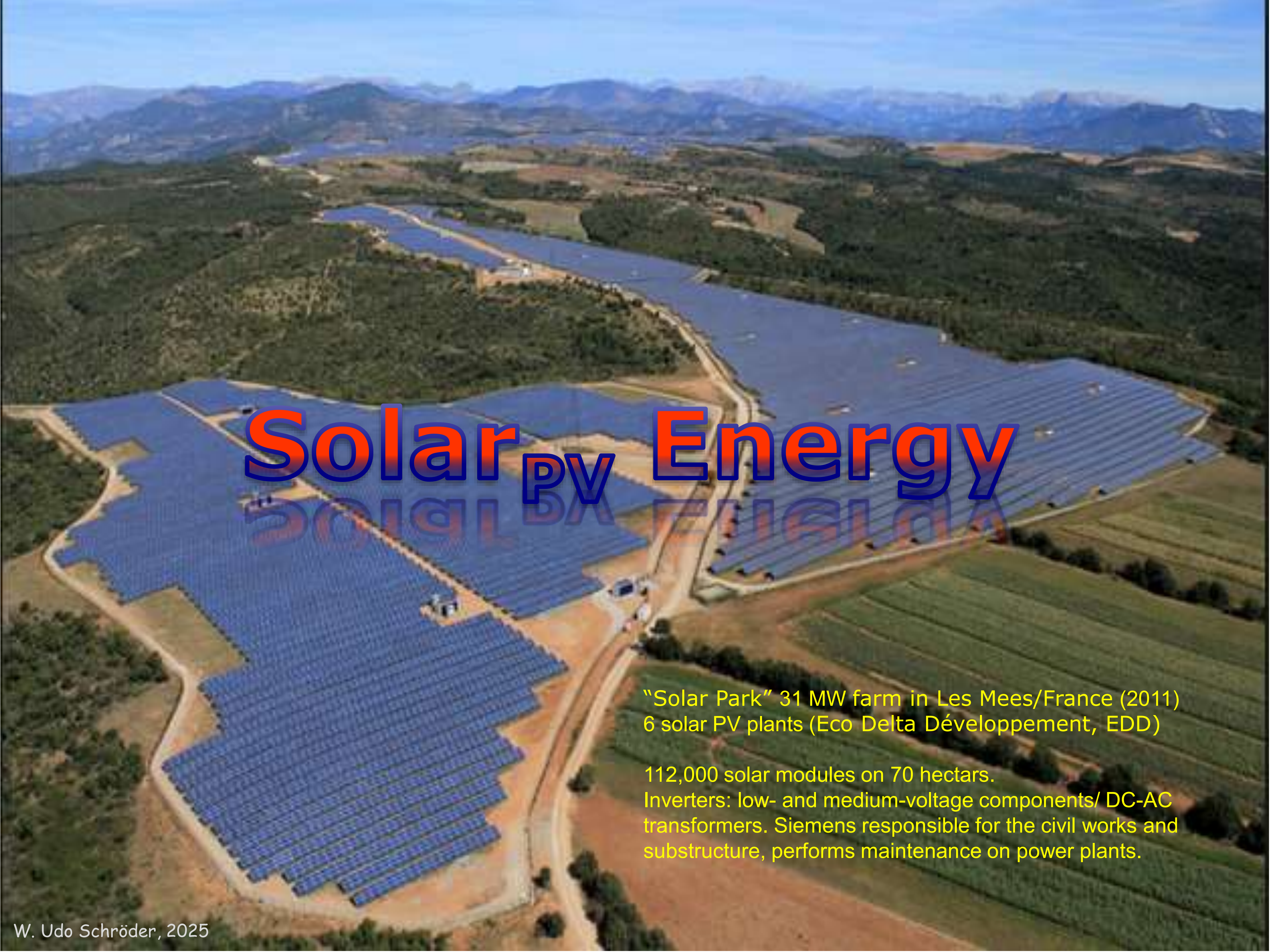
Solar$_{\text{PV}}$ Energy



“Solar Park” 31 MW farm in Les Mees/France (2011)
6 solar PV plants (Eco Delta Développement, EDD)

112,000 solar modules on 70 hectars.
Inverters: low- and medium-voltage components/ DC-AC transformers. Siemens responsible for the civil works and substructure, performs maintenance on power plants.

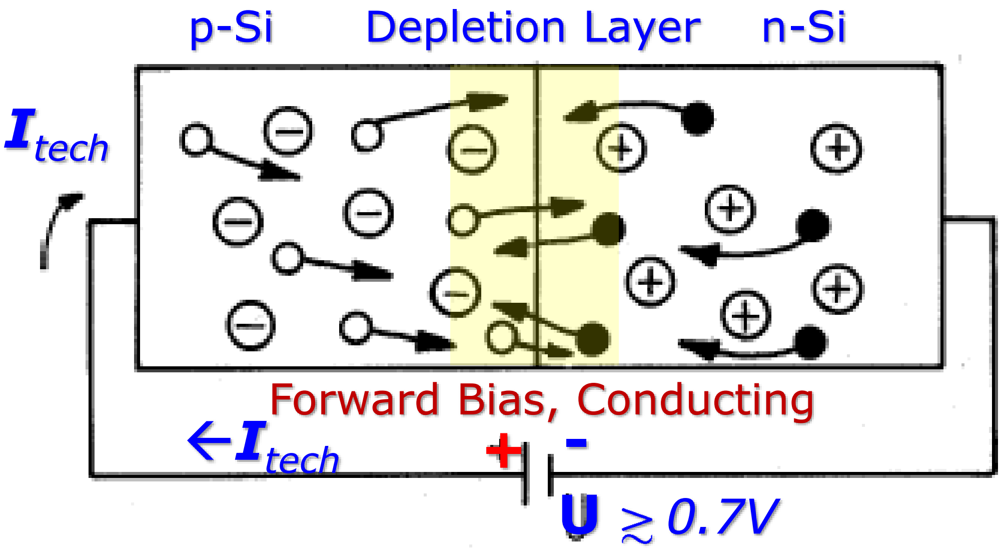
Agenda: RenE Solar PV Energy Conversion

- Intro: Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays

- Silicon solar photo-voltaic (PV) technology
  - Semiconductor band structure, gap, junctions
  - Charge carriers in n-type and p-type semiconductors
  - Photocell operation, efficiency
  - Silicon wafer, cell manufacture
  - Materials and emissions in construction

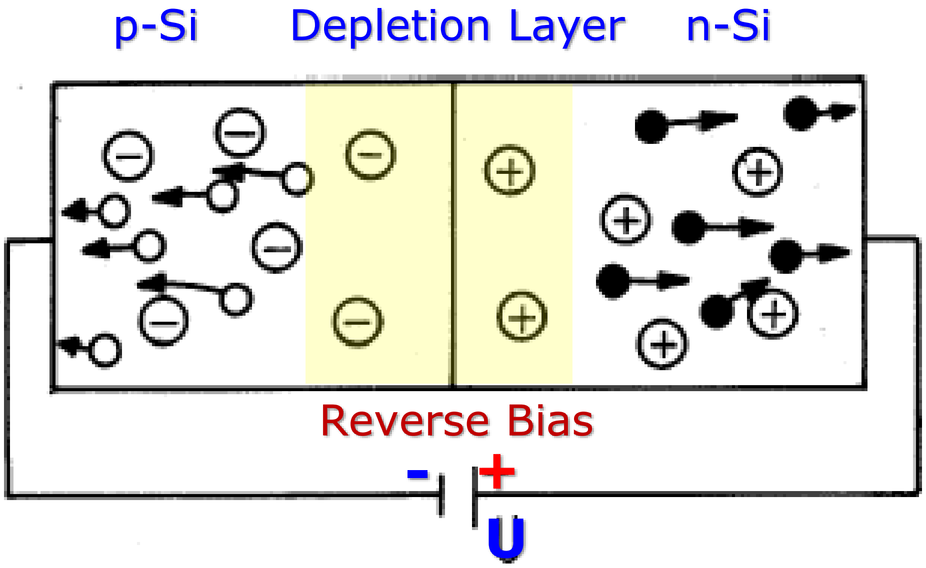
- US and World installations and performance, system cost and incentives
- Solar power strategic issues

p-n Junction Diode

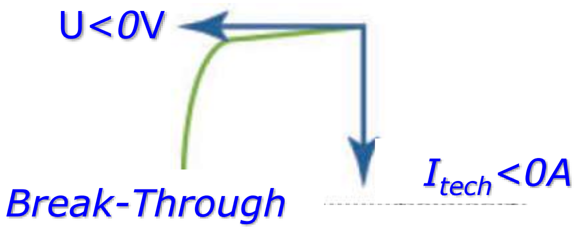


Cross diffusion of ***e^-*** and ***h^+*** in junction zone → recombination & Potential E diffusion barrier B(Si)=0.7eV → Depletion Layer (DL): has no free charge carriers

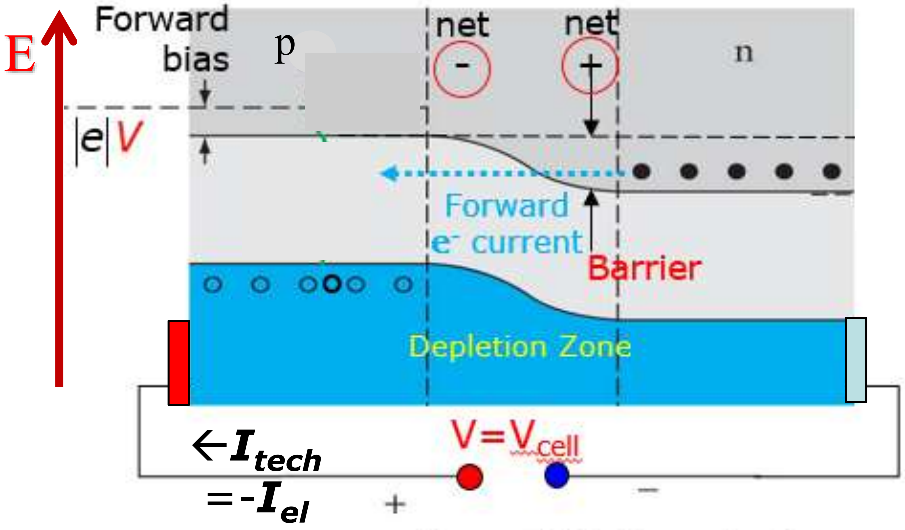
Forward bias $U \gtrsim +0.7V$ (@Si) reduces barrier & width of DL: n-Si electrons move through p-Si part → ≈"short circuit"



