# "Solar Energy" WS 2014/2015

## Lecture 8: Amorphous Silicon Thin Film Solar Cells

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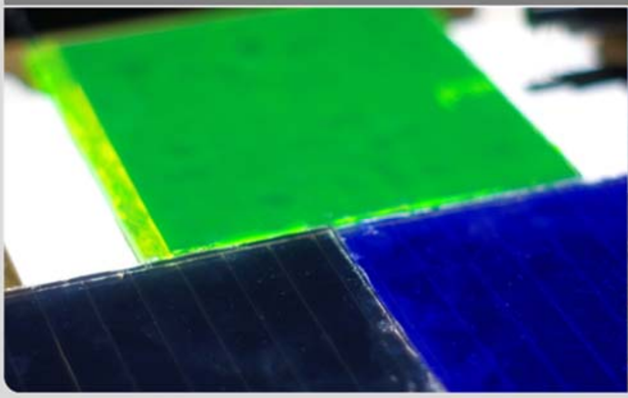
KIT Focus Optics & Photonics

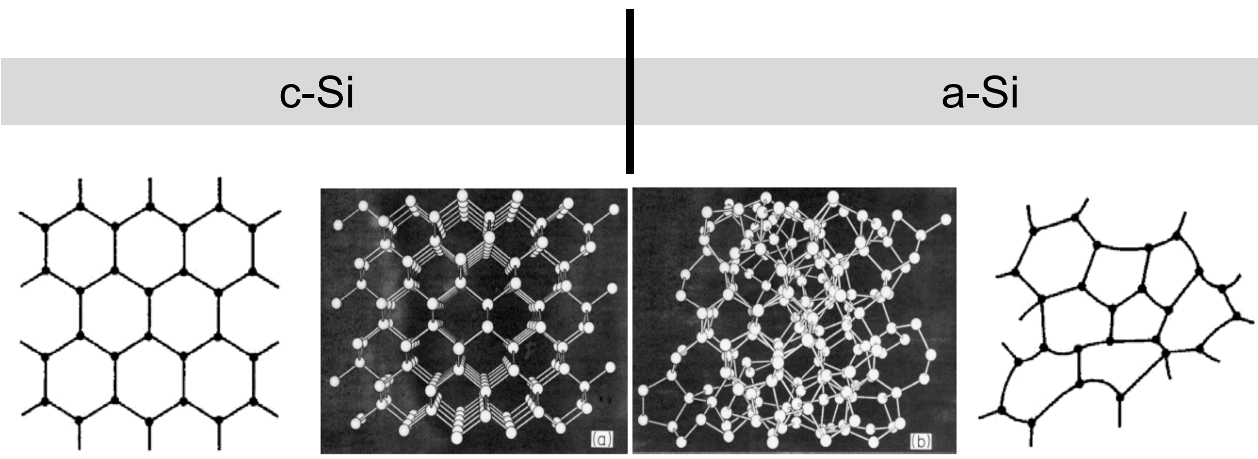




# Amorphous

"Amorphous" commonly refers to non-crystalline materials:

- chemical bonding of atoms nearly unchanged from crystals
- small, disorderly variation in the angles between the bonds eliminates regular lattice structure



# a-Si History

First thin films of amorphous silicon (a-Si) layers deposited in 1965 from silane in radio frequency glow discharge system

10y later, Spear and LeComber (Dundee University, Scotland) reported that a-Si had semiconducting properties ⇒ conductivity of a-Si can be improved by orders of magnitude by adding phosphine (P dopant) or diborane (B dopant) gas

Not recognized immediately that hydrogen plays very important role, but is this actually an alloy of silicon and hydrogen. Thus, electronic grade material is called hydrogenated amorphous silicon (a-Si:H)



# Also a Long History

Created huge interest, due to:

i) high absorption coefficient ($\alpha$) of a-Si:H in visible spectrum ⇒ 1 µm-thick a-Si:H layer can absorb 90% of usable solar energy in this range.

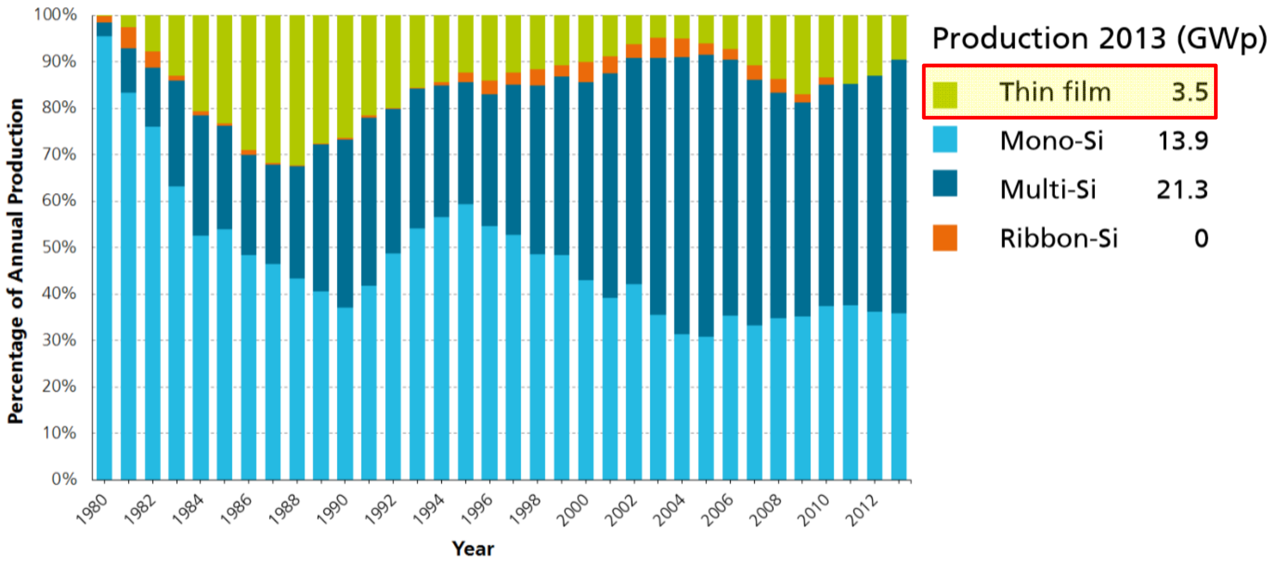
ii) glow discharge technique, also called plasma enhanced chemical vapour deposition (PECVD) ⇒ enabled production of a-Si:H films over >1m$^2$ area and at low-T (100–400°C)

⇒ low T enables use of low cost substrates, e.g. glass, metal or polymer foil

First a-Si:H solar cell Carlson and Wronski made in 1976 had $\eta$ = 2.4%, today capable of producing solar cells with *initial* efficiencies >15%

