Thin Film Photovoltaics

- Thin film modules are fabricated by depositing extremely thin layers of photosensitive materials onto a low-cost backing such as glass, stainless steel or plastic.
- This results in lower production costs compared to the more material-intensive crystalline technology, a price advantage which is currently counterbalanced by substantially lower efficiency rates.

Thin Film Photovoltaics

- Three types of thin film modules are commercially available at the moment. These are manufactured from
  - amorphous and μ-crystalline silicon (a-Si, μc-Si),
  - copper indium diselenide (CIS, CIGS)
  - cadmium telluride (CdTe).

Advantages of thin film PV technologies:

- savings in material and energy consumption
- large area deposition
- monolithic integration
- energy pay back time
- implementation in building industry

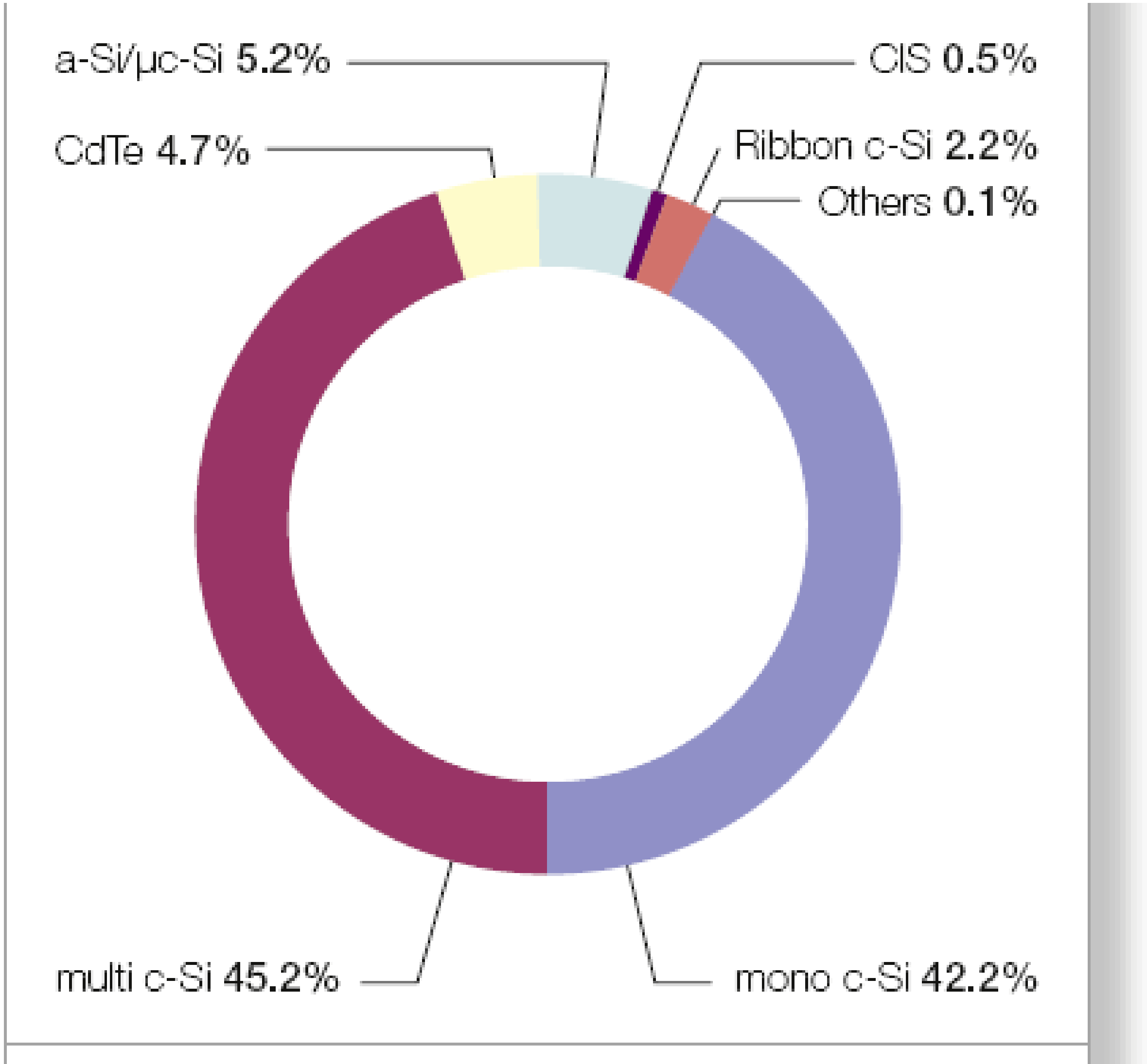
Comparison Thin Film - Crystalline

Table 1.1: Module and cell efficiencies

Technology	Thin Film				Crystalline wafer based	
	Amorphous silicon (a-si)	*Cadmium telluride (CdTe)*	*CI(G)S*	*a-Si/m-Si*	*Monocrystalline*	*Multicrystalline*
Cell Efficien-cy at STC*	5-7%	8-11%	7-11%	8%	16 –19%	14 – 15%
Module Efficiency					13 – 15%	12 – 14%
Area needed per kW (for modules)**	15 m²	11 m²	10 m²	12 m²	app. 7 m²	app. 8 m²

* Standard Testing Conditions: 25°C, light intensity of 1,000W/m², air mass = 1.5
** kW = kilowatt. Solar PV products and arrays are rated by the power they generate at Standard Testing Conditions

Market Share c-Si vs. thin-film



Source: Photon International, March 2008

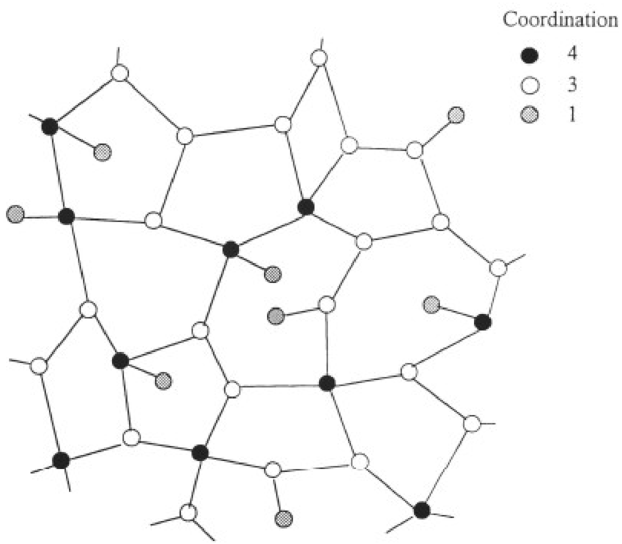
Thin-film silicon solar cells

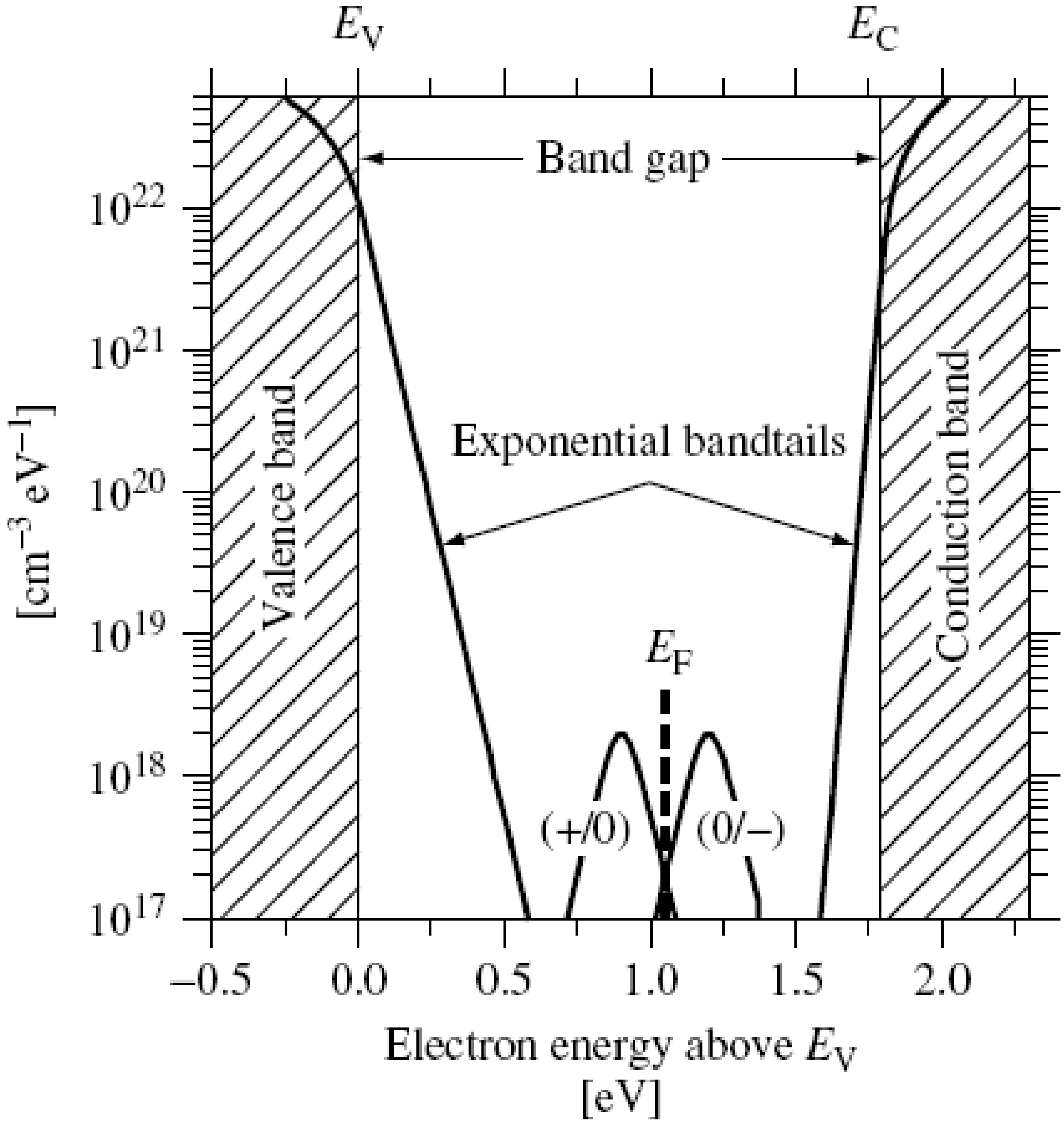
- Thin-film silicon solar cells usually contain amorphous silicon layers deposited by plasma enhanced chemical vapor deposition (PECVD).
- This CVD method has the advantage that large-area devices can be manufactured at a low processing temperature, thus facilitating low-cost solar cells on glass, metal foil, or polymer foil.