Reverse bias $U < 0V$ *increases* barrier & width of DL: n-Si electrons are repelled from DL through → ≈"open circuit"



Semiconductor Junction Diodes



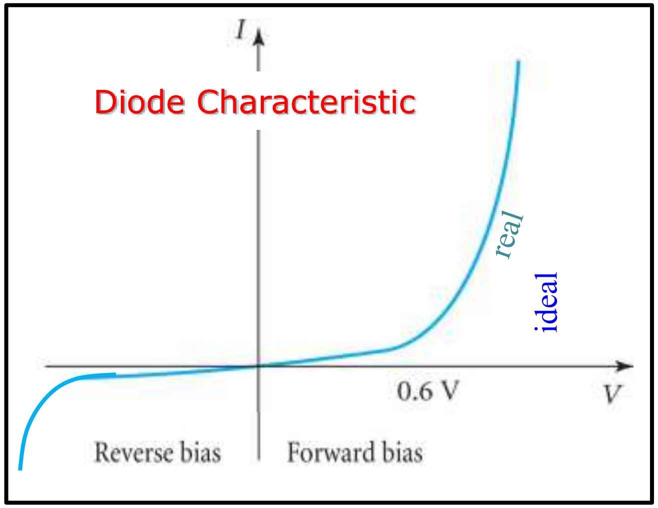
Forward bias lowers barrier

Forward: normal $I_{el} = -I_{tech}$: n→p across junction due to thermal→

No Bias applied *→ I ≈ 0*

Applied forward bias lowers barrier *→ I ≠ 0, increases. Opto-induced current in opposite direction*

Applied reverse bias: smaller p→n reverse e^- current due to thermal transitions over higher barrier. → *Diode Characteristic*



$$Normal\ Dark\ Current\ tunneling \sim I_{sat}$$

$$\rightarrow in\ normal\ n \rightarrow p\ (diode\ conduction)\ direction$$

$$External\ bias \rightarrow$$

$$V = V_{cell} - induced : I(V) = I_{sat} \cdot \left\{ e^{+e \cdot V/kT} - 1 \right\}$$

$$Ambient\ T: \quad kT = 25\ meV\ @\ T = 293K$$

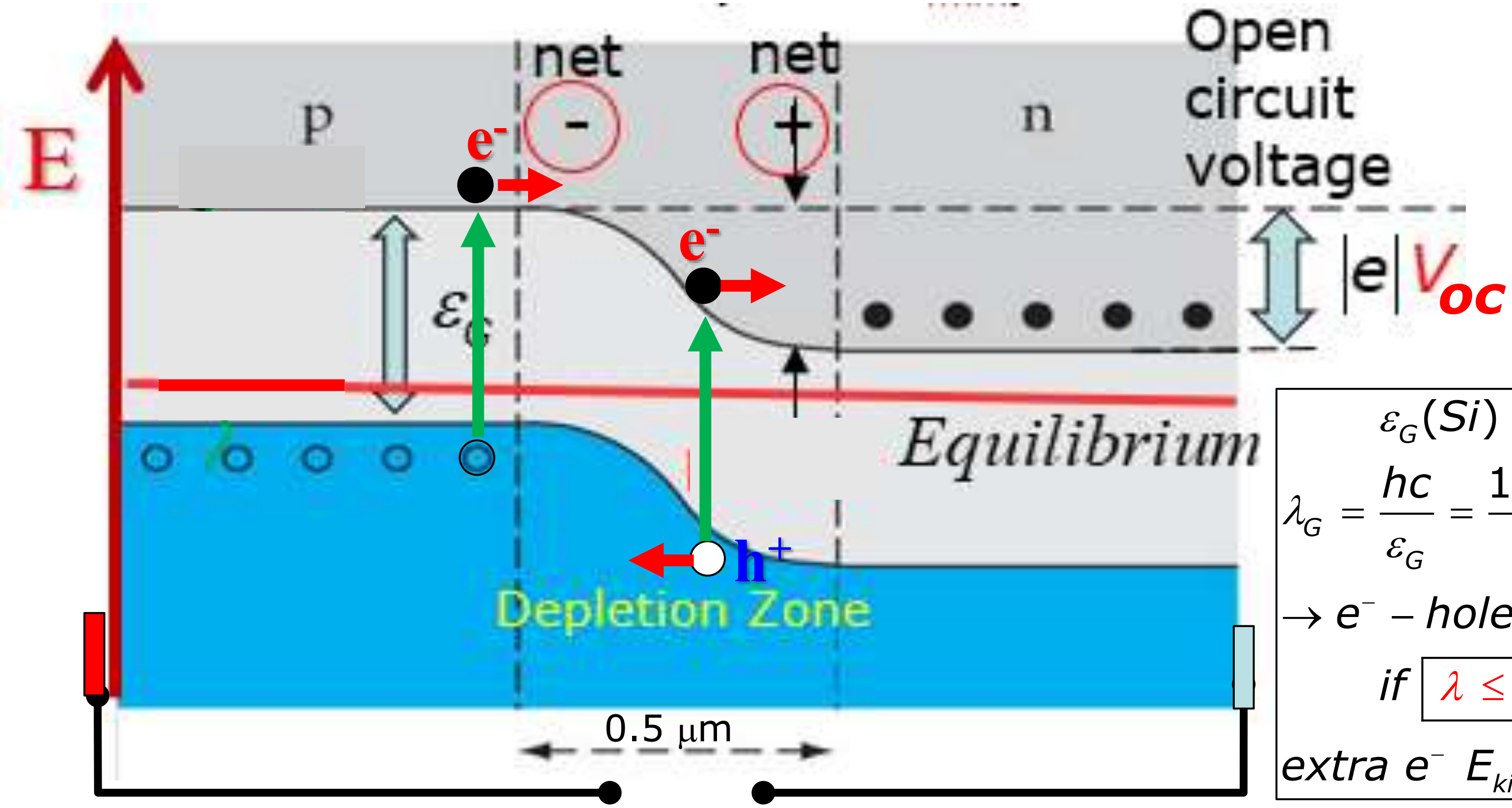
$$Elementary\ charge\ e,$$

$$"Saturation"("dark", "field")\ current\ I_{sat}$$

Semiconductor Junction Diode

In asymmetric junction zone, no free charge carriers (e$^-$ or holes) → Depletion Zone. Extra + charges in n-region → e- have lower energy (more strongly bound). Equivalent to effective barrier preventing additional migration of charges→ charge-free zone (except thermal e flow to left) But photo excitons → photo electrons go to the right →

photo holes go to the left ← !



$$\varepsilon_G(Si) = 1.1\ eV$$

$$\lambda_G = \frac{hc}{\varepsilon_G} = \frac{1.24\,eV}{\varepsilon_G}\ \mu m$$

$$\rightarrow e^- - hole\ excitation$$

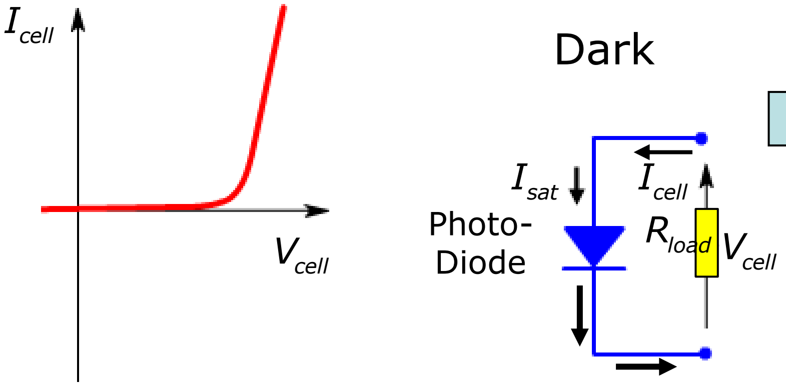
$$if\ \boxed{\lambda \le \lambda_G}$$

$$extra\ e^-\ \ E_{kin}\ dissipates$$

Cell Equivalent Electronic Circuits

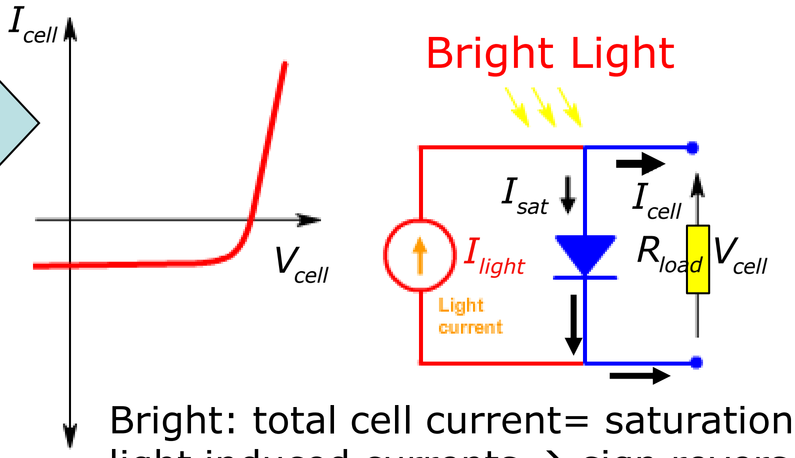
Ohm's Law: I_{cell} can be measured @ R_{load} → scan by changing R_{load}