Today, regarded as a mature thin film solar cell technology

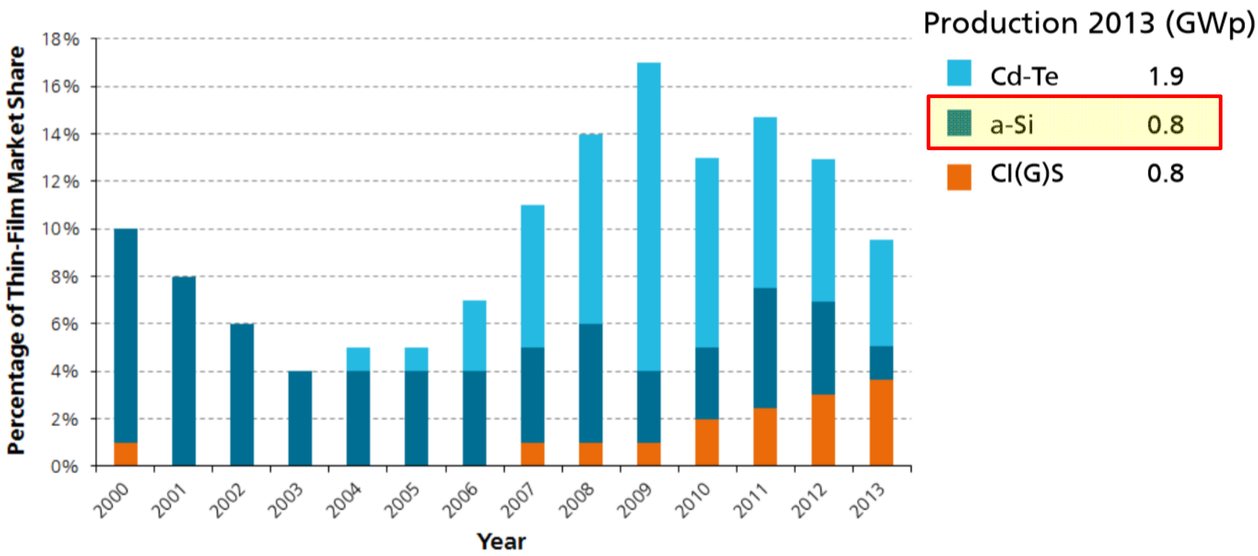
# Market Today




*Source:* http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf



# Market Today



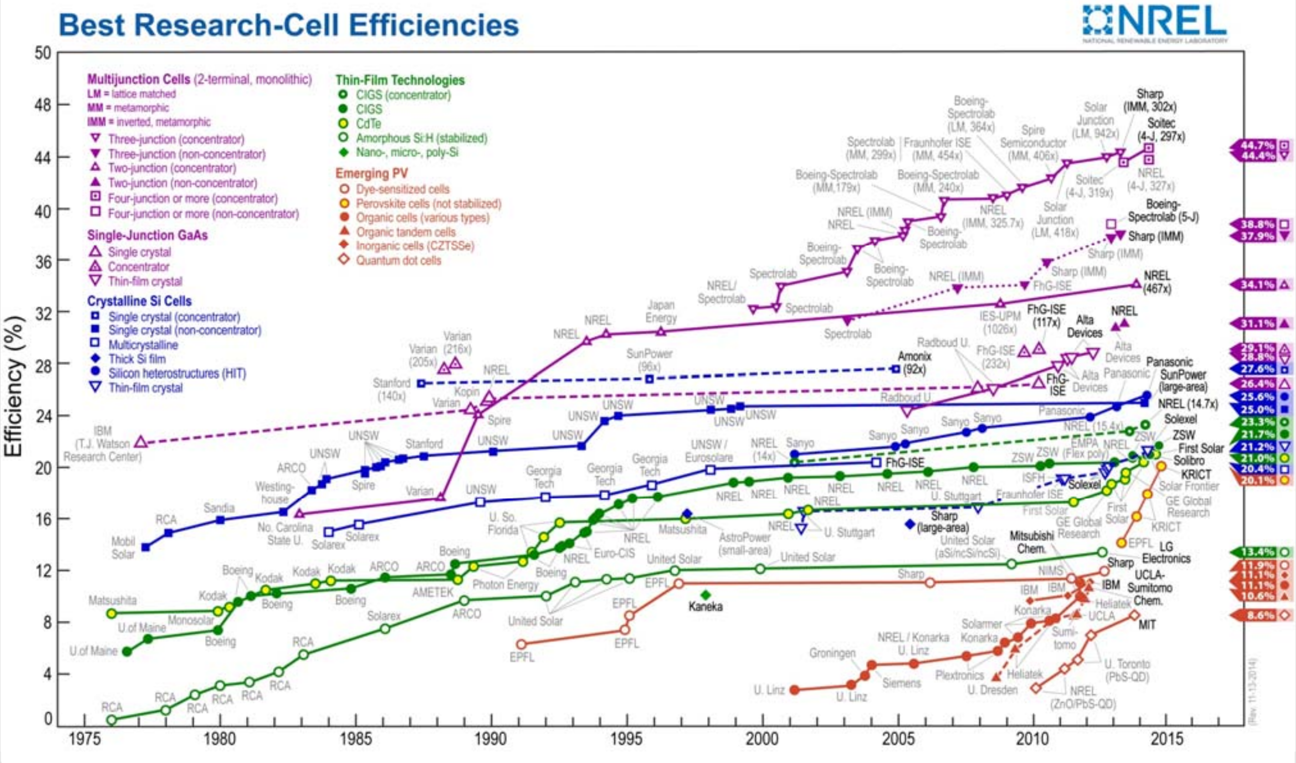

*Source:* http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

# Advantages of a-Si:H over c-Si

- Technology is relatively simple and inexpensive for a-Si:H
- For a given layer thickness, a-Si:H absorbs much more energy than c-Si (about 2.5 times)
- Much less material required for a-Si:H films, lighter weight and less expensive
- Can be deposited on a wide range of substrates, including flexible, curved, and on roll-to-roll processes
- Overall efficiency of around 10%, still lower than crystalline silicon; but improving ……?



# Solar Cell Efficiencies

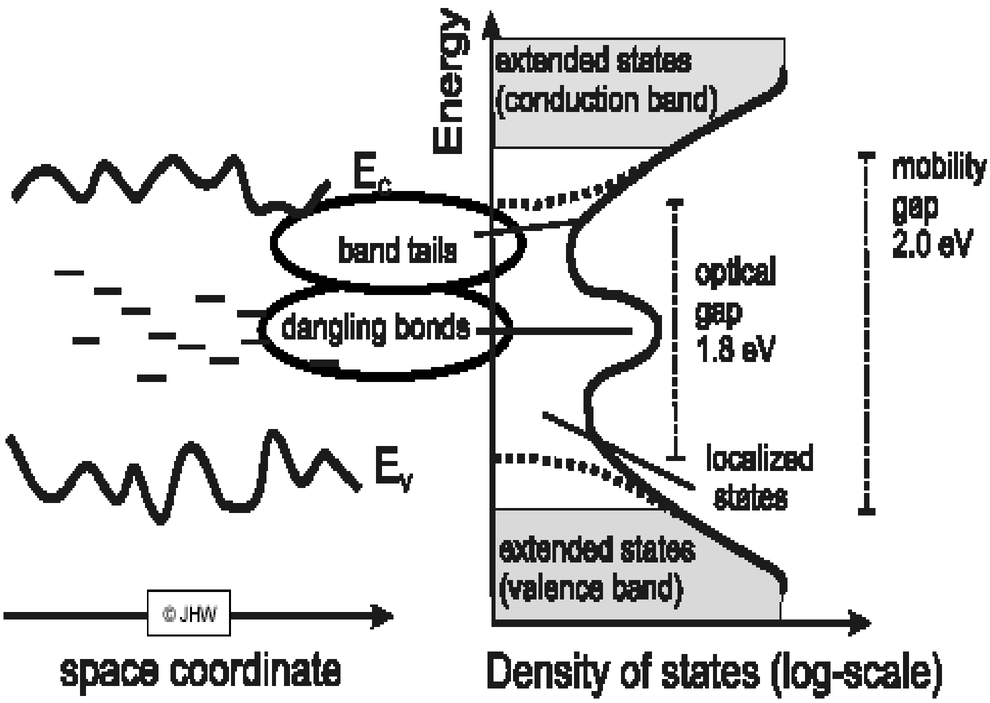


# Electronic Properties of a-Si:H

- no *k*-selection rules for optical transitions
- a-Si:H ⇒ direct bandgap
  ⇒ high absorption ~ $10^5$ $cm^{-1}$
- Bands are "smeared" ⇒ no clear bandgap
- Fluctuation of the band edges
- Irregularity ⇒ band tail
  ⇒ states at the band centre



