**	**63.0**



Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[d] (%)	Test Centre[e] (and Date)	Description
Silicon							
Si (crystalline)	24.7 ± 0.5	4.00 (da)	0.706	42.2	82.8	Sandia (3/99)	UNSW PERL[9]
Si (multicrystalline)	20.3 ± 0.5	1.002 (ap)	0.664	37.7	80.9	NREL (5/04)	FhG-ISE[10]
Si (thin film transfer)	16.6 ± 0.4	4.017 (ap)	0.645	32.8	78.2	FhG-ISE (7/01)	U. Stuttgart (45 μm thick)[11]
III–V Cells							
GaAs (crystalline)	25.1 ± 0.8	3.91 (t)	1.022	28.2	87.1	NREL (3/90)	Kopin, AlGaAs window[12]
GaAs (thin film)	24.5 ± 0.5	1.002 (t)	1.029	28.8	82.5	FhG-ISE (5/05)	Radboud U., NL[13]
GaAs (multicrystalline)	18.2 ± 0.5	4.011 (t)	0.994	23.0	79.7	NREL (11/95)	RTI, Ge substrate[14]
InP (crystalline)	21.9 ± 0.7	4.02 (t)	0.878	29.3	85.4	NREL (4/90)	Spire, epitaxial[15]
Thin film chalcogenide							
CIGS (cell)	18.4 ± 0.5[f]	1.04(ap)	0.669	35.7	77.0	NREL (2/01)	NREL, CIGS on glass[16]
CIGS (submodule)	16.6 ± 0.4	16.0 (ap)	2.643	8.35	75.1	FhG-ISE (3/00)	U. Uppsala, 4 serial cells[17]
CdTe (cell)	16.5 ± 0.5[f]	1.032 (ap)	0.845	25.9	75.5	NREL (9/01)	NREL, mesa on glass[18]
Amorphous/ nanocrystalline Si							
Si (amorphous)[g]	9.5 ± 0.3	1.070 (ap)	0.859	17.5	63.0	NREL (4/03)	U. Neuchatel[19]
Si (nanocrystalline)	10.1 ± 0.2	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass)[20]
Photochemical							
Nanocrystalline dye	**10.4 ± 0.3**	**1.004(ap)**	**0.729**	**21.8**	**65.2**	**AIST (8/05)**	**Sharp**[f]
Nanocrystalline dye (submodule)	4.7 ± 0.2	141.4 (ap)	0.795	11.3	59.2	FhG-ISE (2/98)	INAP
Multijunction devices							
GaInP/GaAs/Ge	32.0 ± 1.5	3.989(t)	2.622	14.37	85.0	NREL (1/03)	Spectrolab (monolithic)
GaInP/GaAs	30.3	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy (monolithic)[21]
GaAs/CIS (thin film)	25.8 ± 1.3	4.00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal)
a-Si/CIGS (thin film)[h]	14.6 ± 0.7	2.40 (ap)	—	—	—	NREL (6/88)	ARCO (4 terminal)[22]
a-Si/μc-Si (thin submodule)[i]	11.7 ± 0.4	14.23(ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film)[23]

[a] CIGS = CuInGaSe$_2$; a-Si = amorphous silicon/hydrogen alloy.

[b] Effic. = efficiency.

[c] (ap) = aperture area; (t) = total area; (da) = designated illumination area.

[d] FF = fill factor.

[e] FhG-ISE = Fraunhofer-Institut für Solare Energiesysteme; JQA = Japan Quality Assurance; AIST = Japanese National Institute of Advanced Industrial Science and Technology.

[f] Not measured at an external laboratory.

[g] Stabilised by 800h, 1 sun AM1.5 illumination at a cell temperature of 50°C.

[h] Unstabilised results.

[i] Stabilised by 174 h, 1-sun illumination after 20h, 5-sun illumination at a sample temperature of 50°C.

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Equations for solar cell operation

$$\frac{\partial \hat{E}}{\partial x} = \frac{\rho}{\varepsilon} = p + N_D^+ - n - N_A^-$$ distribution of electric field

$$J_n = q\mu_n n\hat{E} + qD_n \frac{dn}{dx}, \quad J_p = q\mu_p p\hat{E} + qD_p \frac{dp}{dx}$$ current transport

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G_n - U_n, \quad \frac{\partial p}{\partial t} = \frac{1}{q}\frac{\partial J_p}{\partial x} + G_p - U_p$$ continuity equations

$$G = \alpha N_S \exp(-\alpha x) \quad carriers\,\sec^{-1} cm^{-3}$$ generation

$$U_n = \frac{\Delta n}{\tau_n} \quad U_p = \frac{\Delta p}{\tau_p}$$ recombination – bulk (Auger, radiative, SRH) and surface