Dark



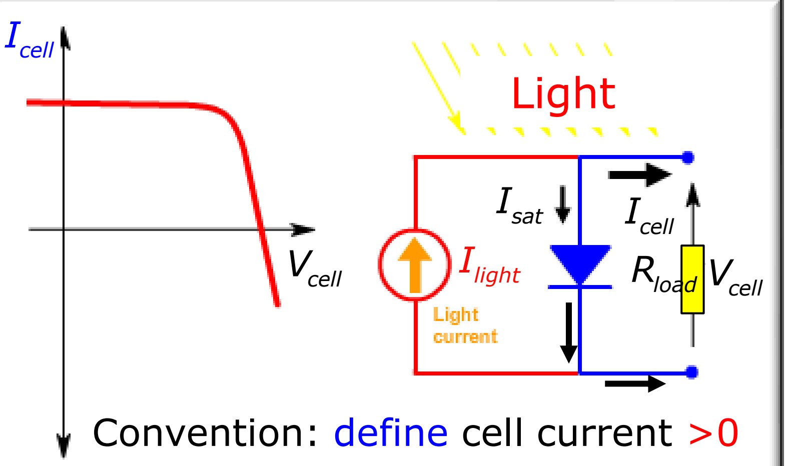
Dark: normal diode functions, "saturation" dark current, $\boldsymbol{R}_{load} \approx \infty$

Bright Light



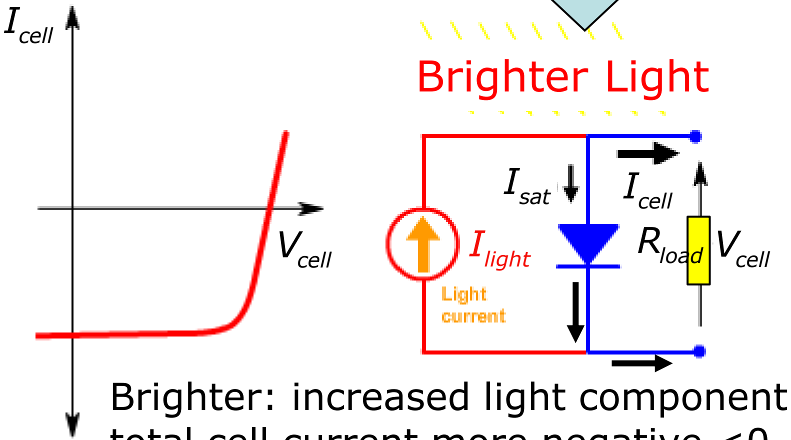
Bright: total cell current= saturation – light induced currents → sign reversed

Light



Convention: define cell current >0

Brighter Light

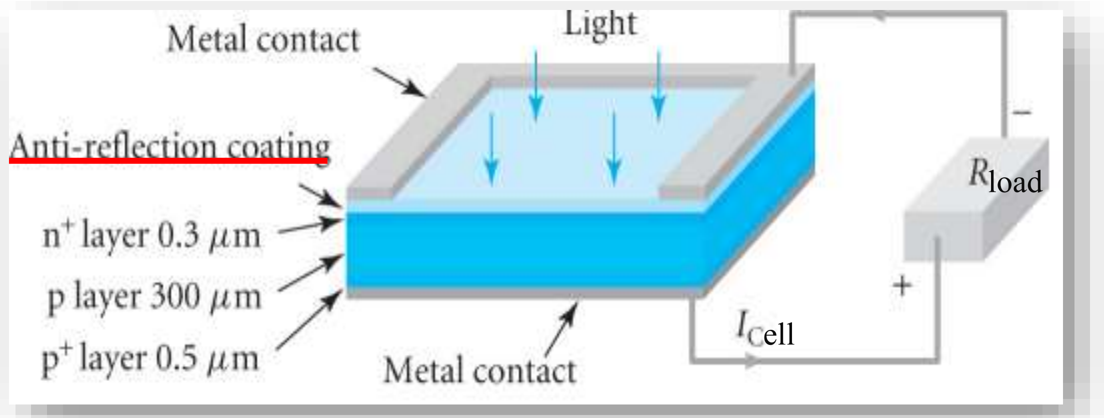


Brighter: increased light component → total cell current more negative <0

By Convention

Observables in Photocell Operation

Observables: V_{cell}, I_{cell}



⁺ indicates extra doping, lower resistance.

Light sensitive (solar) cell
mode of operation

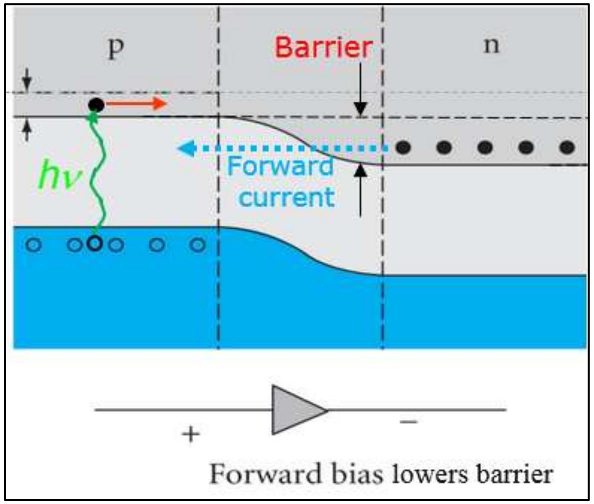
Ohm's Law $I_{cell} = V_{cell}/R_{Load}$

"Thermal voltage" $\rightarrow I_{sat}$

$V_{th} := kT/e = 25mV$

I_{cell} dependence on R_{load}

Photon $h\nu$ produces e⁻/hole pair in *p* domain & *DZ* →
→ inverse current of electrons (holes equivalent)



$$I_{cell} = I_{Light} - I_{sat}\cdot\left\{e^{e\cdot V_{cell}/kT} - 1\right\} =$$

↳ $\vec{I}_{Light} \uparrow\downarrow \vec{I}_{sat}$

$$= I_{Light} - I_{sat}\cdot\left\{e^{R_{Load}\cdot I_{cell}/V_{th}} - 1\right\}$$

$R_{Load} \rightarrow \infty$ (*open circuit*): $I_{cell} \rightarrow 0$, $V_{cell} =: V_{OC}$

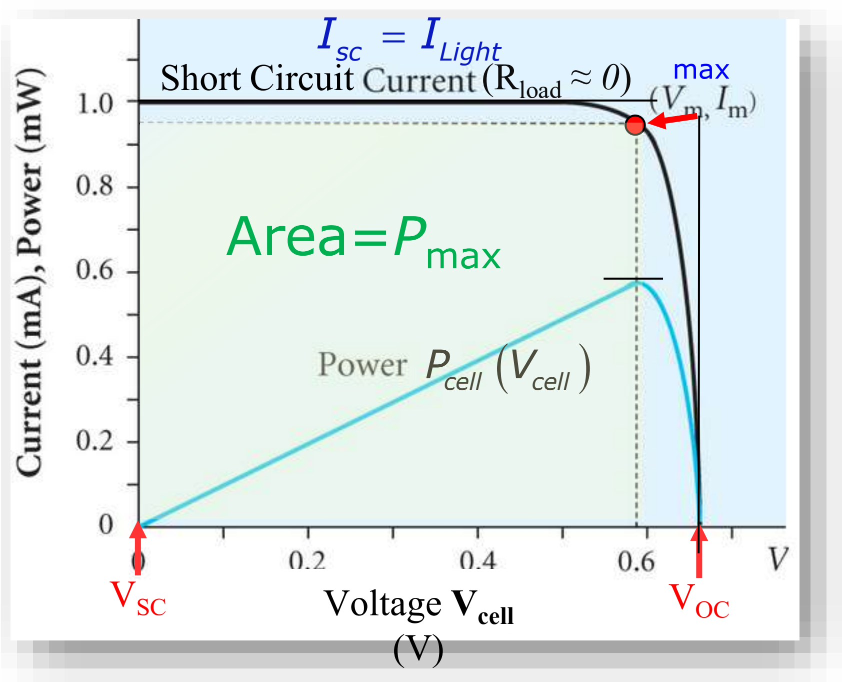
$$V_{OC} = V_{th}\cdot Ln\left[1 + \frac{I_{Light}}{I_{sat}}\right] \approx V_{th}\cdot Ln\left[\frac{I_{Light}}{I_{sat}}\right] \Rightarrow$$

$$\boxed{\begin{array}{l} V_{OC} = \left(V_{cell}\right)_{max} \\ I_{Light} \gg I_{sat} \end{array}}$$

$R_{Load} = 0$ (*short circuit*): $I_{cell} = I_{sc} = I_{Light}$

Cell Power Characteristic

Cell Current-Voltage Characteristic



Power P_{cell} generated by illuminating cell, scan by varying light intens. or R_{load}

$(R_{Load} \ll R_{diode}) \rightarrow (R_{Load} > R_{diode})$

Rise and fall between short-circuit (SC) ($\boldsymbol{V_{cell}} \approx 0$) and open circuit ($\boldsymbol{I_{cell}} \approx 0$).

Between above limits, power evolution :

$$P_{cell} = I_{cell} \cdot V_{cell}$$

$$P_{cell} = I_{cell}^2 \cdot R_{load} \quad (Ohm's\ Law)$$

Current $\boldsymbol{I_{cell}}$ and power $\boldsymbol{P_{cell}}$ decrease with decreasing light intensity.

Typical nominal values: $\boldsymbol{I_{cell}}$ = 1mA, $\boldsymbol{I_{sat}}$ **=** 10^{-12} A, $\boldsymbol{V_{OC}}$ **=** 0.66 V,

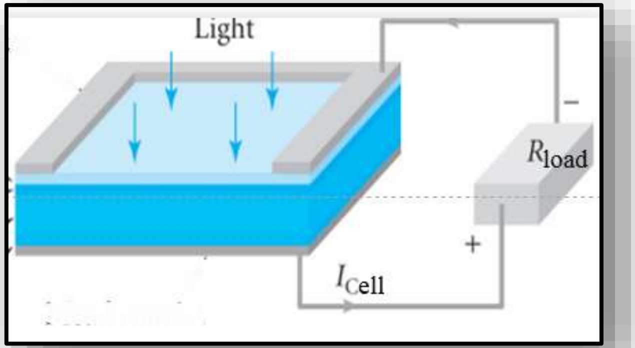
Actual $\boldsymbol{P_{cell}} \leq \boldsymbol{P_m}$=0.58 mW, $\boldsymbol{V_{cell}} \leq V_m$=0.58V →const $\boldsymbol{I_{cell}} \leq I_m = I_{sc}$=0.95 mA

$$\text{"}Fill\ Factor\text{"}: FF = P_{\max} / (I_{SC} \cdot V_{OC})$$

$$Deduce\ from\ \{I_{SC}, V_{OC}\} \rightarrow P_{\max} = FF \cdot I_{SC} \cdot V_{OC}$$

FF=Ratio of area under power curve to limiting rectangle→ measure of steepness (ideal) of diode I-V characteristic.