Thin Film Si Photovoltaic cells

- Material: Silicon in different phase: amorphous; microcrystalline; crystalline
- Most common one: amorphous hydrogenated Si (a-Si:H)
- a-Si:H: short-range order; H plays a role in the fabrication and in the passivation of dangling bonds
- Due to deviation from the ideal crystalline structure the density of states features band tails; defects lead to mid-gap states

a-Si:H Density of States

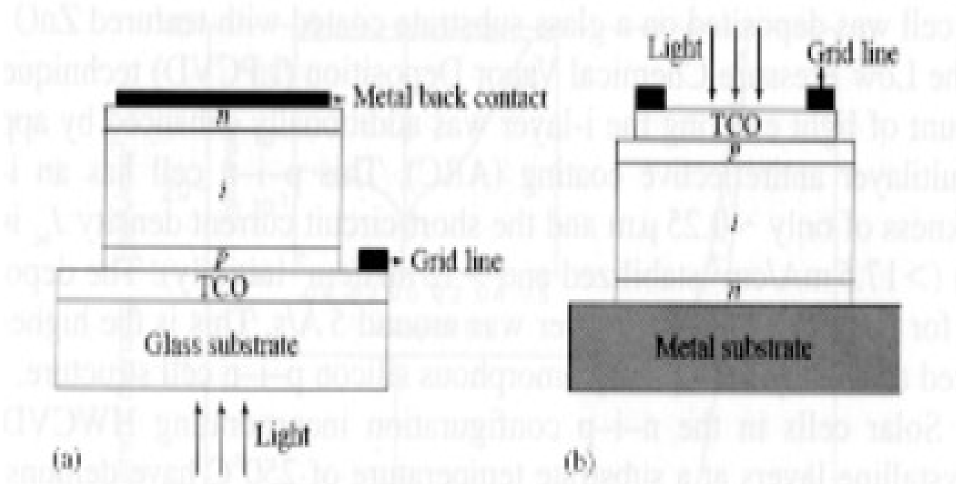




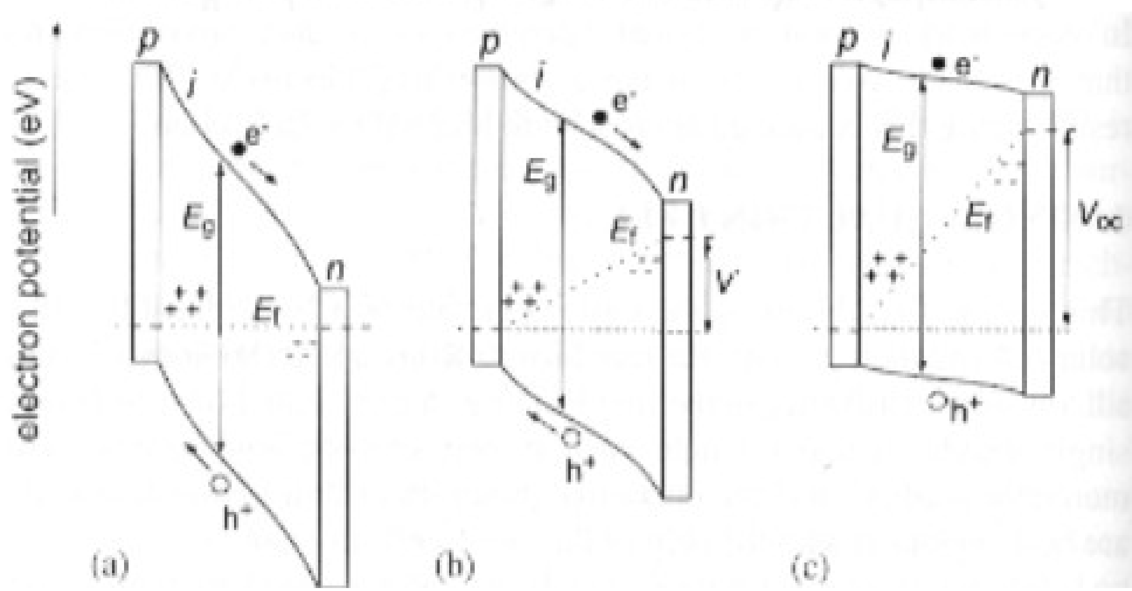
Architecture for Thin Film Photovoltaic cells

- Defects cause large recombination rates;
- As a consequence the simple PN junction with extended neutral regions, requiring large diffusion length is not suitable
- The P-i-N structure with two thin doped (N, P) regions and an extended (100 nm – 1um) intermediate intrinsic (i) region is adopted

Thin-Film Si PiN solar cell



Architecture of the PiN cell: superstrate (a) and substrate configurations (b)



Band configuration on a PiN cell: equilibrium (a), direct bias (b) and open-circuit (c)

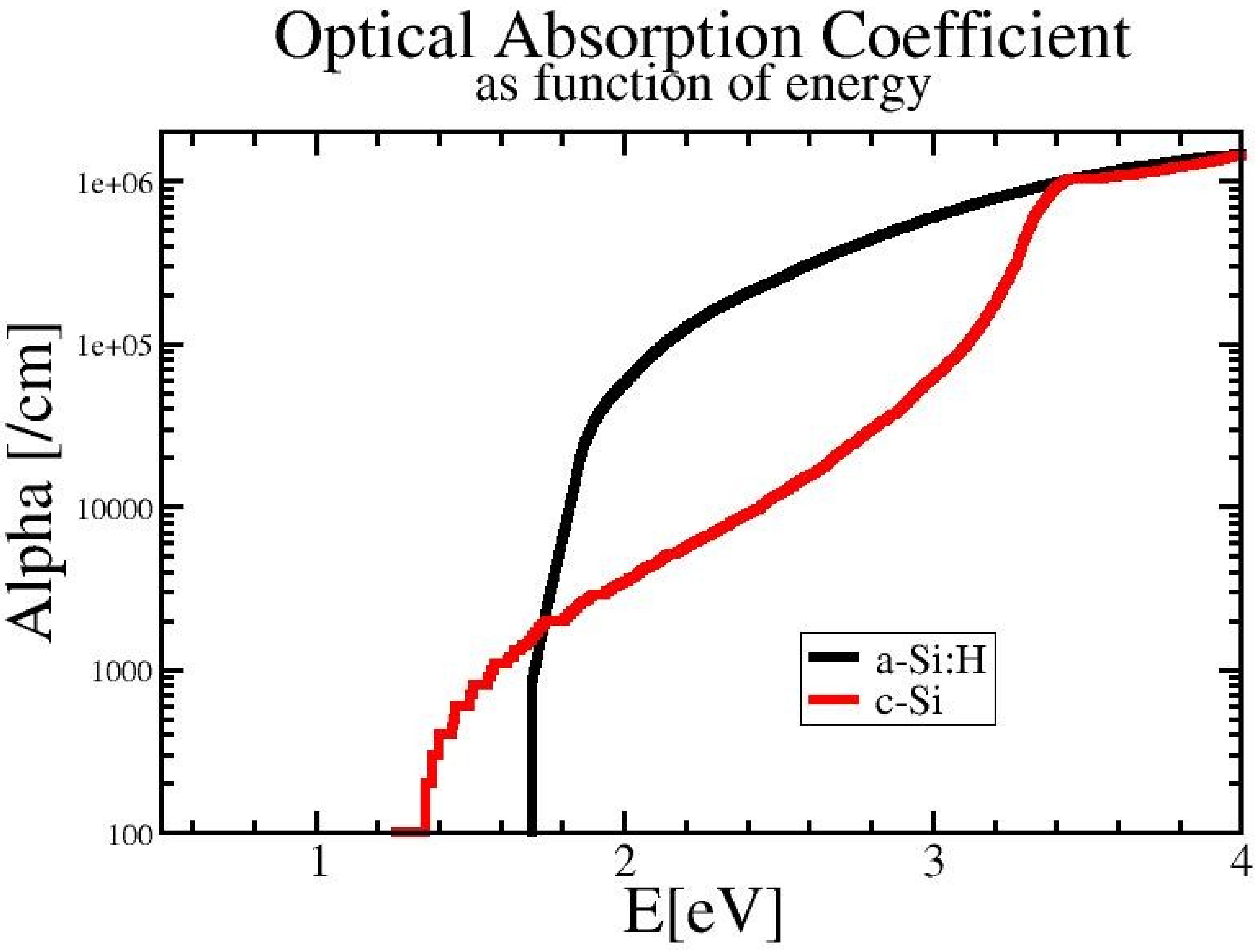
Soga, “Nanostructured materials for solar energy conversion”, Elsevie, 2006