# Electronic Properties of a-Si:H



# Electronic Properties of a-Si:H

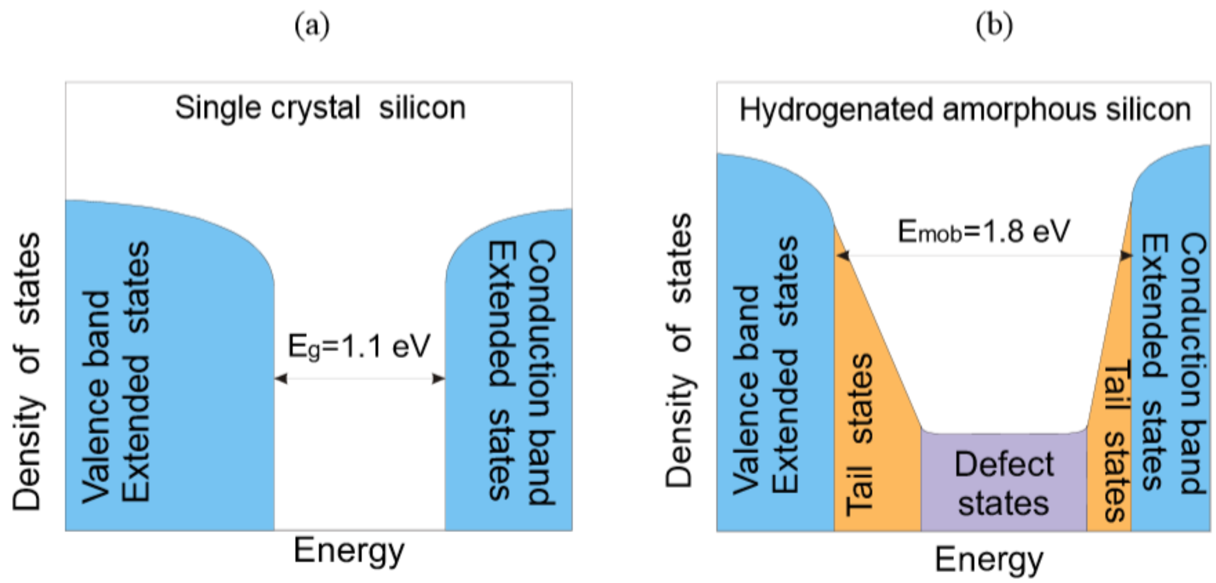
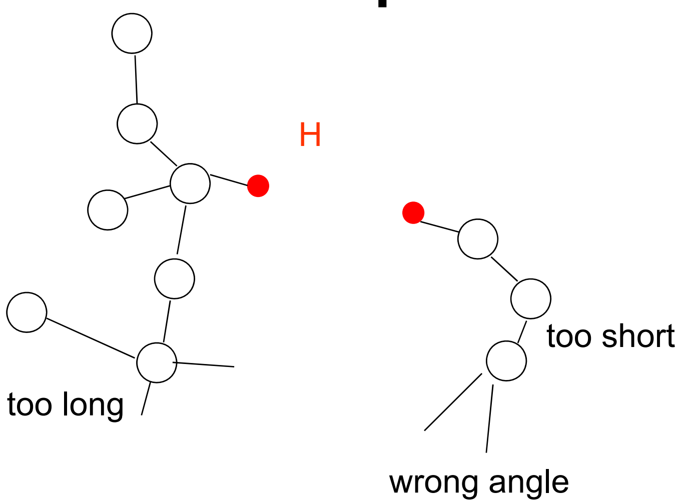


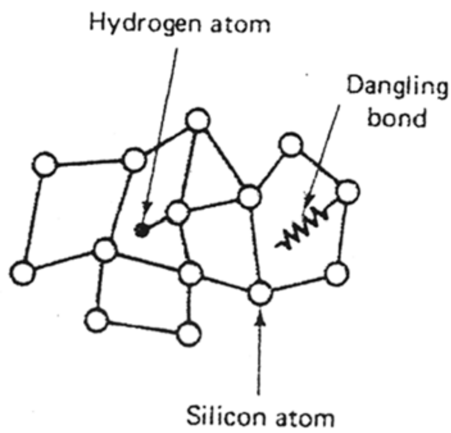

Figure 7.2. The schematic representation of the distribution of density of allowed energy states for electrons for (a) single crystal silicon (b) *a*-Si:H.

*Source:* http://ocw.tudelft.nl/fileadmin/ocw/courses/SolarCells/res00030/CH7_Thin_film_Si_solar_cells.pdf



# Electronic Properties of a-Si:H




- Dangling bonds are passivated with H
- a-Si: H contains ~10% H ⇒ hence termed an “alloy” and not a “dopant”
- defect density $10^{16}/cm^3$ (c.f. $10^{21}/cm^3$ for non-hydrogenated a-Si)
- Problem: not all Si-H bonds are light stable

  ⇒ light induced degradation

# Electronic Properties of a-Si:H

Doping: in principle the same as with c-Si, but doping efficiency << in a-Si:H (~ unity in c-Si, but in range $10^{-2} – 10^{-3}$ in a-Si:H)

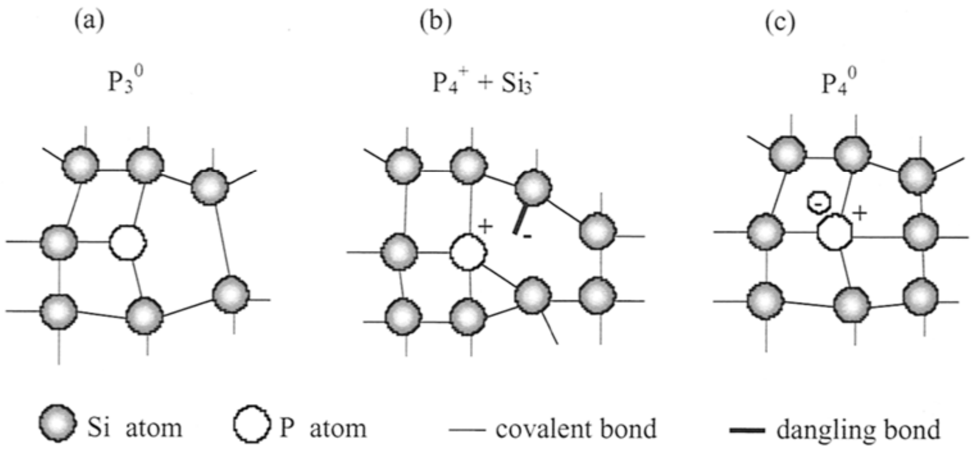



**Figure 5.8** Possible configurations of a phosphorous atom in an a-Si:H network: (a) the nondoping state $P_3{}^0$, (b) the defect compensated donor state $P_4{}^+ + Si_3{}^-$, (c) the neutral donor $P_4{}^0$.

*Source: Poortmans, "Thin Film Solar Cells – Fabrication, Characterization and Applications"*

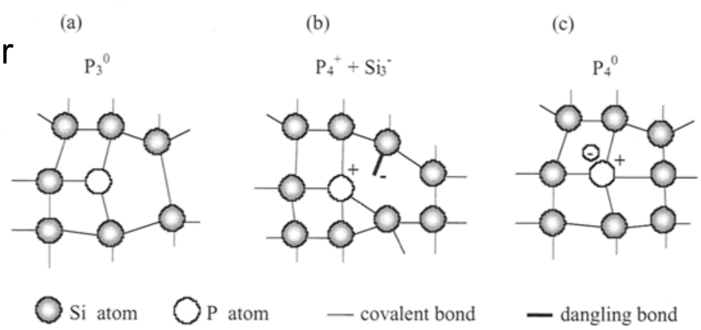

source: J. Poortmans

# Electronic Properties of a-Si:H

a) following "8 − *N* rule" ⇒ P atom with 5 valence e⁻ will incorporate itself in a-Si:H random network by forming 3 covalent bonds
⇒ most common bonding, but <u>electrically inactive</u>!

b) most P atoms that contribute to doping are not neutral donors but charged phosphorus atoms ⇒ formation of charged state accompanied by formation of negatively charged dangling bond ⇒ energetically more favourable than c) ⇒ called "defect compensated donor"

c) P atom introduced in network as neutral donor like in c-Si ⇒ required much higher energy ⇒ therefore unstable in the a-Si:H matrix

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# Electronic Properties of a-Si:H

| a-Si:H | c-Si | |
|---|---|---|
| $\mu_e \approx 20\ cm^2/Vs$ | 1100 | very low mobility with a-Si:H |
| $\mu_h \approx 5\ cm^2/Vs$ | 300 | |

High density of localized states ⇒ carriers spend ~90% of their time in "traps" ⇒ effective mobility is reduced further!