Example



Given: *1-cm²* photocell with saturation current $I_{sat} = 2\cdot 10^{-12}A$ and short-circuit current $I_{sc} = 30mA$.

Calculate the expected maximum power output P_{max} *and the load resistance* R_{Load} *required for max power.*

Thermal voltage

$V_{th} := kT/e = 25mV$

Ohm's Law

$V_{cell} = I_{cell} \cdot R_{Load}$

$$R = 0\ (short\ circuit): \quad I_{sc} = I_{Light} = 30mA$$

$$Thermal\ V_{th} = 0.025V,\ I_{sat} = 2\cdot 10^{-12}A$$

$$V_{OC} \approx V_{th}\cdot Ln\left[\frac{I_{Light}}{I_{sat}}\right] = 0.025V\cdot Ln\left[\frac{30\cdot 10^{-3}A}{2\cdot 10^{-12}A}\right]$$

$$V_{OC} \approx 0.59V$$

$$I_{cell}(V_{cell}) = I_{Light} - I_{sat}\cdot\left\{e^{V_{cell}/V_{th}} - 1\right\}$$

$$= 30mA + 2\cdot 10^{-12}A\cdot\left\{1 - e^{V_{cell}/0.025V}\right\}$$

V_{cell} and I_{cell} can be chosen independently via light int. and R_{load}

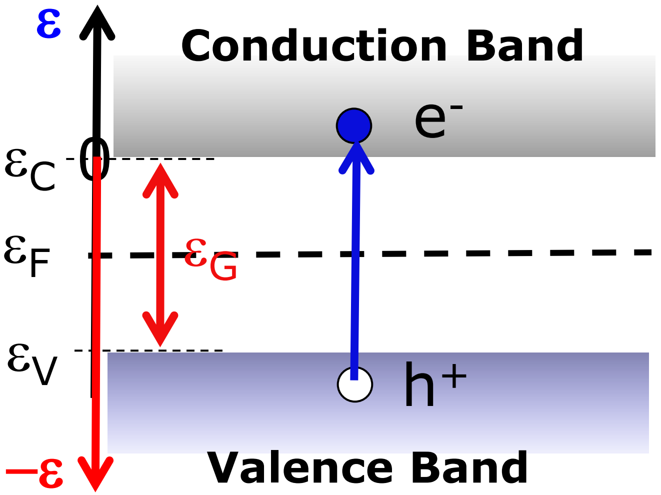
$$\rightarrow P_{cell}(V_{cell}) = I_{cell}\cdot V_{cell} \quad \rightarrow search\ (numerically)\ for\ V_{cell} = V_{max},$$

$$for\ which\ P_{cell} = P_{max} \rightarrow R_{Load} = V_{cell}/I_{cell}$$

Choose this R_{Load} to maximize output power

$$Efficiency \rightarrow \varepsilon = \frac{P_{max}}{insolation\ power}$$

Thermal Currents in Semi-Conductors



$$\text{Define } \varepsilon_C := 0 \rightarrow \varepsilon_F = \varepsilon_C - \frac{\varepsilon_G}{2} = -\frac{\varepsilon_G}{2}$$

$$e^- : f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

$$h^+ : f_h(\varepsilon) = \left[1 + \exp\left(\frac{-\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

Small gaps ε_G (Ge) → large thermal currents.
Reduce by cooling, if possible.

Principle of conversion light → electricity with solar cells relies on near-perfect semi-conductor properties: full VB, empty CB.

Fermion statistics for e^-, h^+:

$$n_e(\varepsilon) = c \cdot \sqrt{\varepsilon} \cdot f_e(\varepsilon)$$

$$n_h(\varepsilon) = c \cdot \sqrt{|\varepsilon|} \cdot f_h(\varepsilon)$$

$$n_e = n_h, \quad kT \ll \varepsilon_G \rightarrow$$

$$f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon - \varepsilon_F}{kT}\right)\right]^{-1} \approx \exp\left(-\frac{\varepsilon + \varepsilon_G/2}{kT}\right)$$

$$\langle n_e^2 \rangle = n_e n_h = c^2 \cdot \langle \varepsilon \rangle \cdot \exp\left(-\frac{\varepsilon_G}{kT}\right)$$

Fermi Gas Parameters:

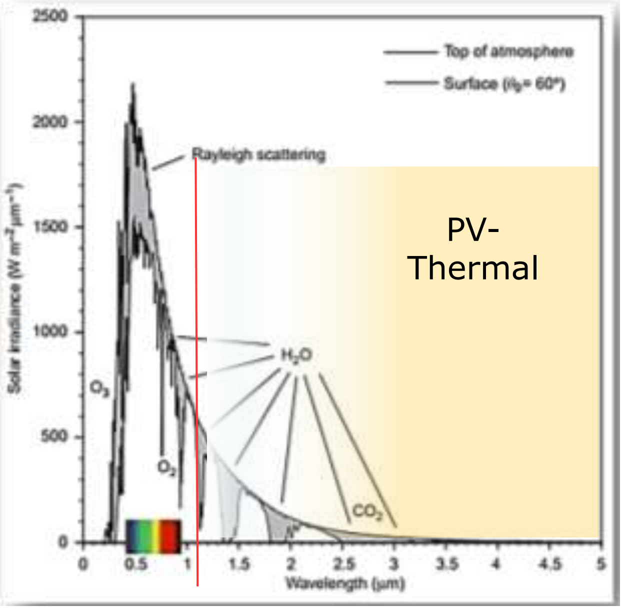
$$c := (2m)^{2/3} V / 2\pi^2\hbar^3$$

$$V := volume,\ m := mass$$

$$\boxed{\langle n_e \rangle_{rms} \sim \exp\left(-\frac{\varepsilon_G}{2kT}\right)} \propto I_{sat} \propto conductivity\ at\ T$$

⇨ High *T* reduces power output

Limits to Power Conversion Efficiency



Useful incoming photon power density *(j=I/area):*

$$j_\gamma = c\cdot\int_0^\infty n_\gamma(\varepsilon)\cdot\varepsilon\cdot d\varepsilon =$$

$$= c\cdot(kT)^4\int_0^\infty\frac{\varepsilon^3 d\varepsilon}{\left[e^\varepsilon-1\right]} = \frac{c\pi^4}{15}\cdot(kT)^4$$

$$\textit{Use app.}\int_x^\infty\frac{\varepsilon^2 d\varepsilon}{\left[e^\varepsilon-1\right]} = x^3e^{-x}+\ldots.$$

To excite *e-h* pairs in Si, photons need

$\varepsilon_\gamma > \varepsilon_G$ or $\lambda_\gamma < \lambda_G =$ *1.1* µ.

Def: $\varepsilon_G = e\cdot V_G$

→ Useful for Si: ≈75% of the insolation spectrum.

Number density of high-energy photons (#/m^2·s·eV) governed by Planck's (BB) radiation law (BE statistics)

$$n_\gamma(\varepsilon_\gamma) = c\cdot\varepsilon_\gamma^2\cdot f_\gamma(\varepsilon_\gamma);\quad f_\gamma(\varepsilon_\gamma) = \left[\exp\left(\frac{\varepsilon_\gamma}{kT}\right)-1\right]^{-1}\quad \textit{Boson statistics}$$

C (solid angle of acceptance for sunlight)→ Useful #γ = other γ's are not absorbed

$$N_\gamma = c\cdot\int_{\varepsilon G}^\infty n_\gamma(\varepsilon)\cdot d\varepsilon = c\cdot(kT)^3\int_{\varepsilon G}^\infty\frac{\varepsilon^2 d\varepsilon}{\left[e^\varepsilon-1\right]}\quad \textit{for area A}$$

Photo-electric current density $j_{light} = e\cdot N_\gamma$ (one e$^-$ per photon). Maximum possible cell power density (cm^{-2})

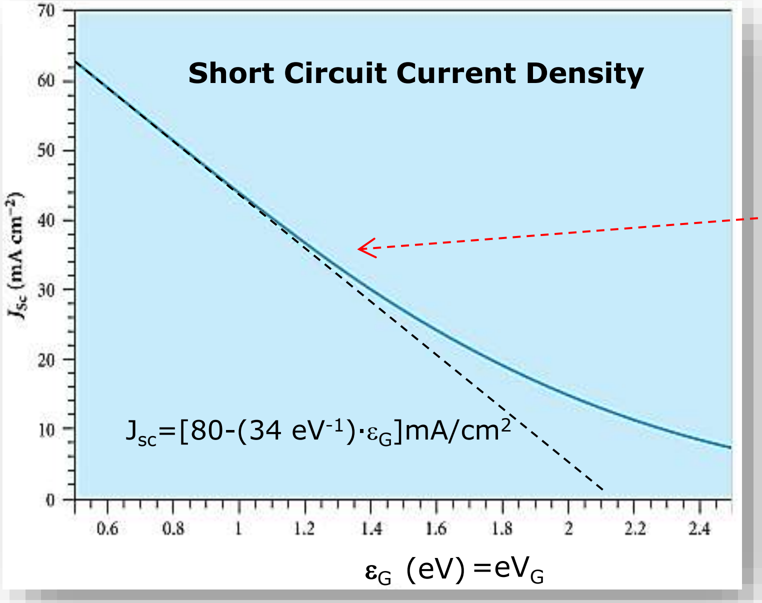
$j_{max} = \varepsilon_G\cdot N_\gamma = V_G\cdot j_{light} = V_G\cdot j_{sc}$

$$\underbrace{j_{light}}_{=j_{sc}} = e\cdot N_\gamma = c\cdot e\cdot(kT)^3\int_{\varepsilon_G}^\infty\frac{\varepsilon^2 d\varepsilon}{\left[e^\varepsilon-1\right]} = \frac{15e}{\pi^4 kT}\,j_\gamma\cdot\int_{\varepsilon_G}^\infty\frac{\varepsilon^2 d\varepsilon}{\left[e^\varepsilon-1\right]}$$

$$\boxed{j_{light} = j_{sc} \approx j_\gamma\cdot\left(\frac{15e}{\varepsilon_G\pi^4}\right)\left(\frac{\varepsilon_G}{kT}\right)^3\cdot e^{-\frac{\varepsilon_G}{kT}}}$$