P-i-N Photovoltaics cells

- The workfunction difference between the N and P regions supports an electric field inside the intrinsic layer
- Most of carrier generation occurs in the intrinsic layer (thanks to its large extension)
- Generated carriers drift towards the N (electrons) and to the P (holes) regions, pushed by the built-in field

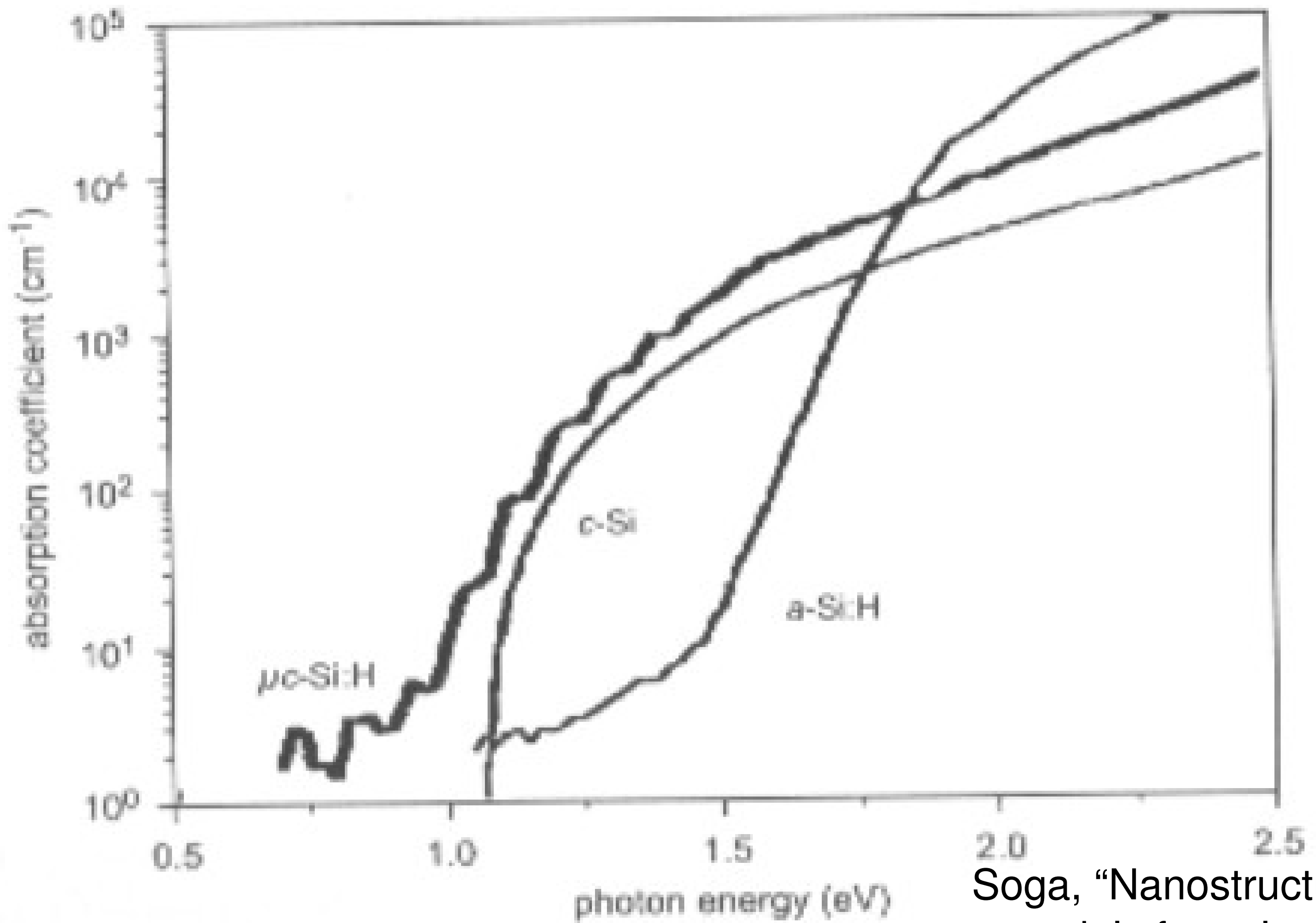
Optical properties of amorphous and μ-crystalline Si

- aSi:H behaves as a direct gap semiconductor with bandgap of 1.7-1.8 EV
- The absorption rate is large, allowing the use of thin layers (200 – 400 nm for single-junction devices)
- μ-c Si (nanocrystals embedded in a-Si:H) features optical characteristics similar to c-Si



Optical Absorption Coefficient
as function of energy
Alpha [/cm]
1e+06
1e+05
10000
1000
100
1
2
3
4
E[eV]
a-Si:H
c-Si

Optical properties of amorphous and μ-crystalline Si



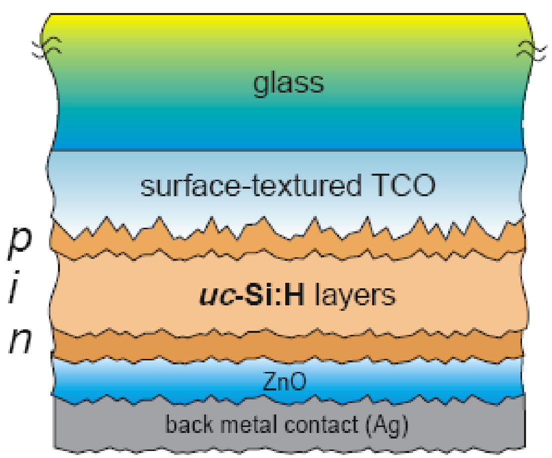
Soga, “Nanostructured materials for solar energy conversion”, Elsevie, 2006

Amorphous and μ-crystalline Si

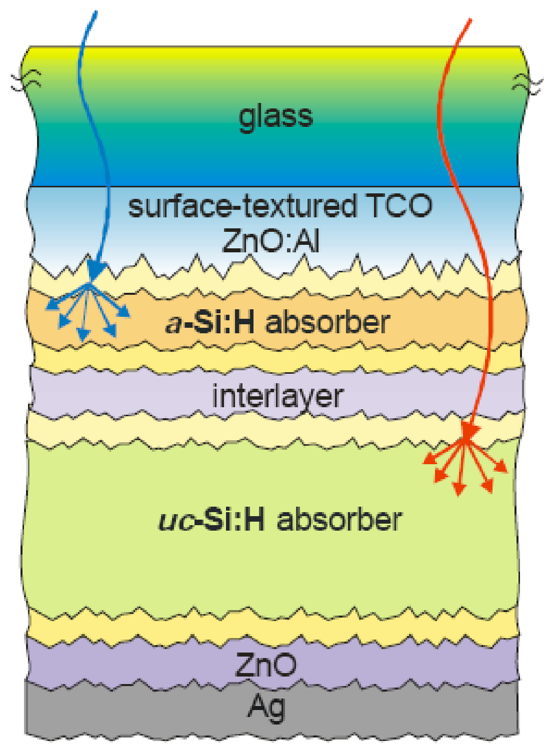
- The possibility to control bandgap opens the opportunity to overcome one of the limitations to conversion efficiency (loss of $h\nu - E_G$)
- Adoption of multi-junction architecture
- The 1.1 eV – 1.8 eV combination is ideal for the case of conversion of solar light.
- Additional possible improvement with a three-junction architecture including an a-SiGe:H layer

Micromorph TF a-Si:h and uc-Si:H Solar Cells

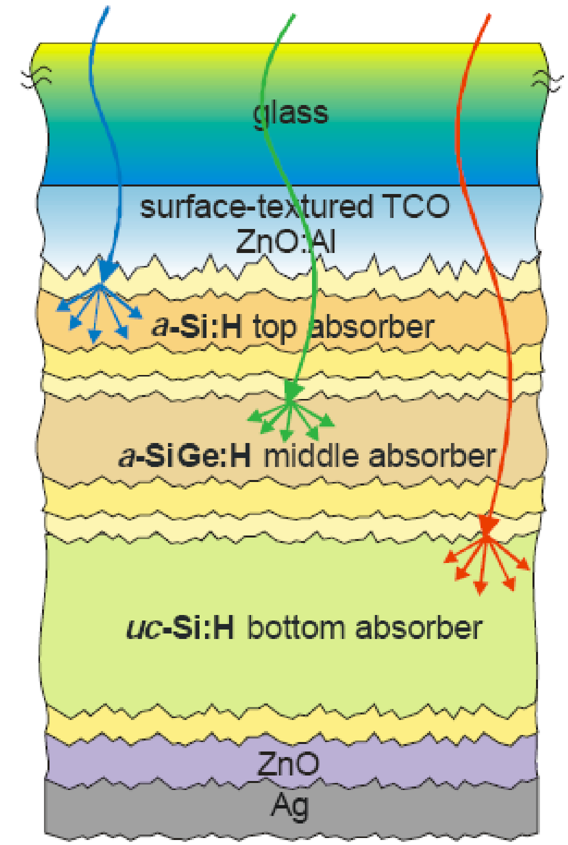
single-junction
amorphous (a-Si:H)
microcrystalline (uc-Si:H)



double-junction
micromorph
a-Si:H/uc-Si:H



triple-junction
e.g. a-Si:H/a-SiGe:H/
uc-Si:H



Record η_{st} (confirmed)