Minority carrier lifetime, $\tau \approx 1$ µs (c.f. 100 µs to 1ms in c-Si)

⇒ Typical $\mu\tau$ product $10^{-6}$ - $10^{-7}$ $cm^2/V$ ($e^-$)

$10^{-7}$ - $10^{-8}$ $cm^2/V$ ($h^+$)

"Drift length": average distance that a carrier with its drift velocity in an electric field *E* im Feld E can travel before it recombines

$$L_E = v_E \tau = \mu\tau \cdot \left|\vec{E}\right| = 1\mu m \qquad , \left|\vec{E}\right| = 10^4 V/cm$$

Diffusionslänge: $L_D = \sqrt{D\tau} = \sqrt{\mu\tau kT/q} \approx 0.15$ µm ($kT/q$ = 25mV)

Since $L_E$ depends on the field ⇒ voltage dependence of the current collection (worse FF)



# *p-i-n* Junction Diodes

Key difference between *p-n* junction and *p-i-n* junction ⇒ layer between *p*-doped and *n*-doped layer has been left undoped and is hence intrinsic, *i*

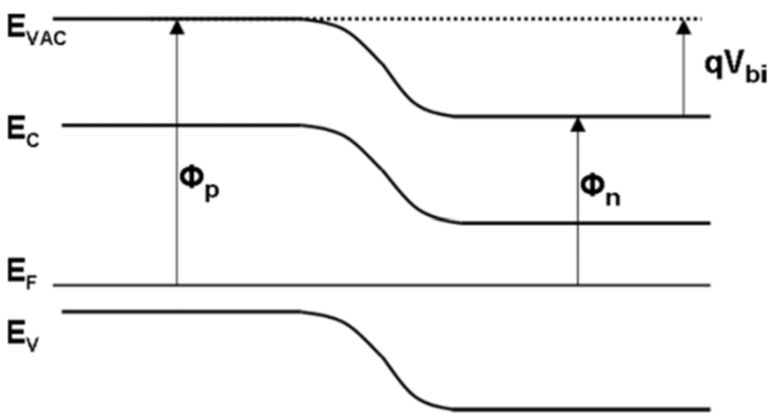
In this case, the built-in bias is the same as for *p-n* junction, but electric field extends over a wider region ⇒ depletion region is elongated.

Preferable in materials with short minority carrier diffusion lengths *L*, where photogenerated minority carriers experience many recombination paths

Work function ≡ minimum energy needed to move $e^-$ from Fermi energy level, $E_F$, to vacuum energy, $E_{vac}$

$$\Phi_w = E_{vac} - E_F$$

For *p-n* junction looks like:



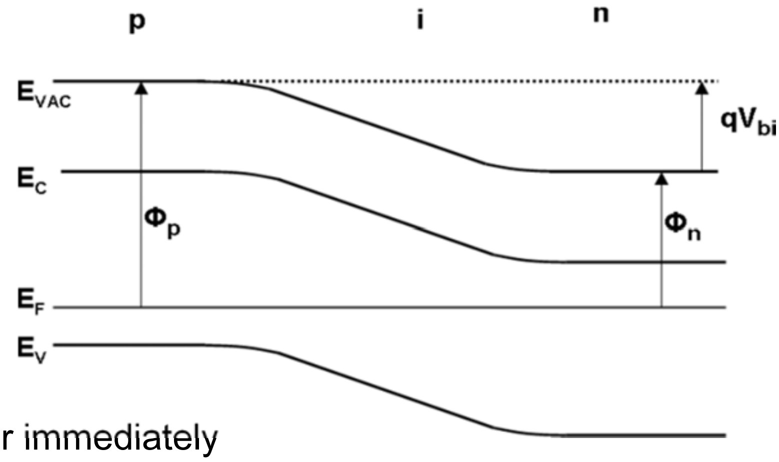

Source: http://org.ntnu.no/solarcells/pages/Chap5.php



source: J. Poortmans

# p-i-n Junction Diodes

For *p-i-n* junction it looks like:




$L_{diff}$ (a-Si:H) ≈ **150 nm** in *i* region ⇒ but then also 2-3 orders of magnitude lower in doped regions
⇒ cannot work as *p-n* junction

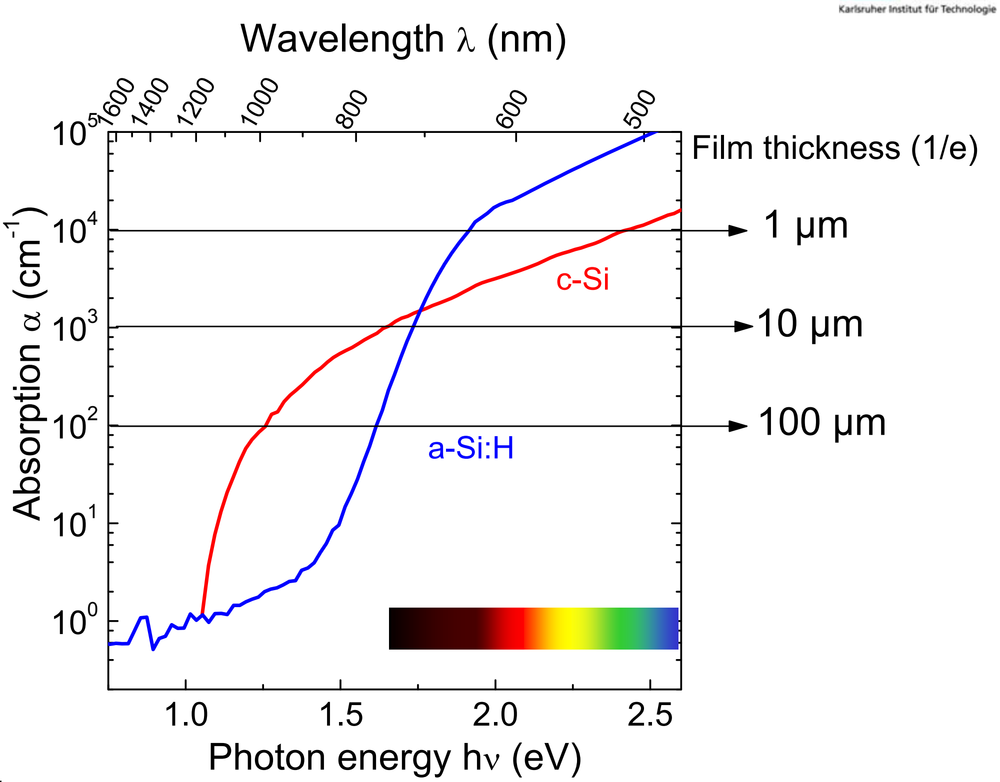
$e^-$-$h^+$ pairs generated in *i*-layer immediately experience internal electric field ⇒ separated carriers drift under influence of this electric field towards doped layers ($e^-$ towards *n*-type layer and $h^+$ towards *p*-type layer) ⇒ collected by electrodes

Dominant transport mechanism of photo-generated carriers is drift in internal electric field ⇒ a-Si:H solar cell is called a drift device

*Source: http://org.ntnu.no/solarcells/pages/Chap5.php*

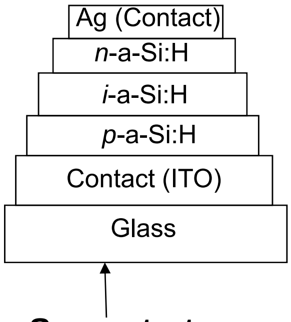

source: J. Poortmans

# Light Absorption in a-Si:H

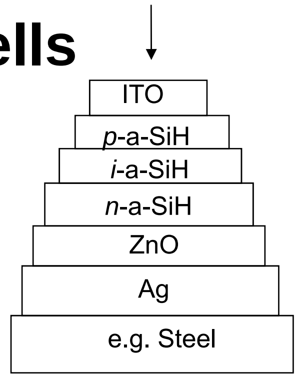



*Courtesy of FZJ – IEF 5*

# Structure of a-Si:H Solar Cells




**Superstrate**




**Substrate**

Advantages and disadvantages

Superstrate or substrate conversation?

- Encapsulation under polymer/glass on front or polymer/foil on back
- Transparent front electrodes made front transparent conducting oxides (TCOs) such transparent conducting oxides (TCOs) such as indium tin oxide (ITO: 90% $In_2O_3$, 10% $SnO_2$) of aluminium-doped zinc oxide (ZnO:Al)
- Deposition temperatures – limit of super/substrate?