Relation j_{sc} ←→ ε_G & *incoming photon* power density

Cell Efficiency ε_G Dependence



Calculate $P_{\max}$ with $\boxed{P_{\max} = FF \cdot I_{SC} \cdot V_{OC}}$

Approximate linear $(j_{SC} := I_{SC}/Si\ cell\ \ area)$

$$\boxed{j_{sc} \approx j_\gamma \cdot \left(\frac{15e}{\varepsilon_G \pi^4}\right)\left(\frac{\varepsilon_G}{kT}\right)^3 \cdot e^{-\frac{\varepsilon_G}{kT}} \approx A - B \cdot V_G}$$

$$V_{OC} \approx V_{th} \cdot Ln\left[I_{SC}/I_{sat}\right] = V_{th} \cdot Ln\left[j_{SC}/j_{sat}\right]$$

$e^- -$(Dark) current from $n-Si \rightarrow p-Si$

$j_{sat} \approx j_0 \cdot \exp(-\varepsilon_G/2kT)$ Boltzmann Factor

$j_0 \sim 2 \cdot 10^{+9}\ mA/cm^2$ ~ typical

$\rightarrow j_{sat}(\varepsilon_G = 1.1eV) \sim 10^{-9}\ mA/cm^2$

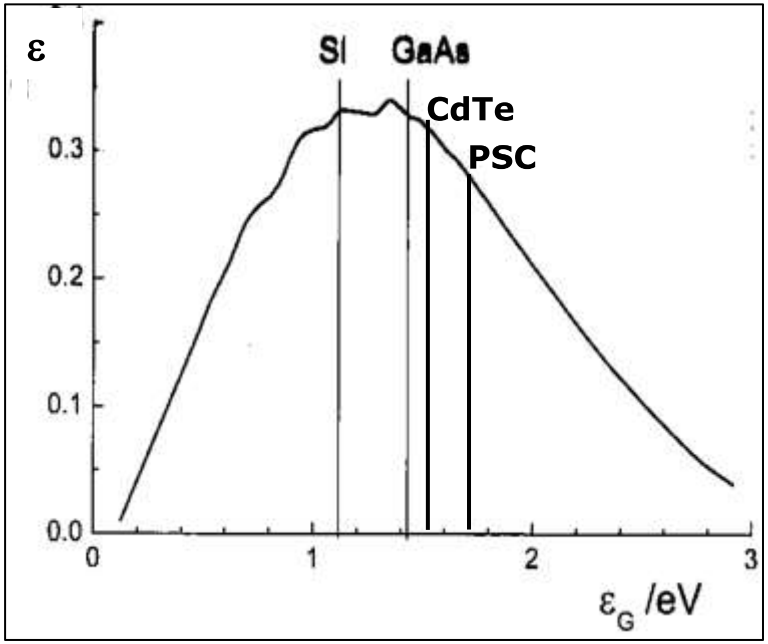
$$V_{OC} \approx V_{th} \cdot Ln\left[\frac{I_{SC}}{I_0} e^{+\varepsilon_G/kT}\right] = V_G - V_{th} \cdot Ln\left[\frac{I_0}{I_{SC}}\right] \rightarrow V_{OC} \approx V_G - 0.5V \text{ empirical}$$

$\rightarrow P_{\max} \approx FF \cdot (A - B \cdot V_G) \cdot (V_G - 0.5V)$ Empirical formula, $(V_G = \varepsilon_G/e)$.

$FF = 0.8 \rightarrow P_{\max} \approx 25mA/cm^2, \rightarrow \boxed{Efficiency\ \varepsilon(\varepsilon_G) = \frac{I_m \cdot V_m}{j_\gamma \cdot Area_{cell}} \le 0.35}$ (Shockley–Queisser)

more typical $\varepsilon = (17-20)\%$

Shockley-Queisser Cell Efficiency



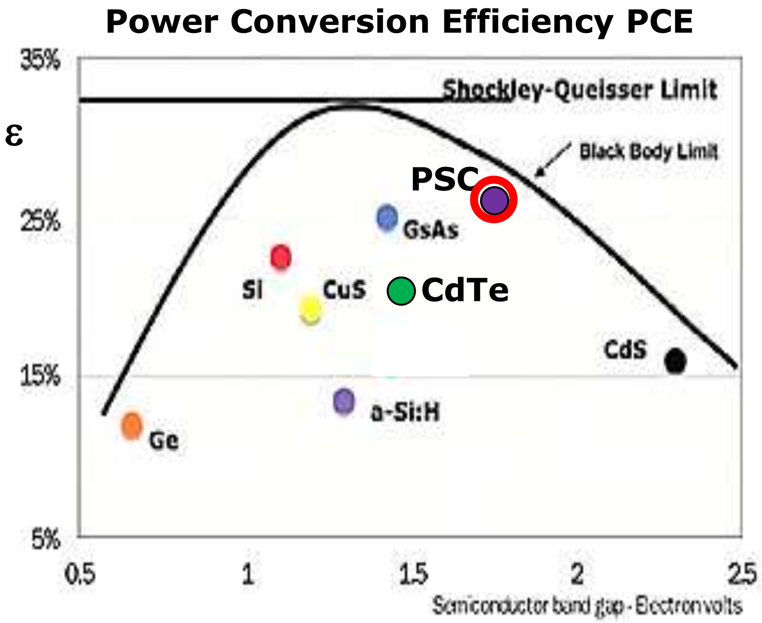
Actual (measured) single-junction solar cell power conversion efficiency for different semiconductor materials.

Theoretical S-Q limit calculated with single-crystal Si material, “1-Sun, A1.5 standard”, radiative recombination .

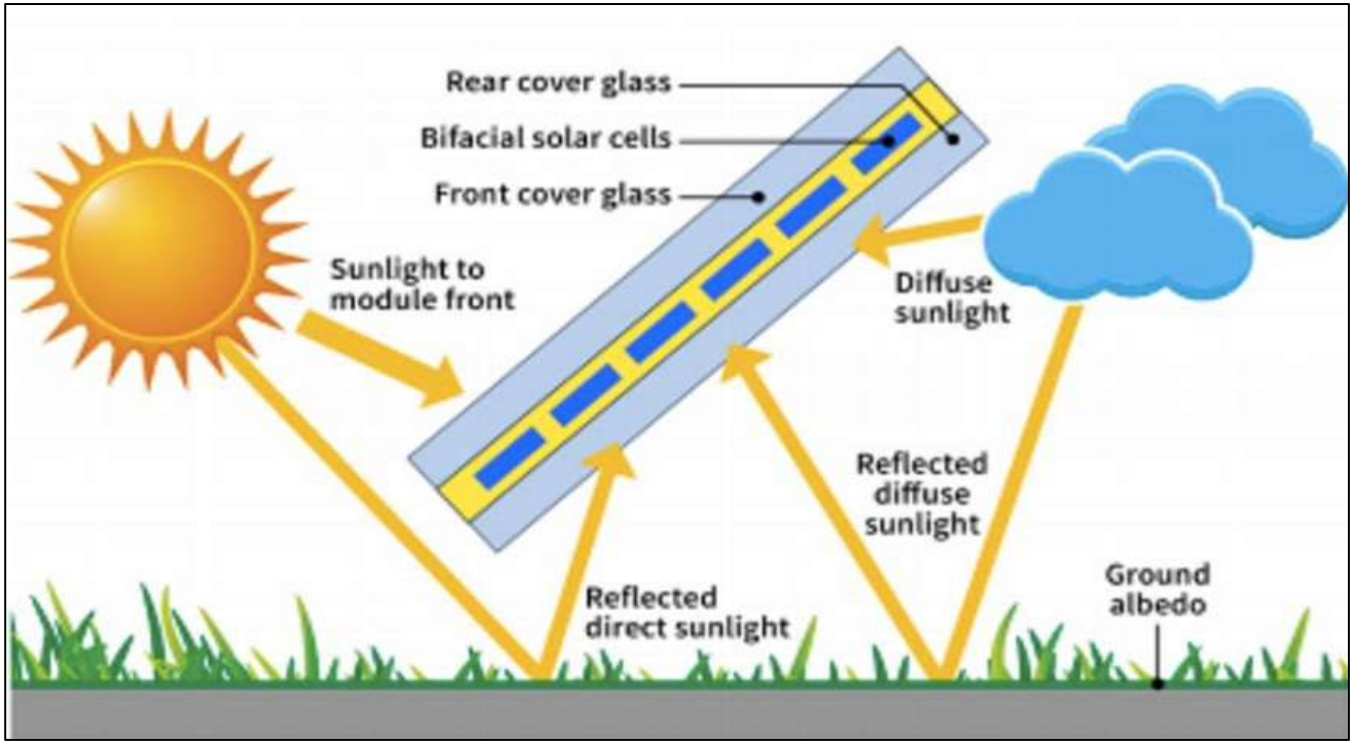
GaAs slightly better than Si but involves more fabrication steps, perovskite (PSC).

Dependence of solar cell maximum efficiency dependence on band gap energy. Max power transfer depends on energy gap ε_G.