9.5% (a-Si) Un. Neuchatel

10.1% (μc-Si) Kaneka

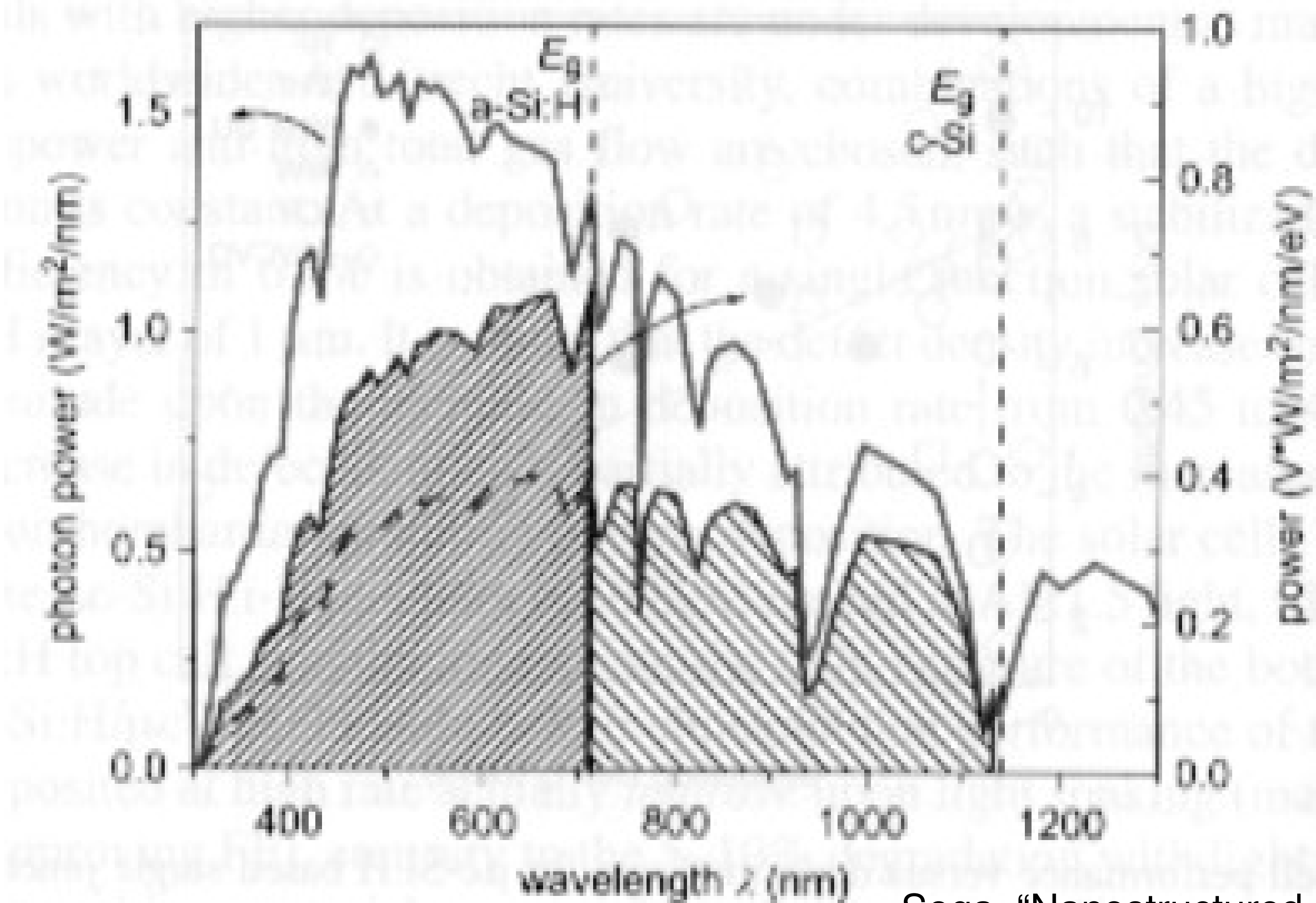
11.7% (a-Si/ μc-Si) Kaneka

12.4% (a-Si/a-SiGe) USSC*

13.0% (Si/SiGe/SiGe) USSC*

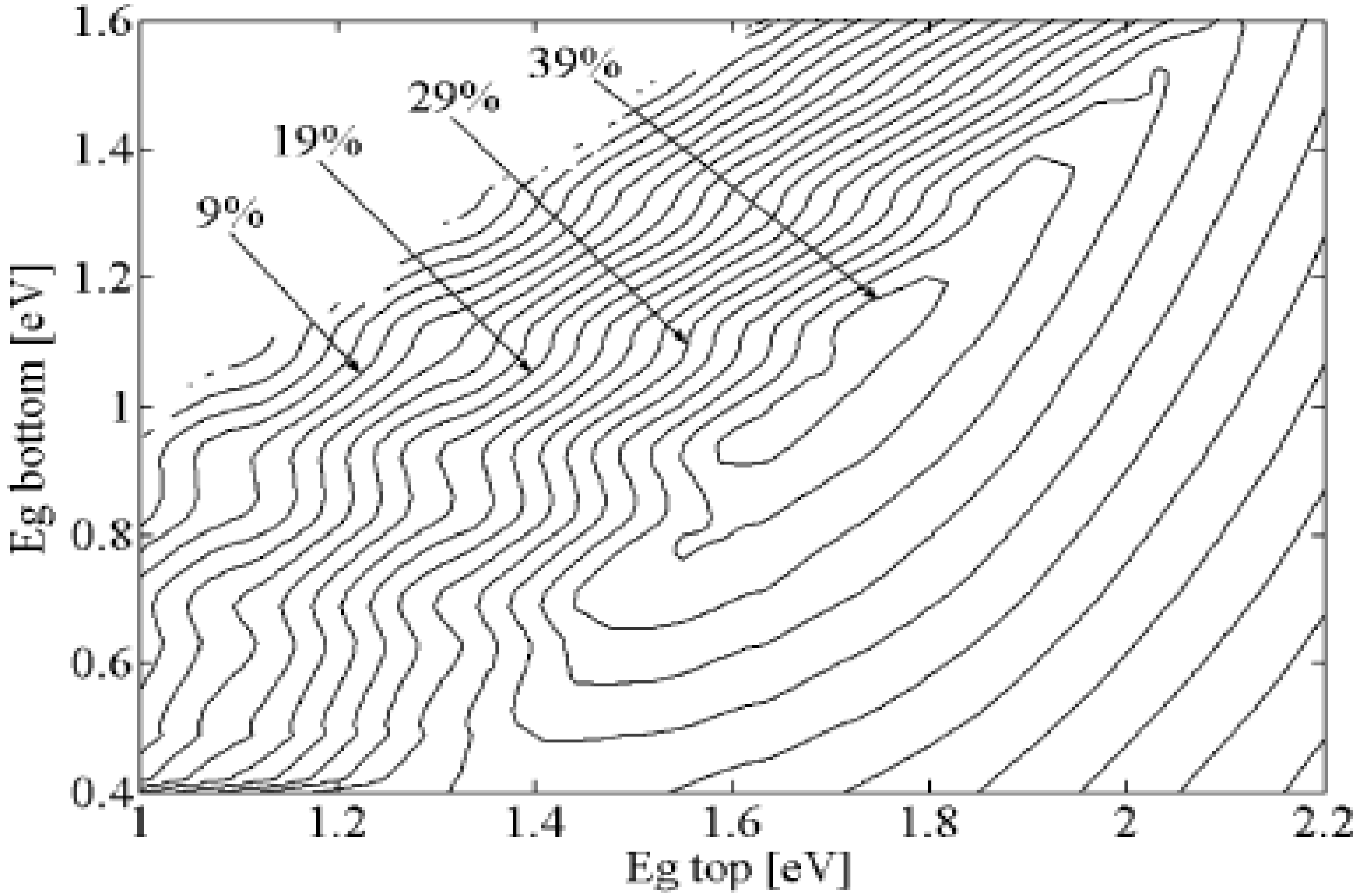
Slides from M.Zeman (Delft University of technology)

Multi Junction a-Si:H - muc-Si:H



Soga, "Nanostructured materials for solar energy conversion", Elsevier, 2006

Multi Junction PV cells



Semi-empirical upper limit of the efficiency g as a function of the energy gap Eg of the bottom and top cells of a tandem solar cell
Journal of Non-Crystalline Solids 338–340 (2004) 639–645