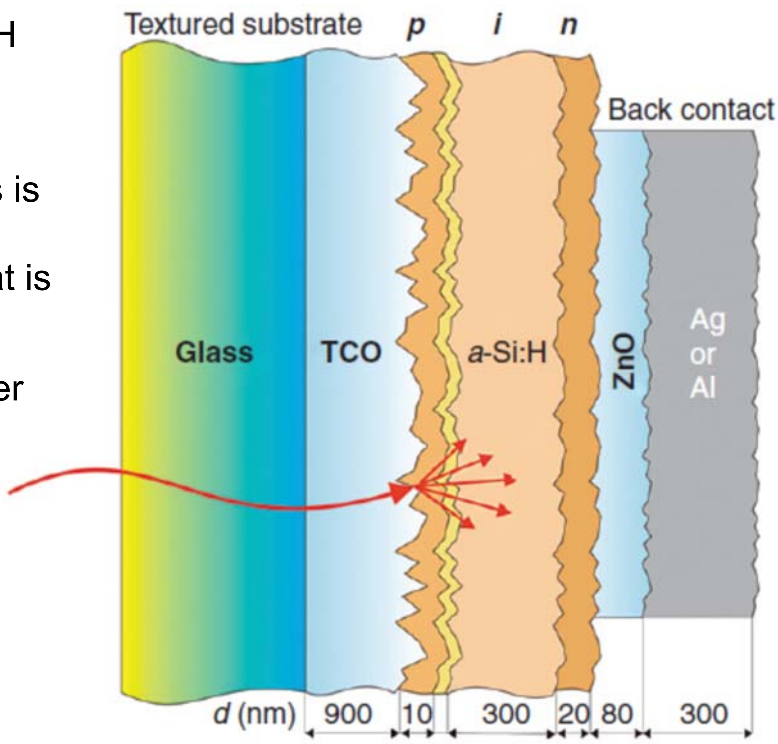
N.B. interconnections integrated are into the manufacturing process



# Structure of a-Si:H Solar Cells

For this single-junction a-Si:H solar cell, some things to consider:

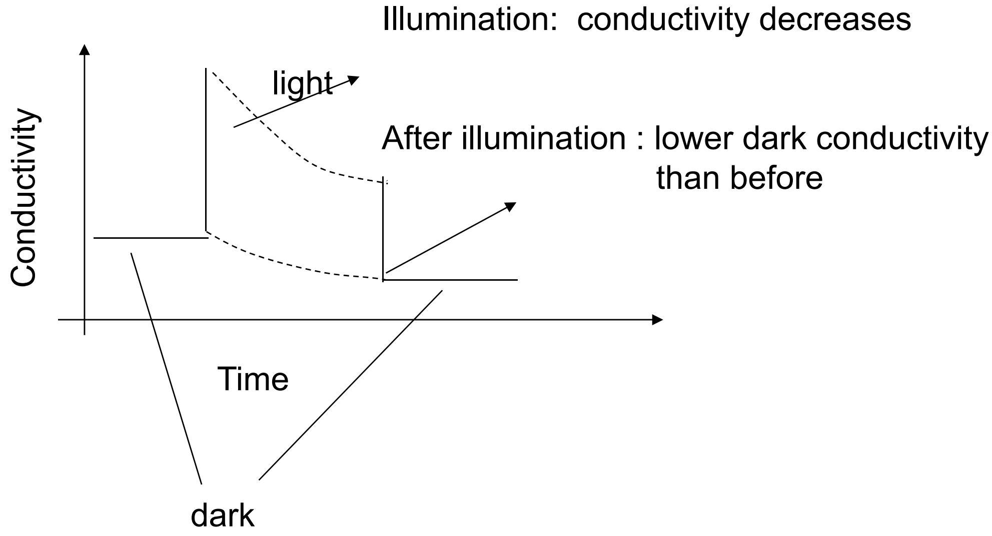
1) Light trapping in thin films is very important – but note here it is not the glass that is textured but the TCO
2) Understand choice of layer thicknesses – there are usually trade-offs!




Source: http://www.sciencedirect.com/science/referenceworks/9780080878737#ancv1

# Staebler-Wronski Effect

The SWE is a light induced degradation of the electronic properties of the a-Si:H

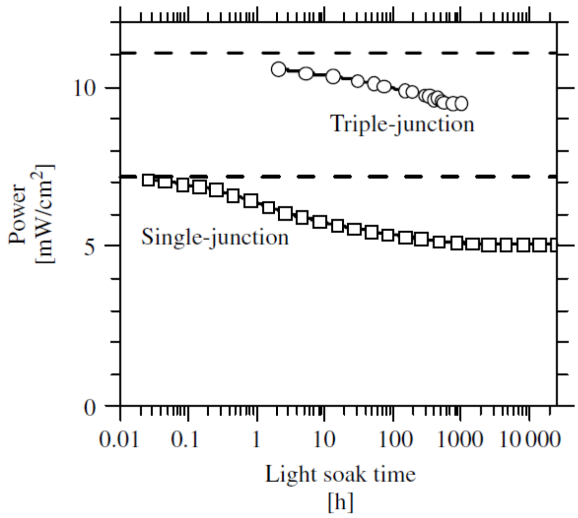


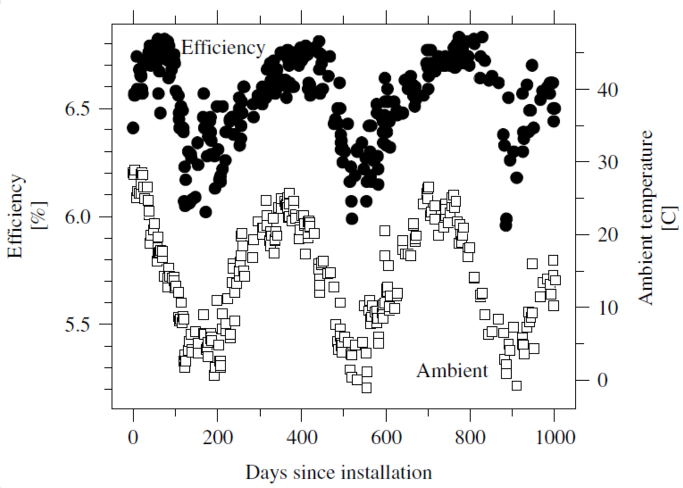

Photoconductivity degrades with time
Can be reversed via heating at T=150°C for a few hours



# Staebler-Wronski Effect

Significant decline in $\eta$ of a-Si:H solar cells during first 100-1000h of illumination $\Rightarrow$ steady- state performance reached after ~1000h




First noticed via seasonal variations in conversion efficiency:

$\Delta T$ = +20°C $\Rightarrow$ there is an increase in $\eta$ with increasing $T$

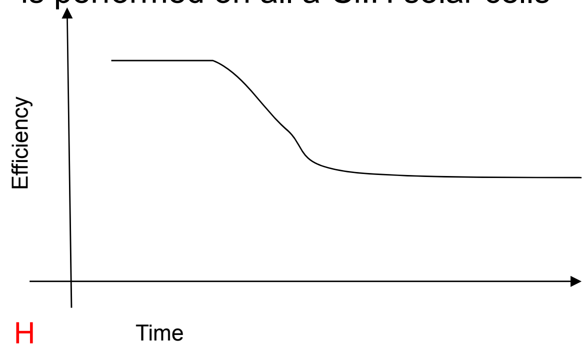
remember, c-Si is opposite, where $\eta$ decreases with increasing $T$

Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

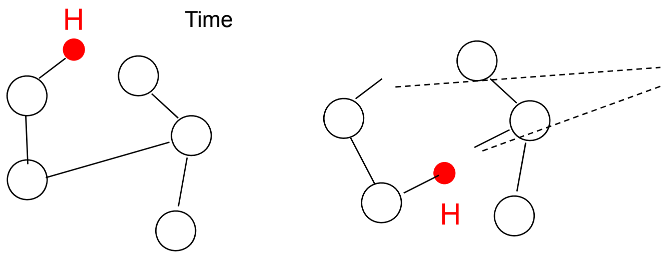
# Staebler-Wronski Effect

Due to SWE, “light soaking” is performed on all a-Si:H solar cells
⇒ two efficiencies quoted:

initial & stabilized




Mechanism:



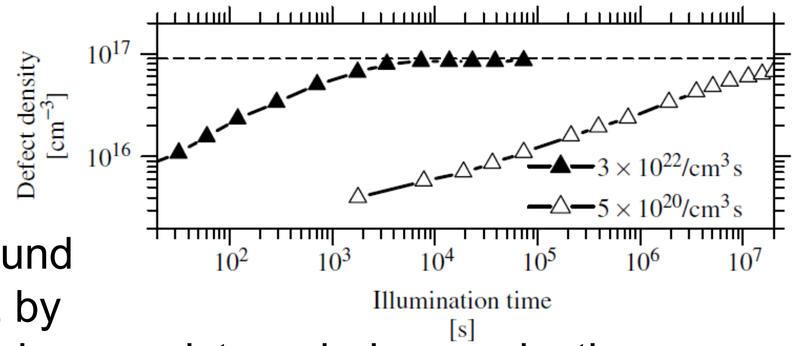

2 non-passivated or “dangling” bonds result

The excess energy of the recombination of $e^-$-$h^+$ pair breaks the weak Si-H bond ⇒ forms dangling bonds, which lie deep in the forbidden band



# Staebler-Wronski Effect

- Performance degrades during illumination because defect density (dangling bonds) increases, which will capture $e^-$ created by photons



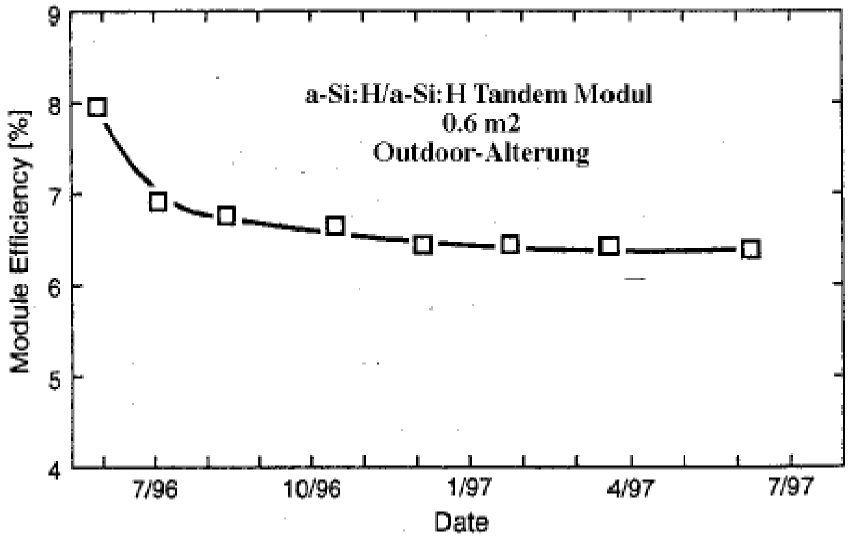

- Researchers have found ways to reduce SWE by incorporating fluorine in gas mixture during production
- Fluorine bonds tighter to silicon than hydrogen, and is less mobile in the a-Si network
- a-Si:F cells show much better stability under light soaking

Source: “Amorphous Silicon-based Solar Cells” by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

## Staebler-Wronski Effect

- Another example for a-Si:H / a-Si:H tandem PV module

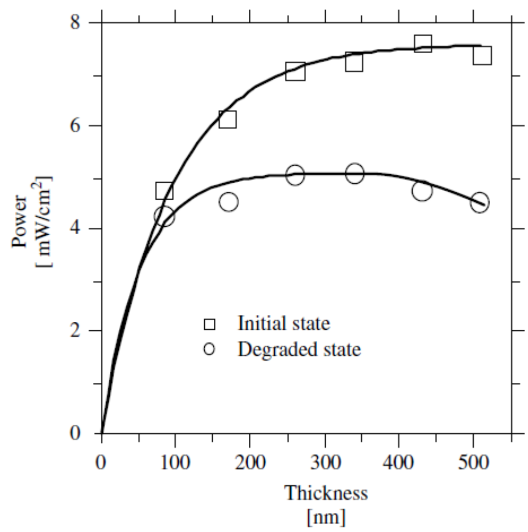
Today: 5 -7 %






## Staebler-Wronski Effect

- SWE worse in thicker absorber layers ⇒ motivation for thinner intrinsic layers in a-Si:H solar cells




Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

**Figure 12.21** Power output (standard solar illumination) for a series of *nip* solar cells with varying intrinsic layer thickness [14]. The degraded state was obtained by 25 000 h of light soaking. The curves are guides only

# Alloys of a-Si:H

- Alloying with elements, such as Ge and C, can be accomplished during film production
- Resulting alloys have wide ranges of bandgaps
- Proven to be very useful for creating multijunction solar cells, where the narrow bandgap of a-SiGe allows for increased absorption of lower energy photons
- No need for lattice matching, as with other crystalline semiconductor systems

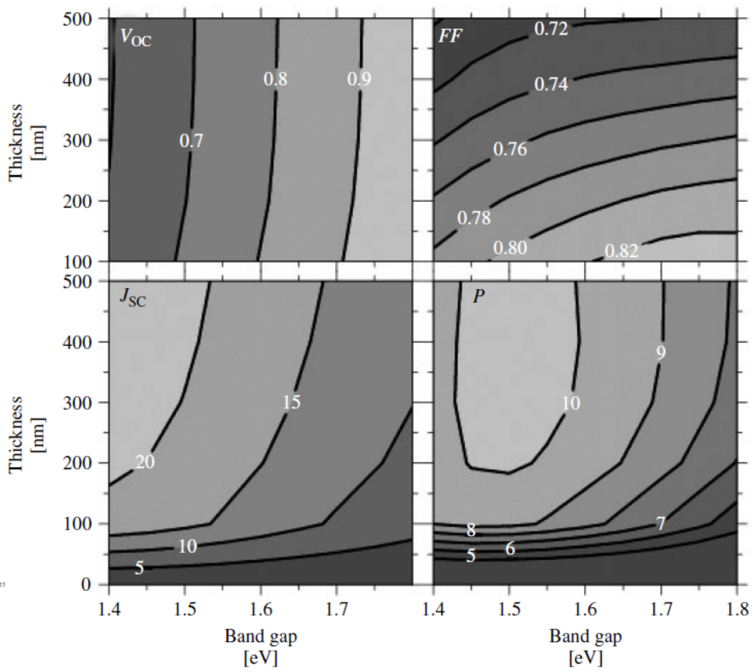
Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus



# Alloys of a-Si:H

Inclusion of C in a-Si: H increases $E_g$ (~2.0 eV for a-SiC:H)

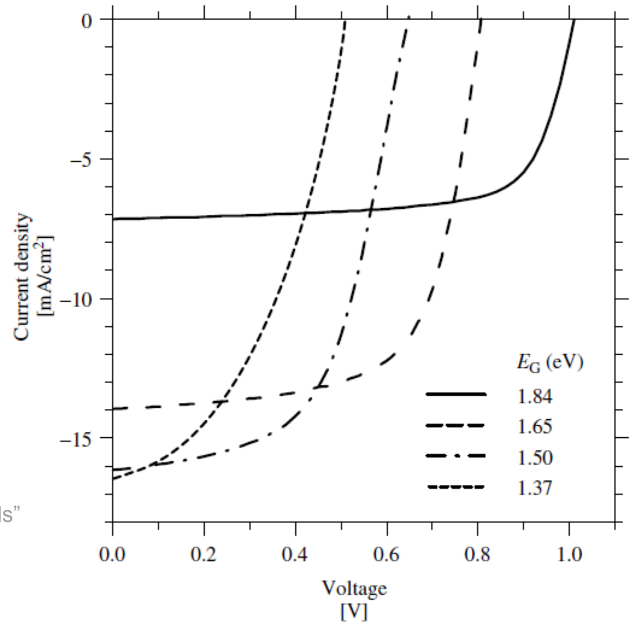
Inclusion of Ge in a-Si: H decreases $E_g$ (~1.0eV for a-Ge:H)




Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

**Figure 12.20** Model calculations of the short-circuit current $J_{SC}$ (mA/cm$^2$), open-circuit Voltage $V_{OC}$, (V), fill factor *FF*, and power *P* under AM1.5 illumination for a-Si:H-based *pin* solar cells with varying intrinsic layer band gaps and thicknesses. No back reflector or texturing effects are included

# Alloys of a-Si:H

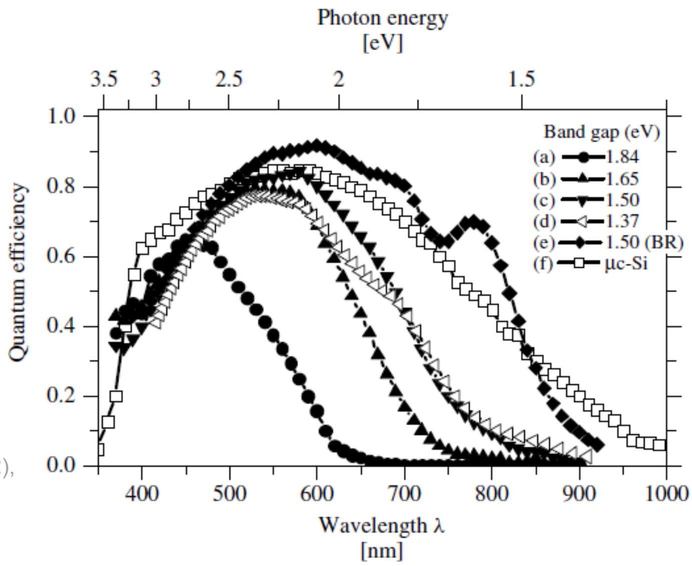



Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

**Figure 12.23** Performance of a-Si and a-SiGe *nip* solar cells with different Ge concentrations in the *i*-layer; the *i*-layer band gaps are indicated in the legend. The fill factors for these cells are 0.70, 0.62, 0.55, and 0.43 for the cells with *i*-layer band gaps of 1.84, 1.65, 1.50, and 1.37 eV, respectively [149]



# Alloys of a-Si:H

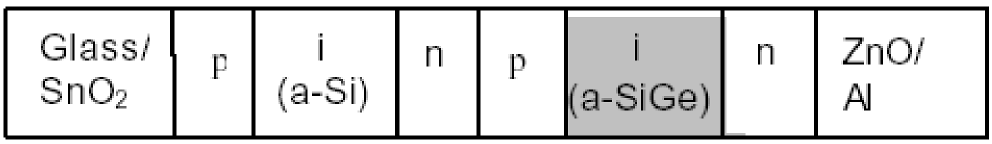



Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

**Figure 12.24** Quantum efficiency (*QE*) spectra for a series of a-Si- and a-SiGe-based *pin* single-junction solar cells. Shown in the figure are *QE* curves for single junction solar cells with (a) 1.84 eV a-Si *i*-layer, (b) 1.65 eV a-SiGe *i*-layer, (c) 1.50 eV a-SiGe *i*-layer, (d) 1.37 eV a-SiGe *i*-layer, (e) 1.50 eV a-SiGe *i*-layer, with the device deposited on a back-reflector (BR), (f) μc-Si *i*-layer. Curve (f) is included here for a later discussion in Section 12.5.4. Curves (a) through (e) are from [149] and curve (f) is from [150]

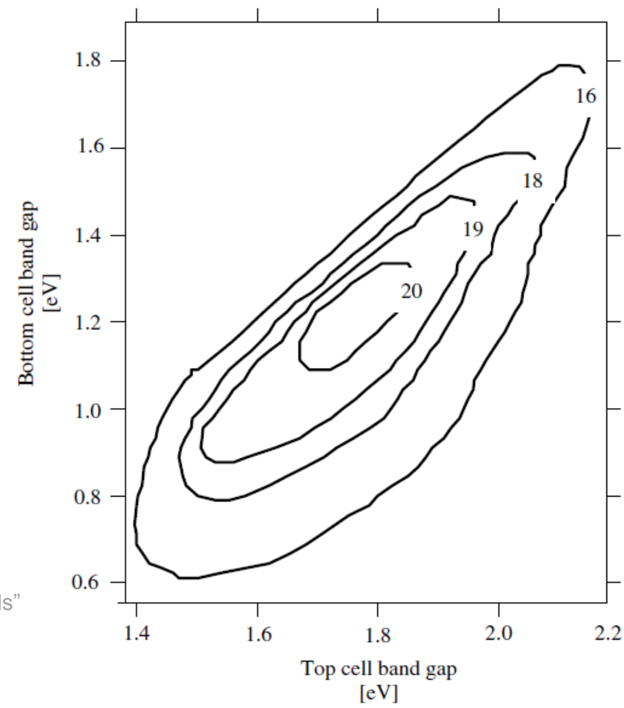
# Multijunction Solar Cells

- Stacking of multiple solar cells on top of one another – also called "tandem" solar cells
- Very thin p⁺/n⁺ tunnel junction allows electrons to "tunnel" through
- The voltages of the two cells in series add
- The current is determined by the minimum of the currents in each device ⇒ tandem solar cells require "current matching"
- With a-Si:H these are typically double junction (shown below) and triple junction devices






# Multijunction Solar Cells

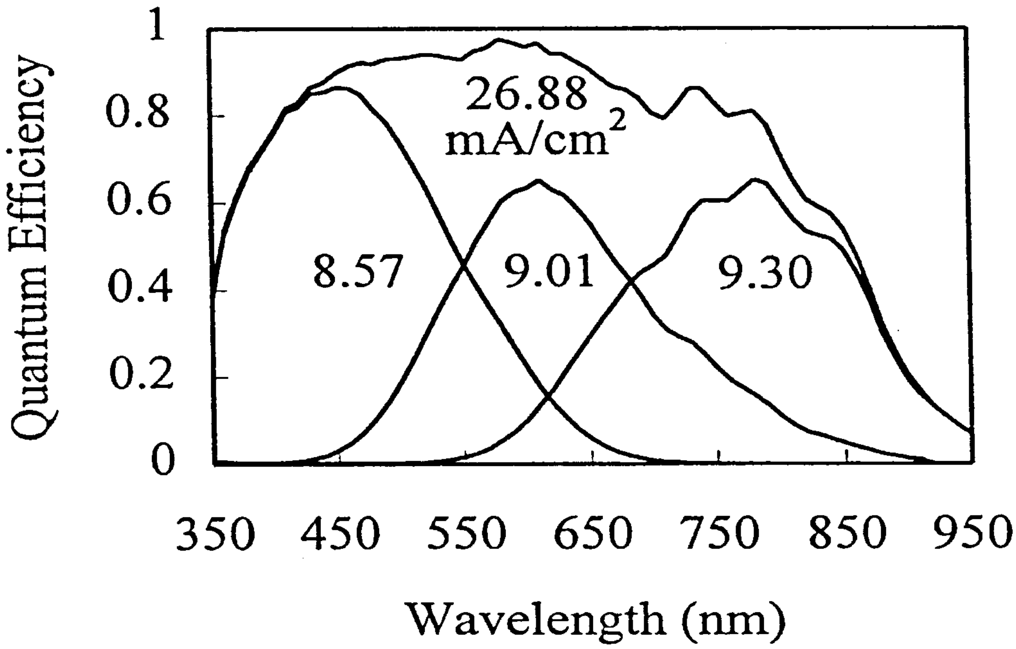



Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

**Figure 12.22** Contour plot of constant solar conversion efficiency for a-Si-based tandem solar cells for varying band gaps $E_G$ of the top cell and the bottom cell [145]