Often used (much more economic) amorphous Si: $\varepsilon_G \sim (1.3\text{-}1.7\ \text{eV})$, Lower efficiency $\varepsilon = (12\text{-}13)\%$



New R&D: Bifacial PV Cells

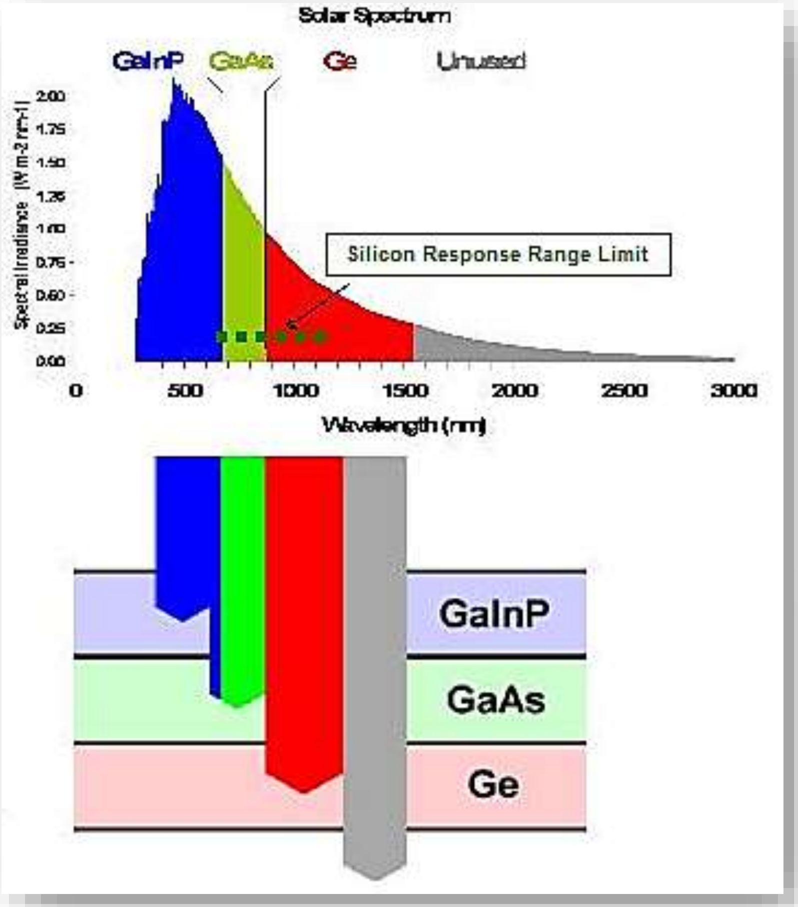


Reflected sunlight has same frequency as incoming light.

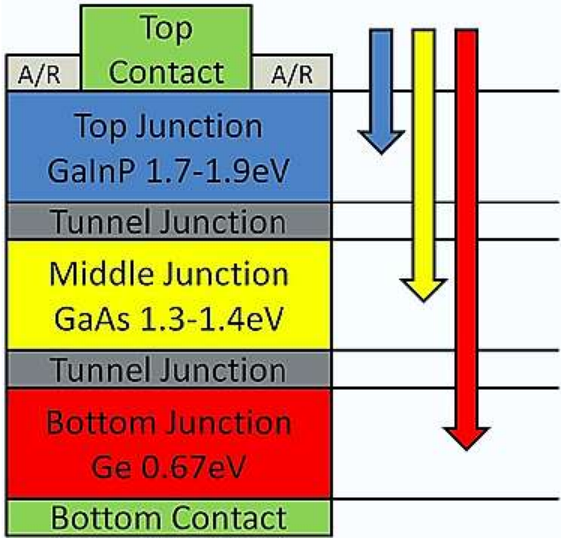
Study determined that two-sided, sun-tracking panels produce an average of 35% more energy than immobile single-panel systems and that they are 16% more cost-efficient.

That holds true even when accounting for changes in weather conditions.

New R&D: Multi-Junction Cells



Multi-junction cells are stacks of different semiconductors, differential absorbers of sequential parts of the spectrum.



A/R | Top Contact | A/R

Top Junction GaInP 1.7-1.9eV

Tunnel Junction

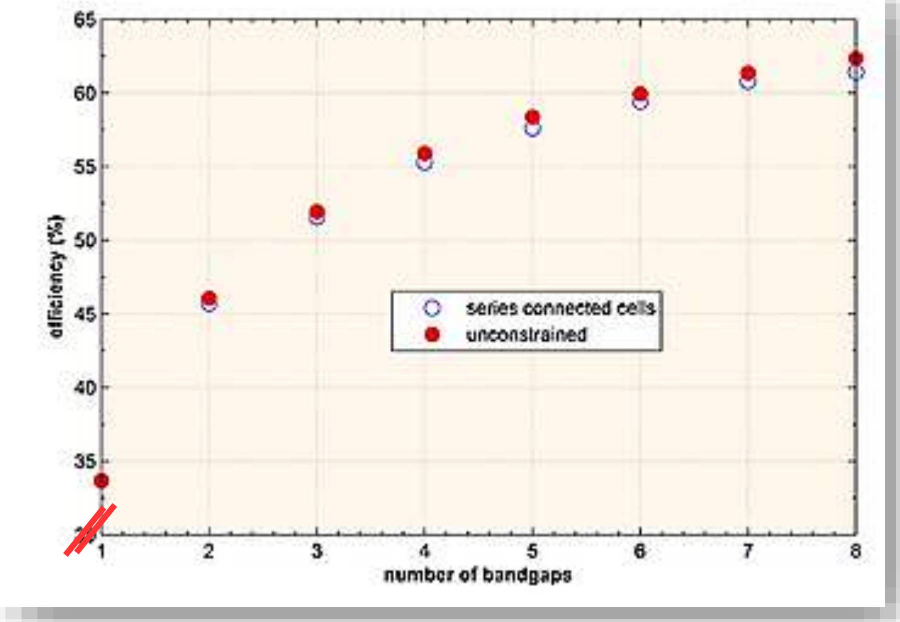
Middle Junction GaAs 1.3-1.4eV

Tunnel Junction

Bottom Junction Ge 0.67eV

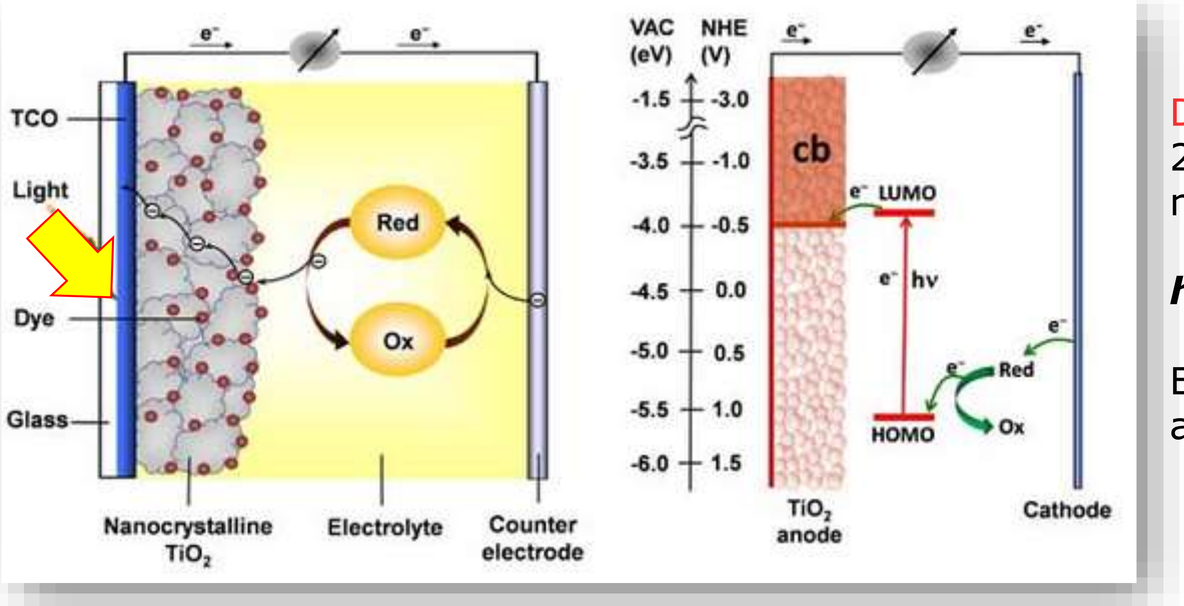
Bottom Contact

Efficiency of Multi-Junction Cells



The maximum efficiency for a two junction tandem under the AM1.5G spectrum and without concentration is 47 %. At the peak efficiency the top cell has a band gap of 1.63 eV and the bottom cell has a band gap of 0.96 eV. Adding more layers makes less and less difference → saturation of efficiency 62.5%.

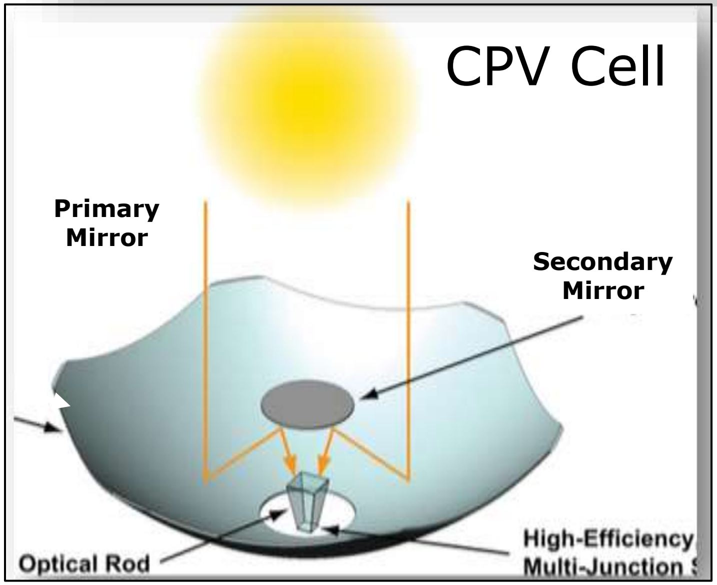
Cell Designs in R&D

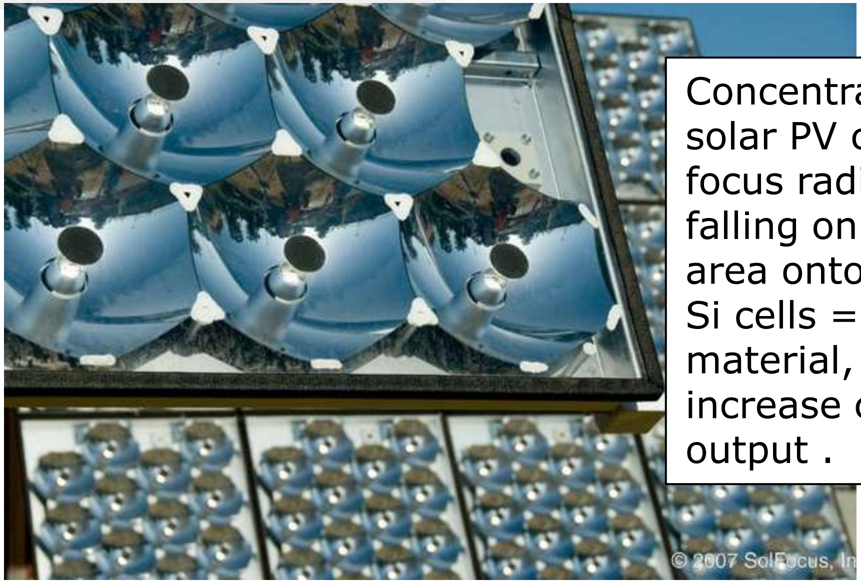


Dye sensitized solar cells:
20-nm, dye-coated $\mathrm{TiO_2}$ nanoparticles in electrolyte.