Si-based Thin-Film Technology

- The common deposition process is Plasma Enhanced Chemical Vapor Deposition (PECVD)
  - RF-generated plasma promotes the deposition of silicon starting from a gaseous precursor
  - Silane (SiH4) molecules dissociate due to interactions with energetic electrons of the plasma, generating neutral radicals, molecules and ions
  - Reactions in the plasma with formation of species (Si, H) that permeates through the surface
  - Realization of hydrogenated Si network and release of H
  - Deposition rate is critical for defect concentration

Si-based Thin-Film PECVD Technology

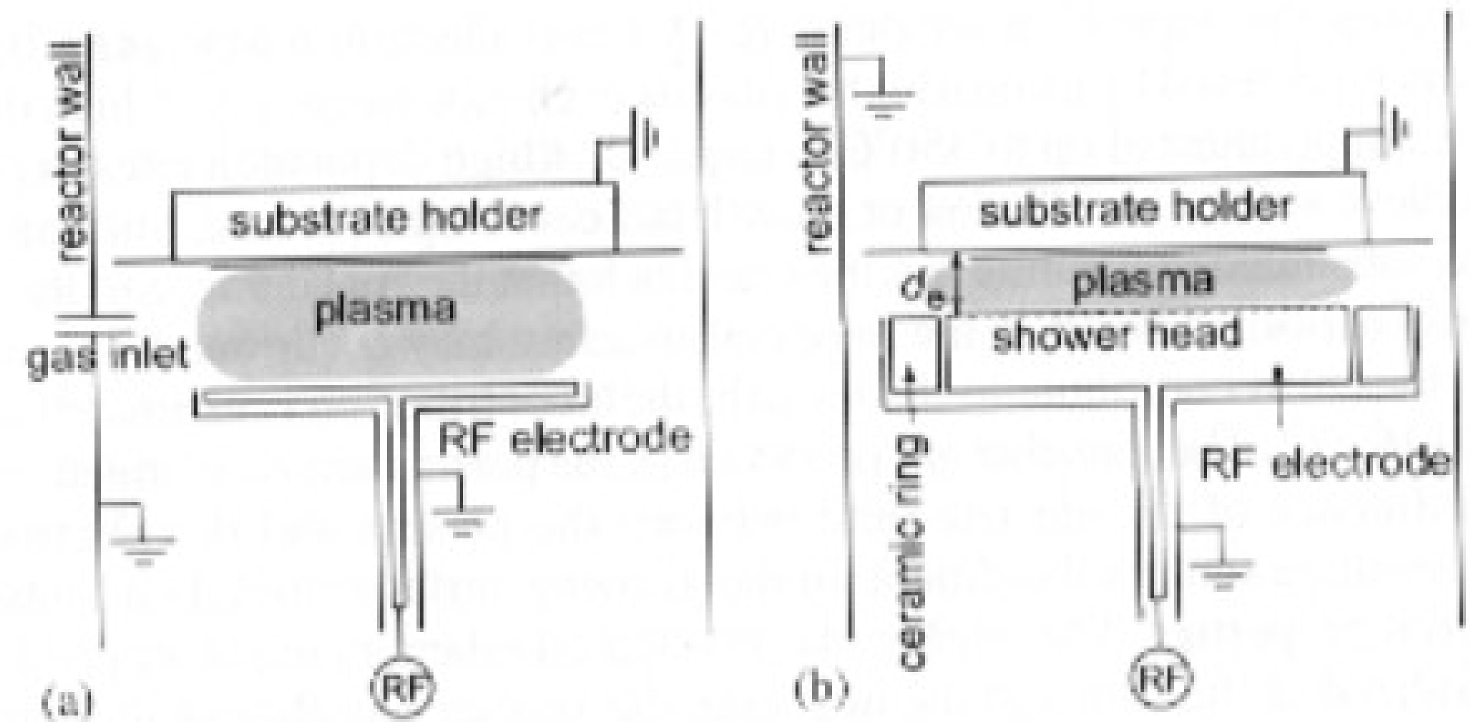


Fig. 5. Schematic diagram of an rf PECVD chamber. (a) A conventional electrode configuration is shown. (b) The configuration is shown for high-pressure conditions at low interelectrode distance. At small interelectrode distances, the use of a shower head is required. Figure from Ref. [100].

Soga, "Nanostructured materials for solar energy conversion", Elsevier, 2006

Long-term reliability

- a-Si:H-based PV cells are affected by degradation (Staebler Wronsky effects)
- This is mainly due to a photo-induced removal of Si-H bonds that passivate dangling bonds
- This degradation tends to saturate and can be partially recovered by thermal treatments

Long-term reliability

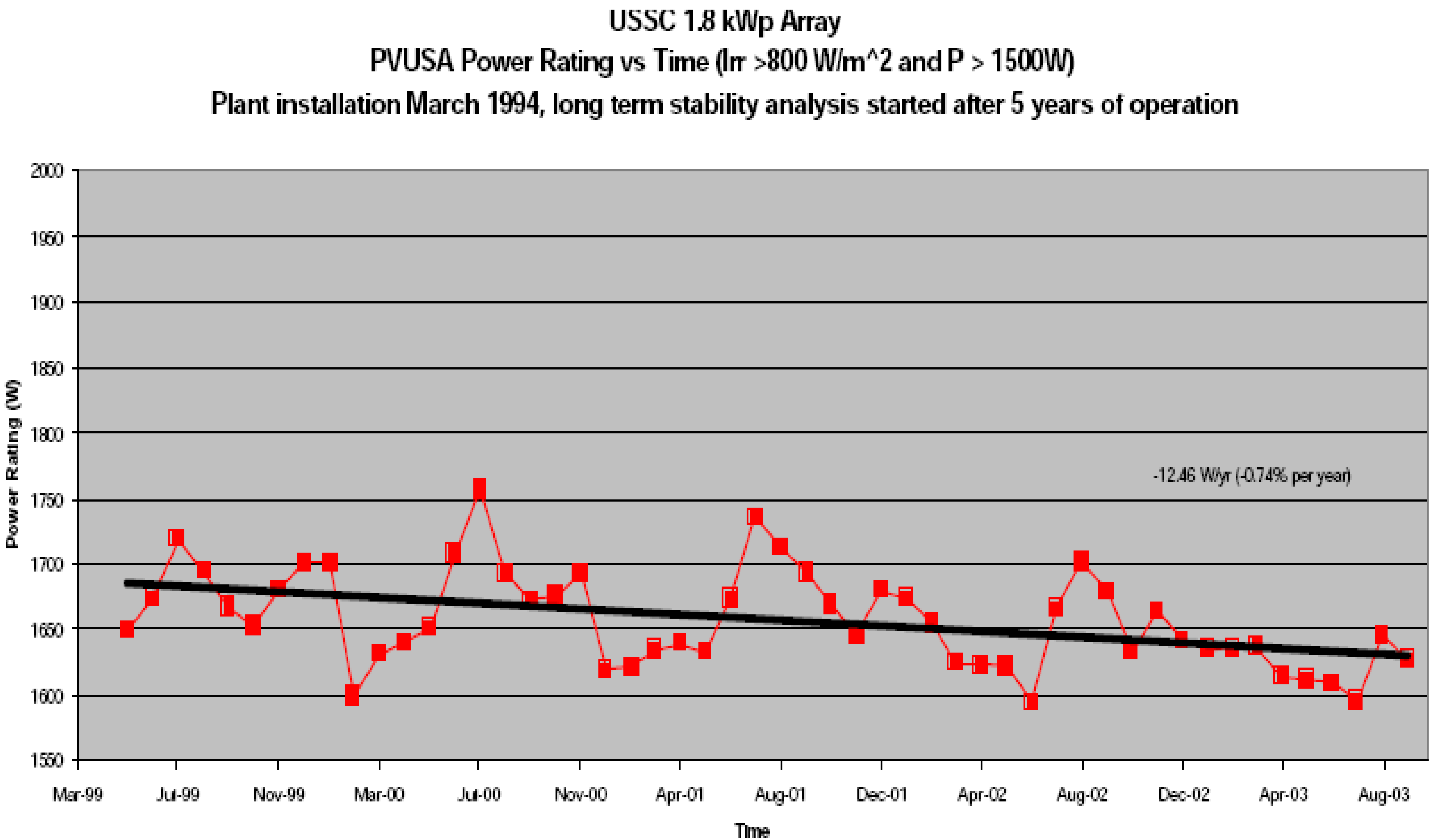
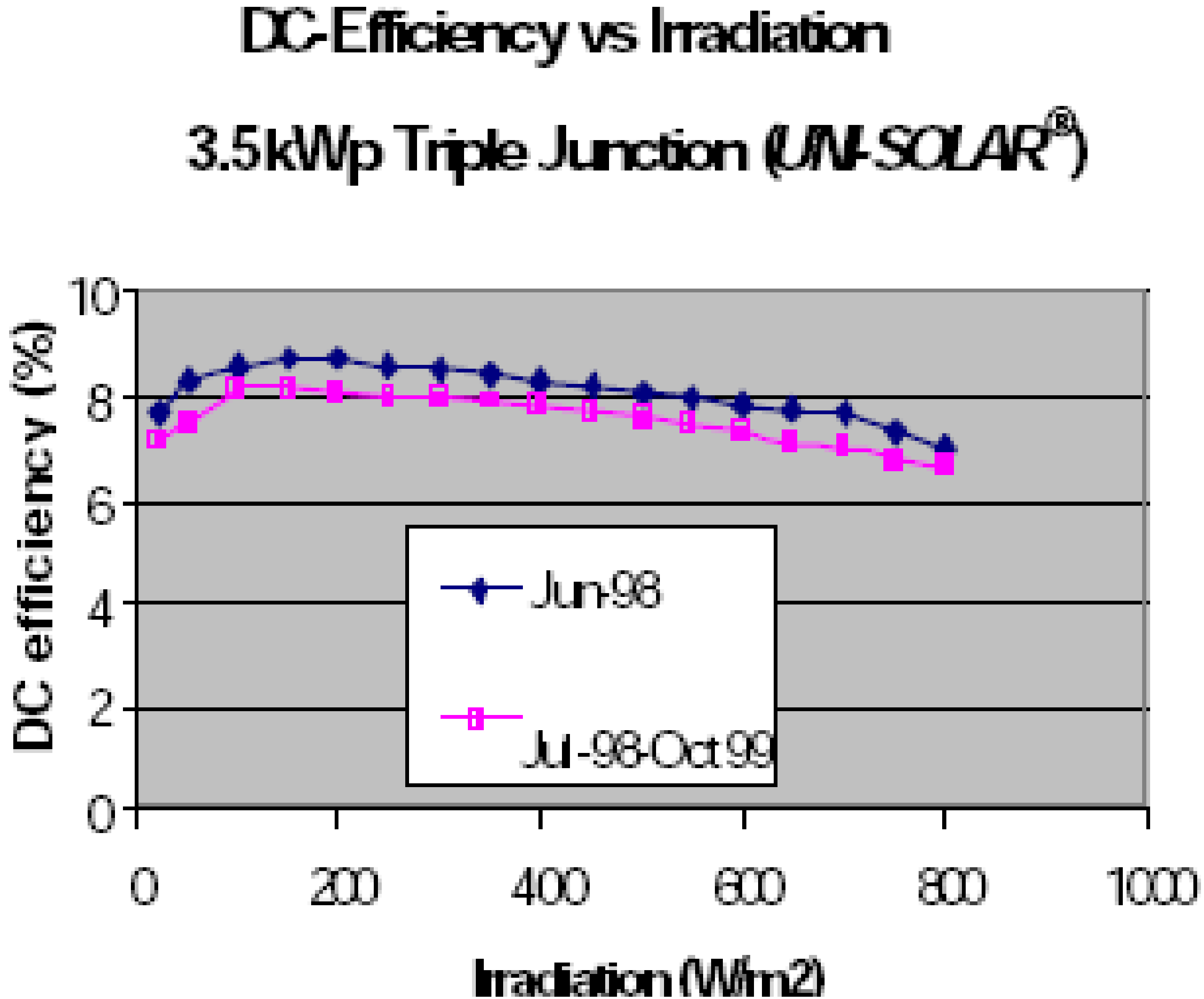
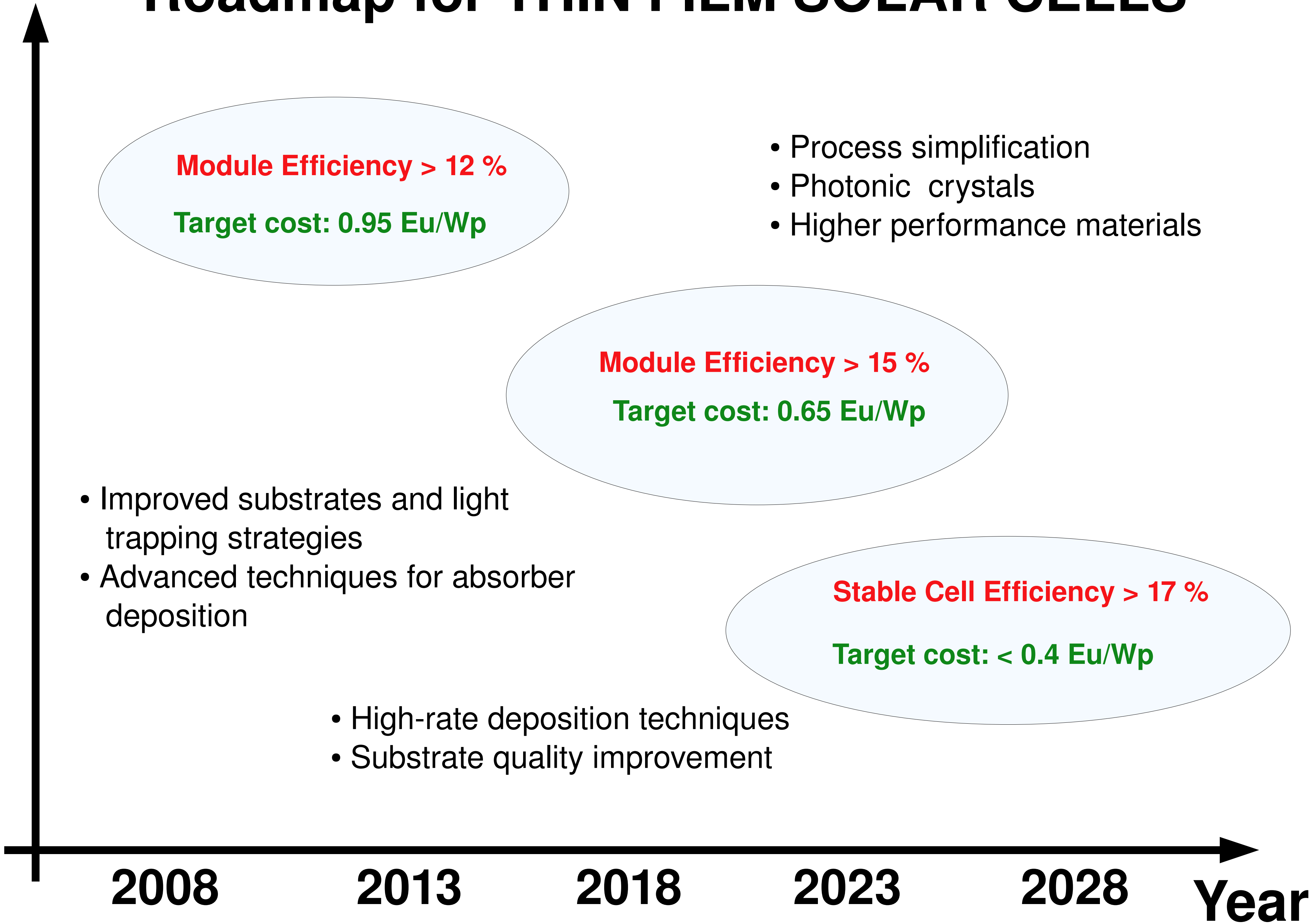


Figure 3: UNI-SOLAR 'Triple Junction'- Technology demonstrates a stabilized Efficiency with annual cyclic variation and an average degradation not higher than 0.74% (NREL Report) [5]