$\boldsymbol{h\nu} \rightarrow$ dye- $\boldsymbol{e^-}$ $\boldsymbol{h}$, $\boldsymbol{e^-} \rightarrow \mathrm{TiO_2}$ CB

Electrolyte ion$^-$ donates $\mathbf{e^-}$ and fills dye-***h***





Concentrated solar PV cells: focus radiation falling on large area onto small Si cells = save material, increase cell output .

Thin-Film PV Solar Cells: CIGS

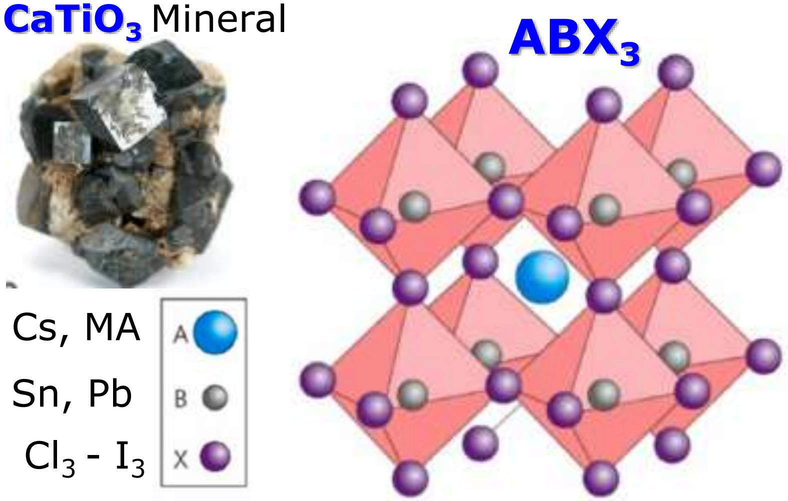
The ZSW institute's building in Stuttgart-Vaihingen has a façade with CIGS panels.

Nano-particles embedded in plastic.

2019: CIGS (Copper, Indium, Gallium and Selenium) p-type $CuInGaSe_2$ joined with n-type CdS, plus contacts. → high cell efficiencies PCE in thin film PV technologies, (23.4% one cell, 17.5% on module).
CIGS has also been deployed in ultra-high efficiency tandem cells, potential to achieve 30% efficiency.
Future efficiency development via band-gap tuning: Perovskite/CIGS tandem

Perovskite Solar Cells (Heterojunction PSL)

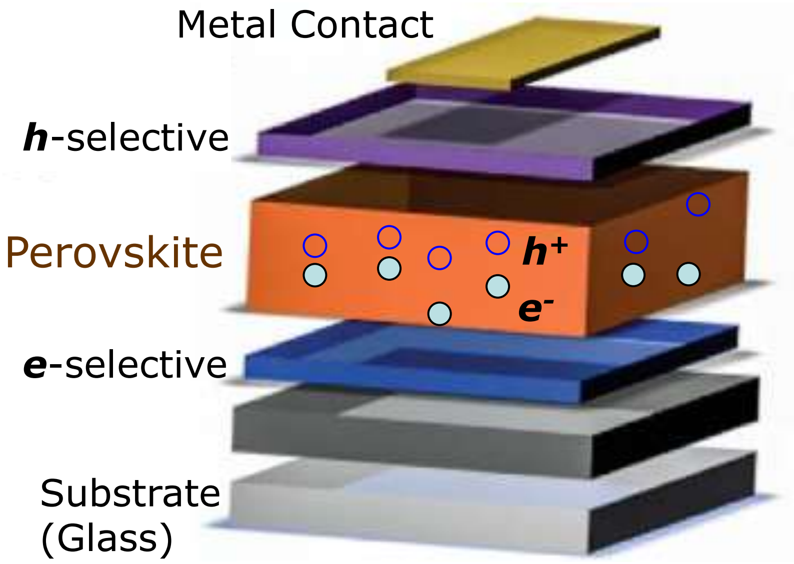
$CaTiO_3$ Mineral



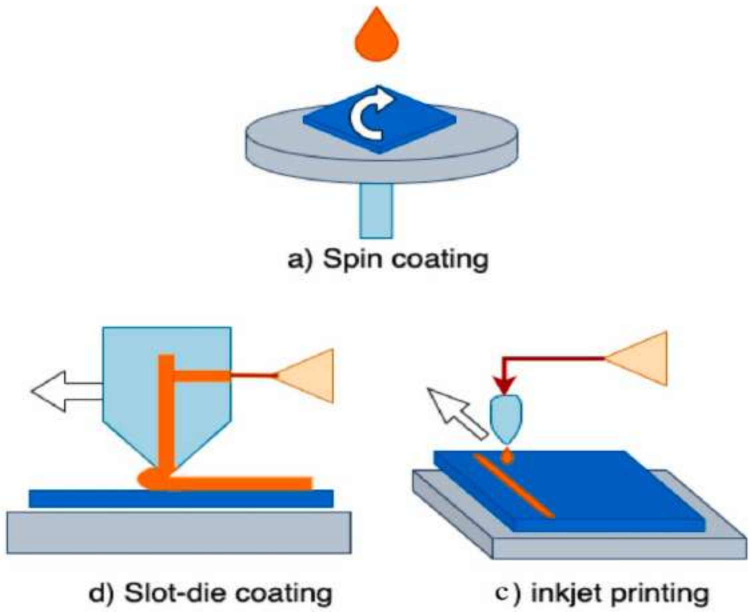
ABX_3 perovskite semiconductors:
Cations A & B, A= Methylammonium (MA)
B= metal (Pb, Sn), X=Halide (Cl, Br, I)

R&D priorities: Light absorbance, exciton lifetime, diffusion length, stability, ease of fabrication, versatility, environment, marketing.