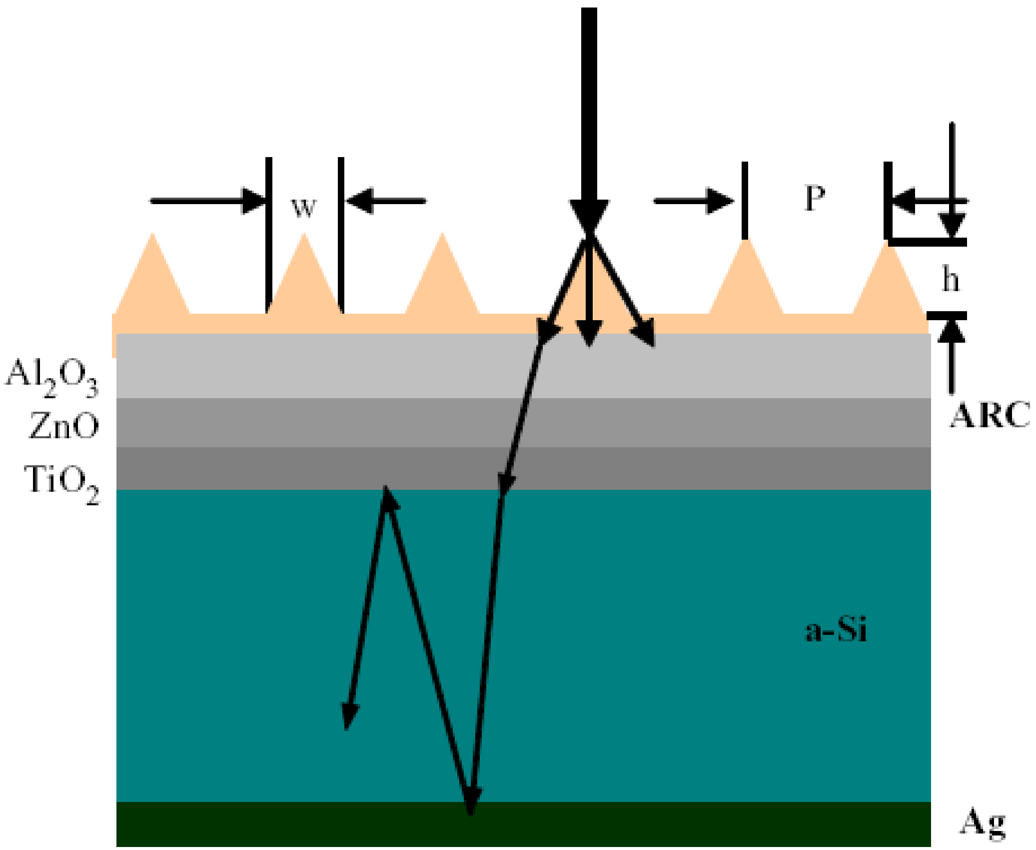
Long-term reliability



Roadmap for THIN FILM SOLAR CELLS

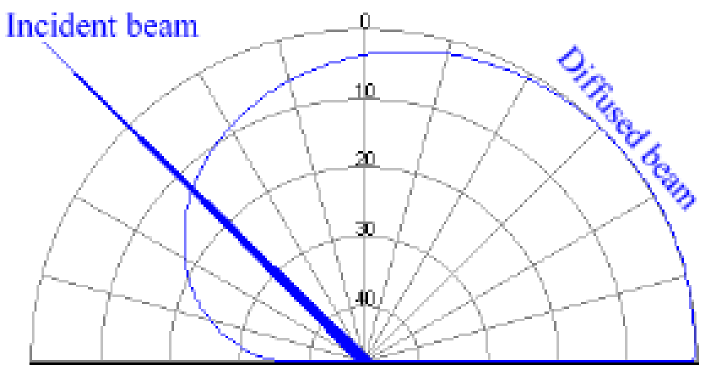


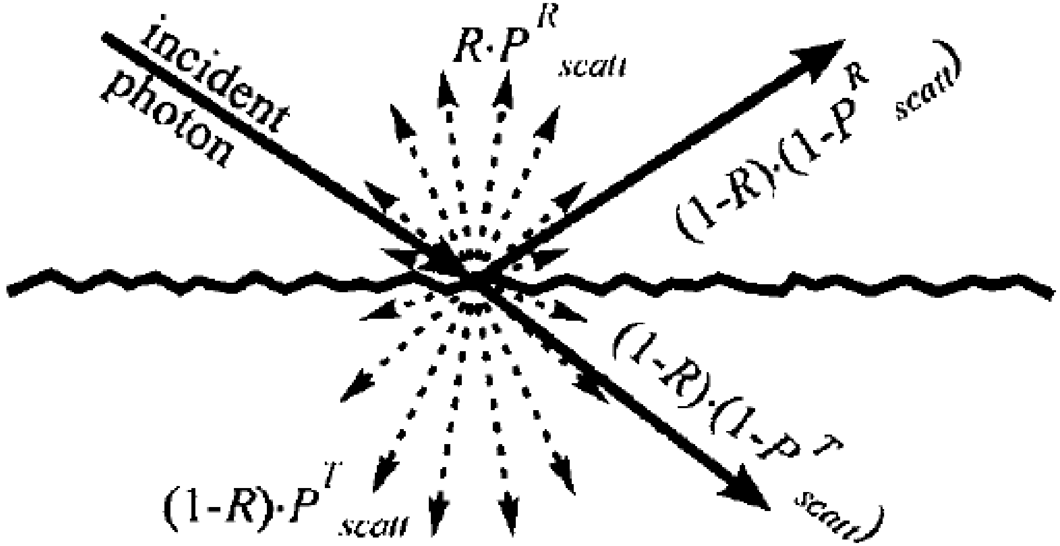
Geometrical light confinement: surface texturing

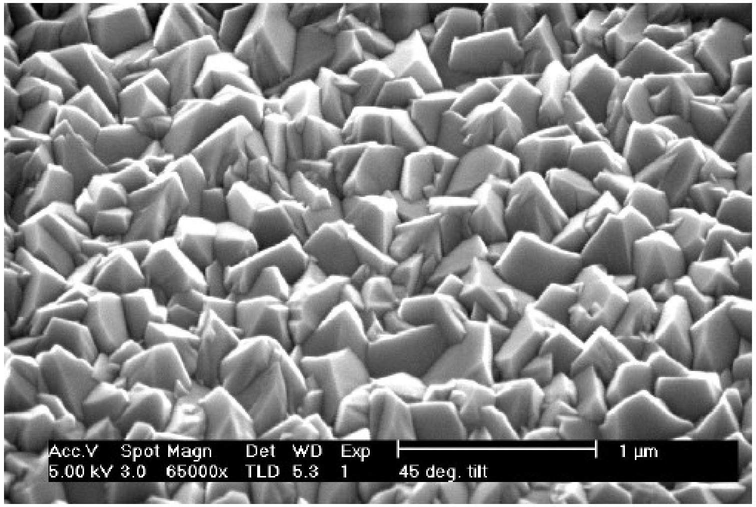


•The geometrical size of texture elements (w, p, h) is typically much smaller than λ.

Geometrical light confinement: surface texturing







SEM picture of Asahi U-Type surface

Light trapping techniques

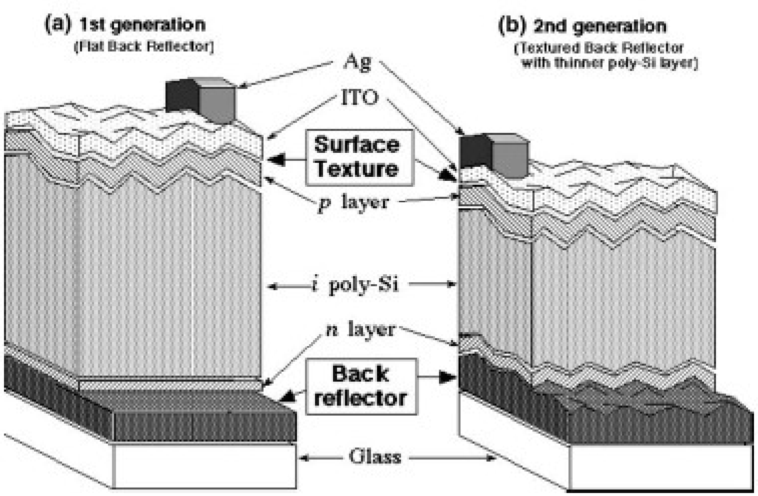
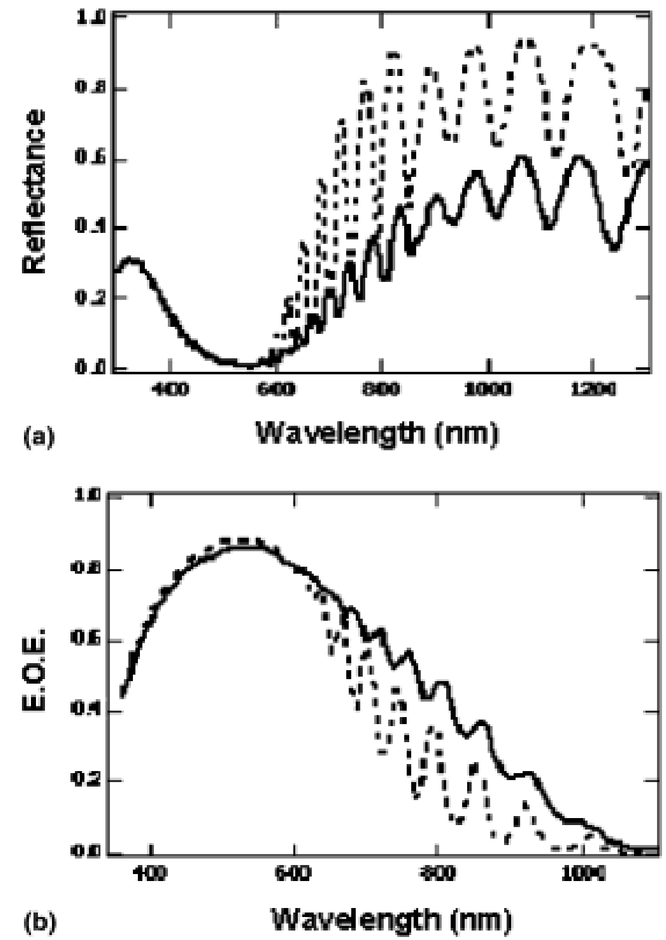


Fig. 3. Cross-sections through light-trapping microcrystalline silicon solar cell devices: (a) first generation (flat back reflector); (b) second generation (textured back reflector, thinner polycrystalline silicon layer).