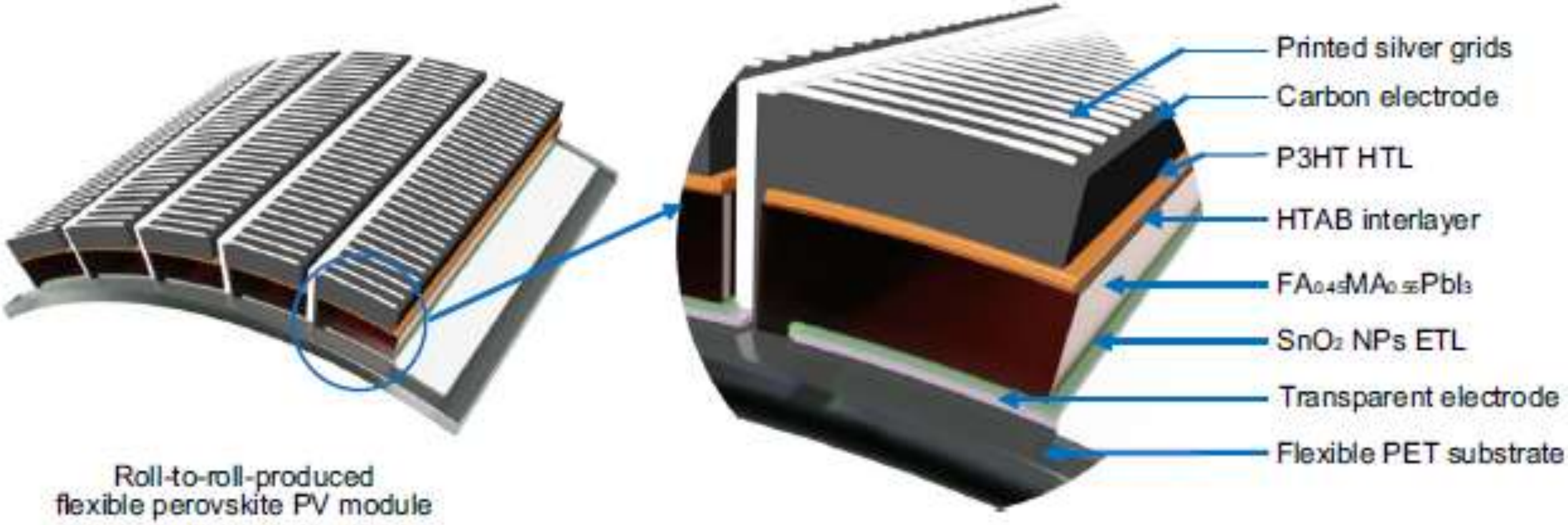
Planar heterojunction PSL



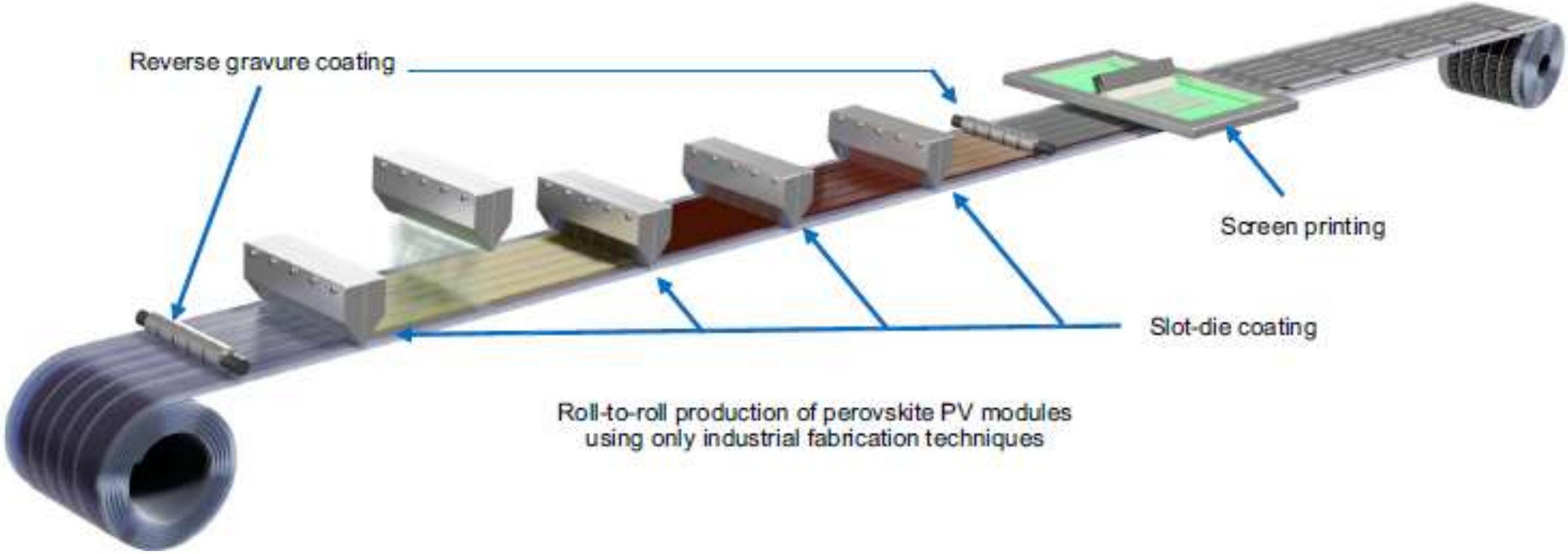
Thin-Film Fabrication Methods



Thin-Film Perovskite Solar Cells



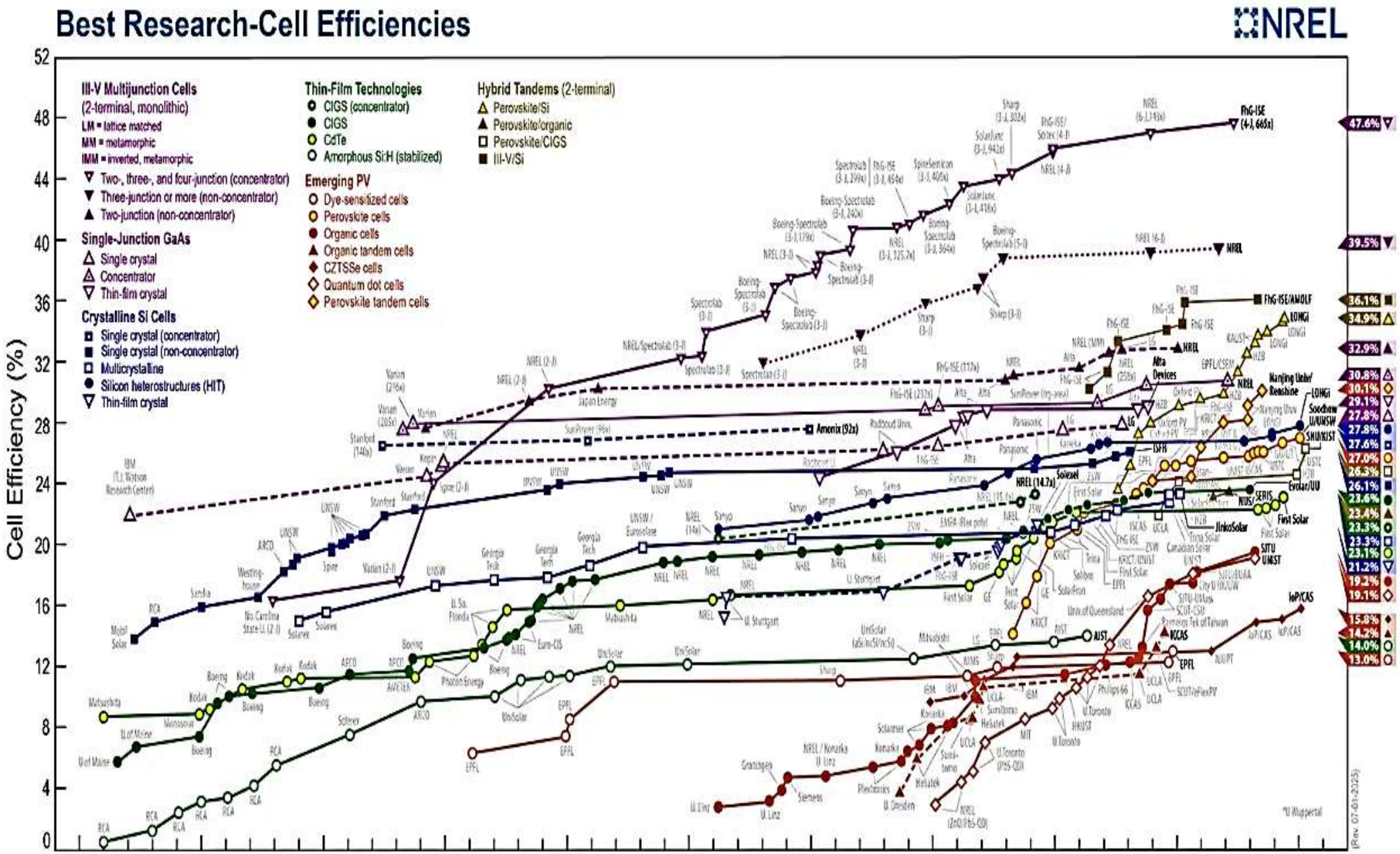
Roll-to-roll-produced
flexible perovskite PV module



Roll-to-roll production of perovskite PV modules
using only industrial fabrication techniques

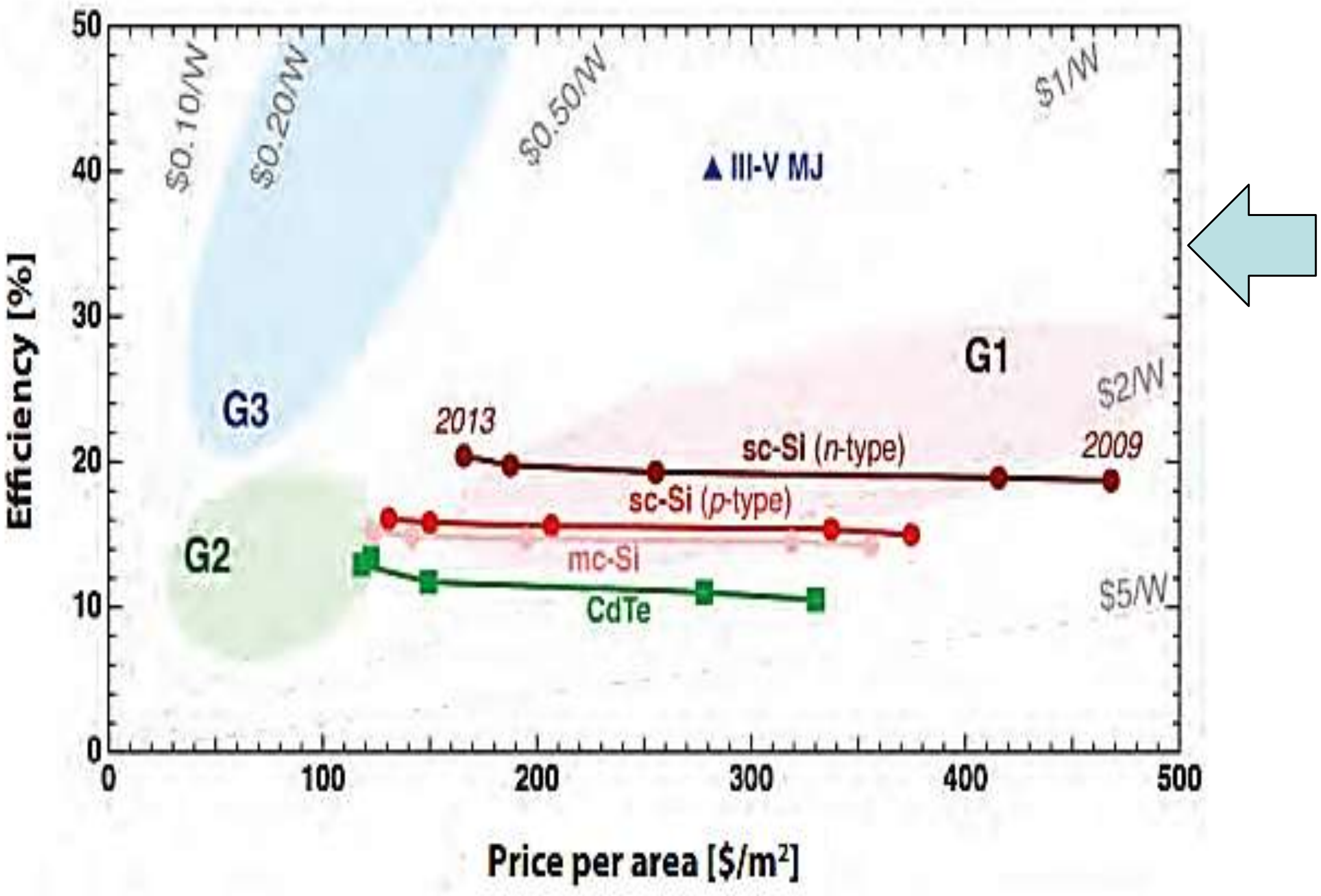
Ongoing R&D: Efficiencies of Solar Cells

Standard with conventional processes: flat-panel multi-crystalline cells (240-250)W, e ≤ 20%.



Mainstay Si cell production

Trends in Commercial PV Price/Performance



PV module efficiency and price per area (period 2009-2013).Conventional generations: G1 in red, G2 in green, and G3 in blue.

Current G1 and G2 modules cluster near the region originally defined as G2.

Agenda: RenE Solar PV Energy Conversion

- Intro: Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays

- Silicon solar photo-voltaic (PV) technology
  - Semiconductor band structure, gap, junctions
  - Charge carriers in n-type and p-type semiconductors
  - Photocell operation, efficiency
  - Silicon wafer, cell manufacture
  - Materials and emissions in construction

- US and World installations and performance, system cost and incentives
- Solar power strategic issues

Agenda

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