K. Yamamoto et al. / Solar Energy 77 (2004) 939–949

Light trapping techniques

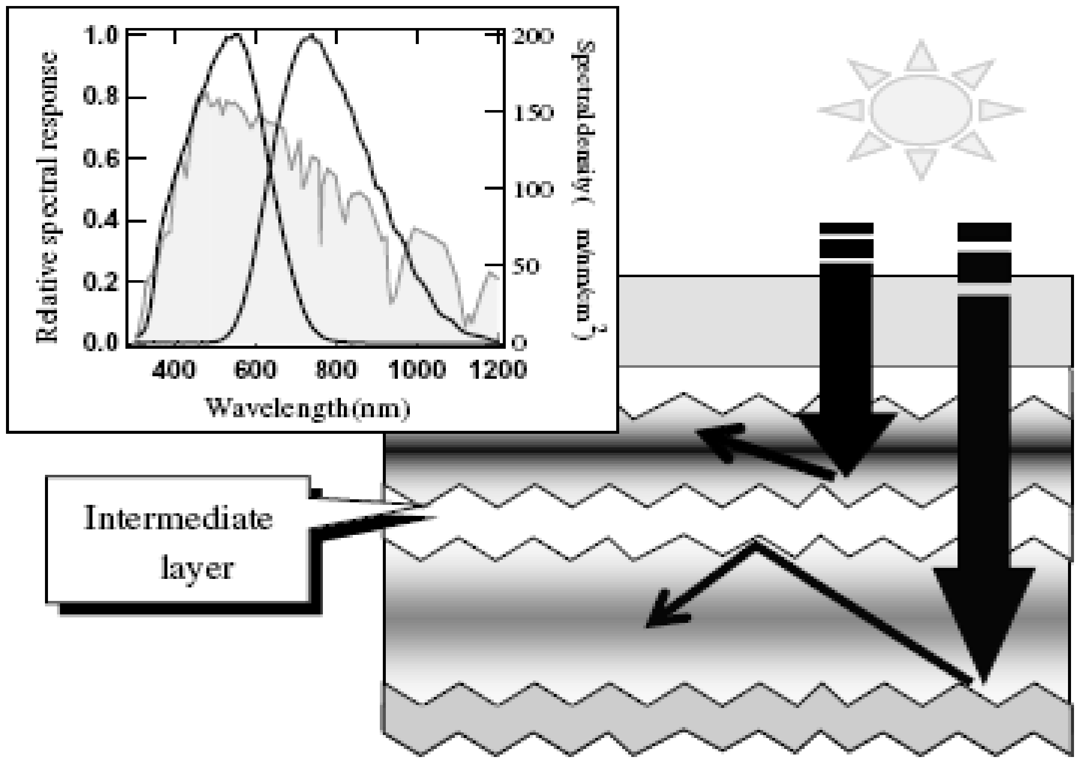


Fig. 8. Schematically drawn concept of inter-layer.

K. Yamamoto et al. / Solar Energy 77 (2004) 939–949

Non Silicon-based thin film PV cells

- CdS, CuInSe2 (CIS) are promising materials for thin film cells at low cost
- CdS/CIS solar cells offer efficiencies up to 17% thanks to the large absorption coeff. of CIS
- p-CIS and n-CdS form an heterojunction with bandgaps 1.02 eV and 2.41 eV, respectively
- CdS acts as a window for photons with hv < 2.41 eV that are absorbed by CIS
- Charge separation occurs at the junction

CdS/CIS solar cells

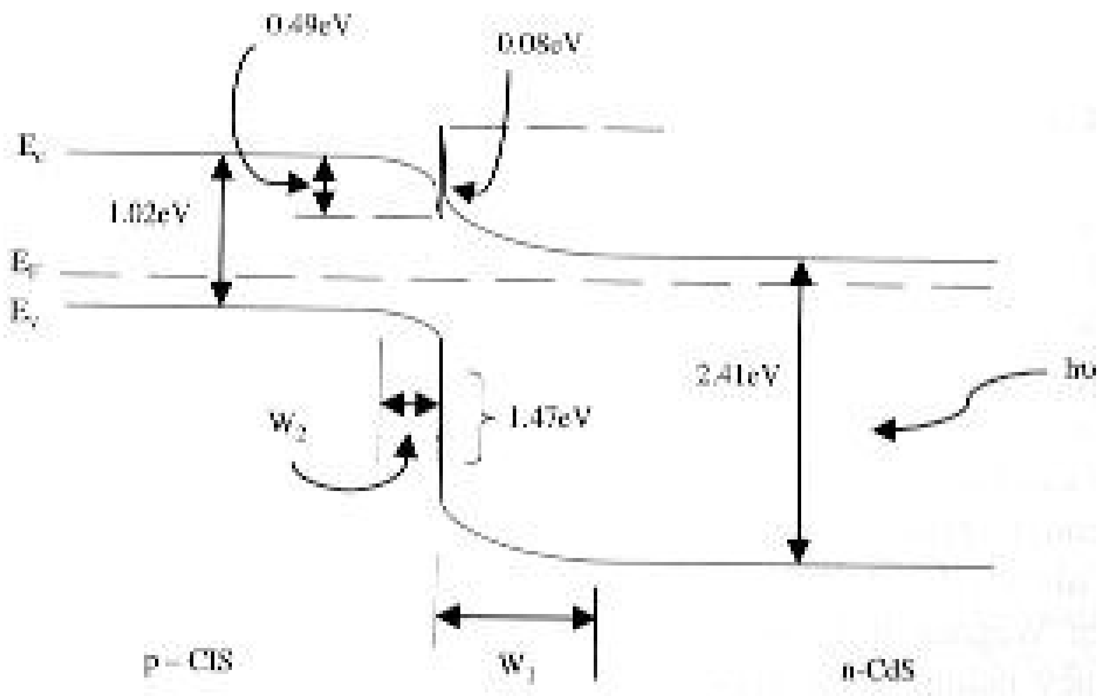


Fig. 1. Energy band diagram of CIS/CdS heterojunction.

Soga, "Nanostructured materials for solar energy conversion", Elsevier, 2006

CdTe – based thin-film PV cells

- Among the candidates for thin-film solar cells capable CdTe has shown considerable promise
- CdTe has the advantage of a nearly ideal band gap for solar terrestrial photoconversion (1.45 eV) and a short absorption length when compared to grain sizes typically encountered
- This latter property reduces recombination at grain boundaries a major problem with other polycrystalline materials
- As a result, a large fraction of the photogenerated carriers are generated within the depletion layer allowing more efficient collection.

CdTe – based thin-film PV cells

- Because it is difficult to produce thin-film CdTe solar cells with thin n-CdTe layers, heterojunctions utilizing wide-band-gap n-type semiconductors and p-CdTe are most common
- CdS has a band gap of 2.42 eV and is the most commonly employed heterojunction partner to p-CdTe due to its similar chemical properties.
- Necessity to use a small thickness of CdS for enhanced short-wavelength response.

CdTe – based thin-film PV cells

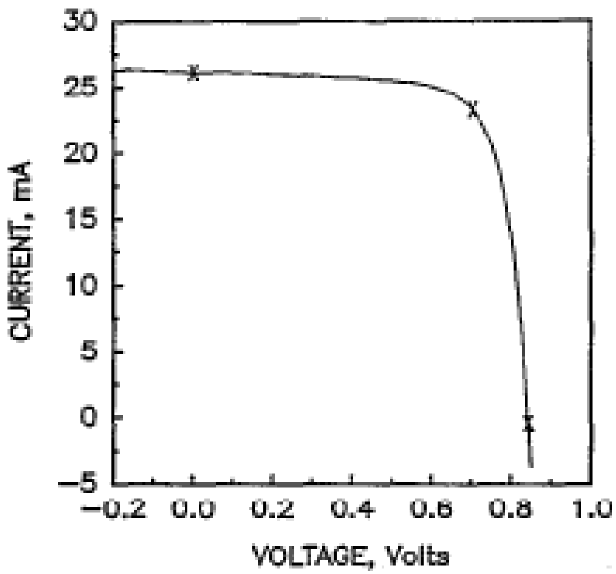


FIG. 2. Current-voltage characteristics of a thin-film CdS/CdTe solar cell under global AM1.5 conditions. Area = 1.05 cm^2, V_{oc} = 0.8429 V, J_{sc} = 25.09 mA/cm^2, fill factor = 74.48%, and efficiency = 15.8%.

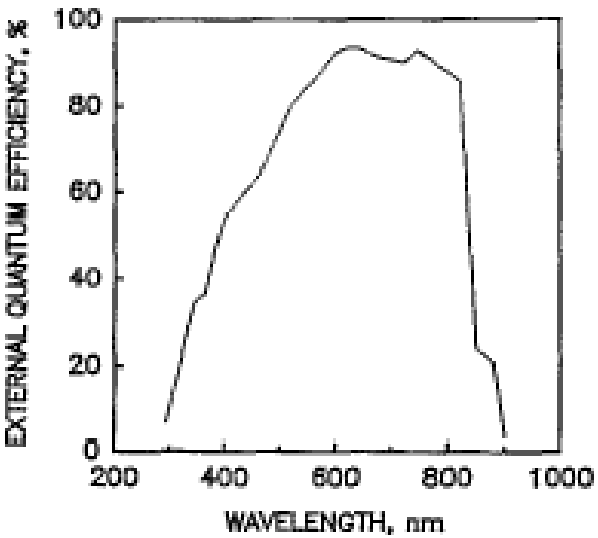


FIG. 3. The quantum efficiency of the thin-film CdS/CdTe solar cell shown in Fig. 2.

J. Britt and C. Ferekides Appl. Phys. Lett., Vol. 82, No. 22, 31 May 1993

CdTe – based thin-film PV cells

- Recently, cheap fabrication process have been developed and this technology is gaining great relevance
- Approximately 10% efficiency at less than 1$/Watt installed
- Prospect for 12% efficiency in commercial products by 2012

CdTe – based thin-film PV cells

1 Mwatt PV field installed on the roof of the Bentegodi Stadium in Verona