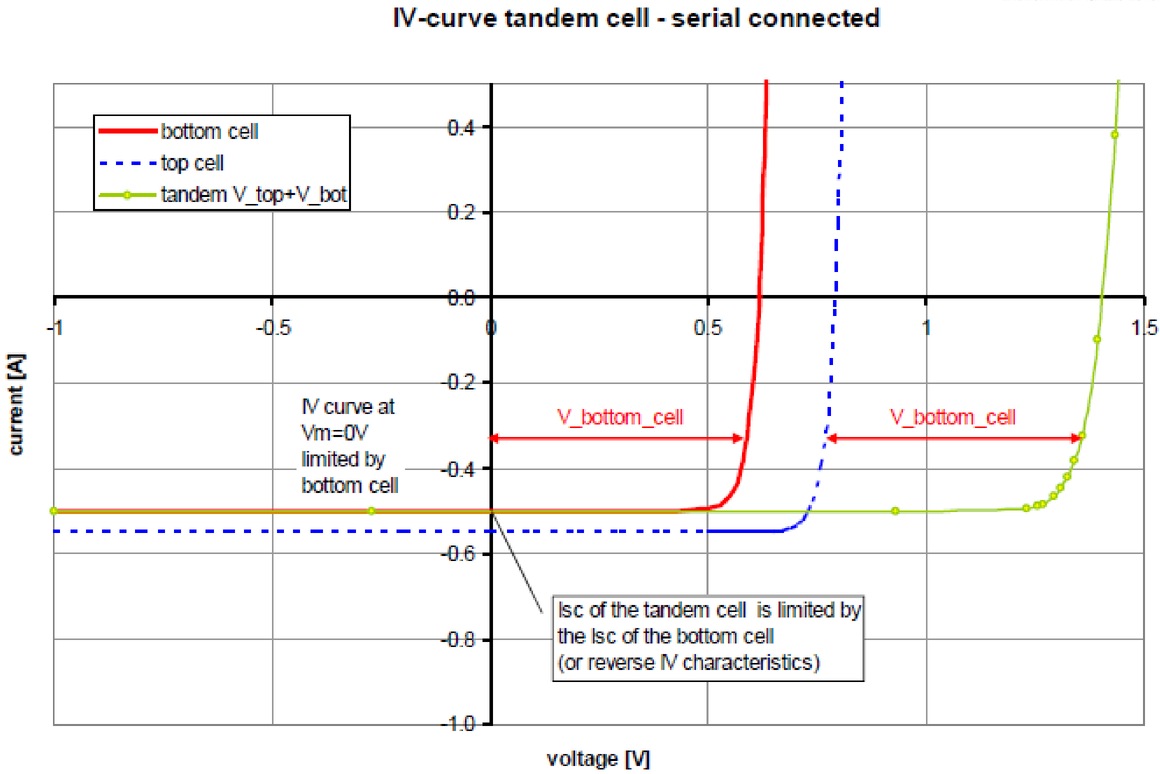
# Multijunction Solar Cells

Current matching in triple junction device



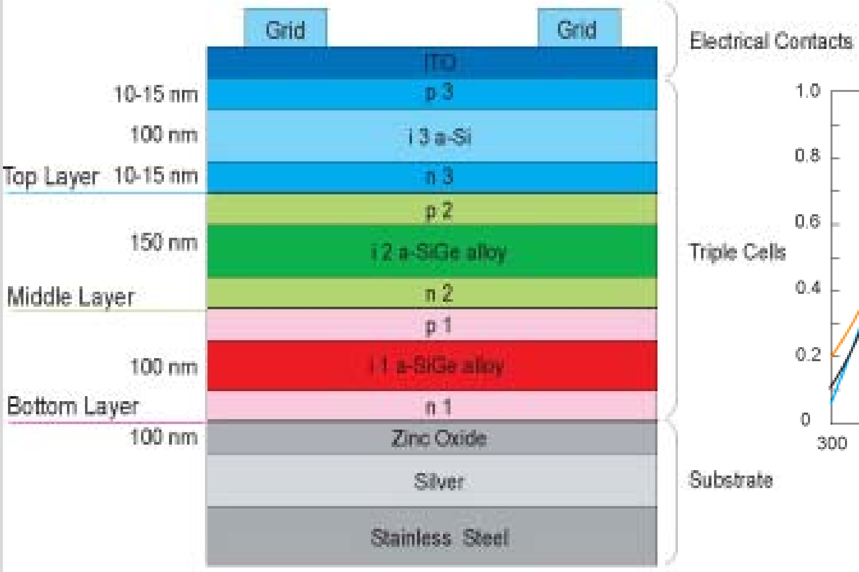



# Multijunction Solar Cells

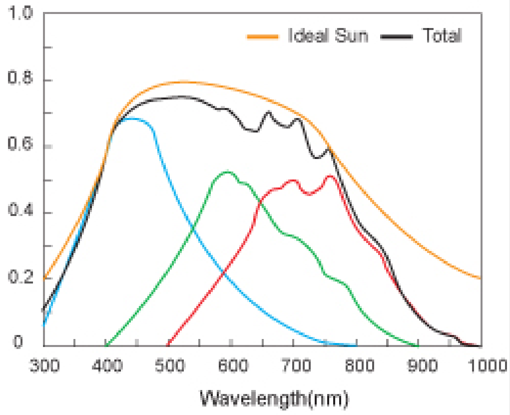



Source: Franz Baumgartner, www.zhaw.ch/~bauf/ ; 2011-03-01; OTTI Staffelstein, BRD

# Multijunction Solar Cells



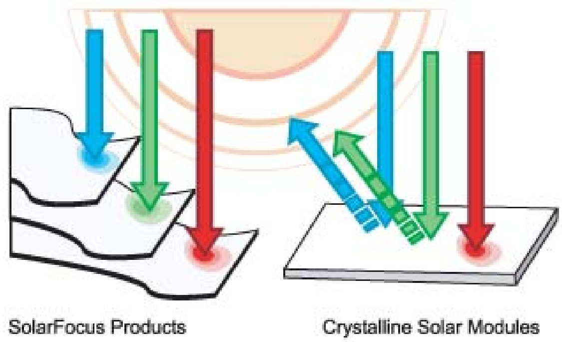

Schematic of a triple junction cell

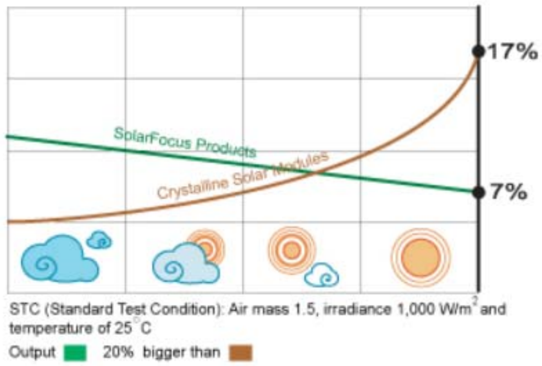



Source: http://www.solarmio.com/en/StandardCards.aspx?type=1SC1

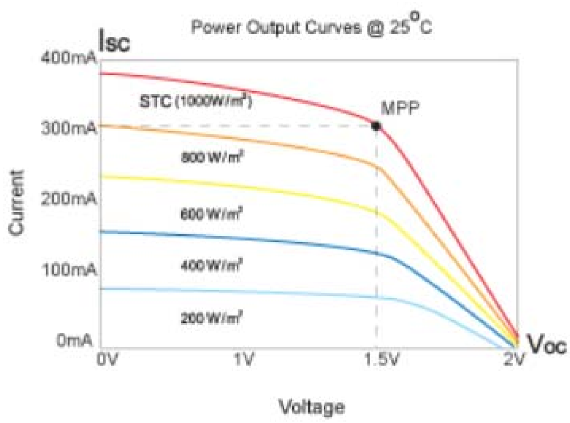


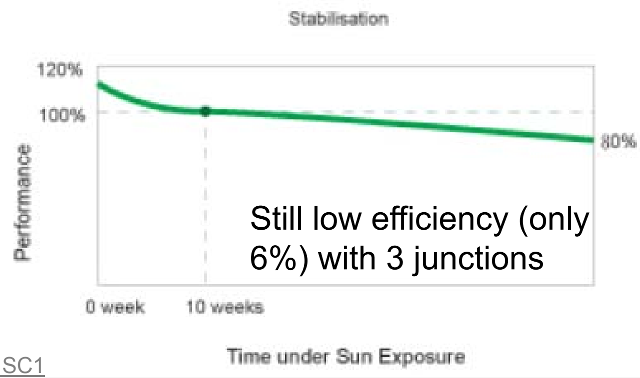
# Multijunction Solar Cells




Power output in different conditions




Still low efficiency (only 6%) with 3 junctions

Source: http://www.solarmio.com/en/StandardCards.aspx?type=1SC1

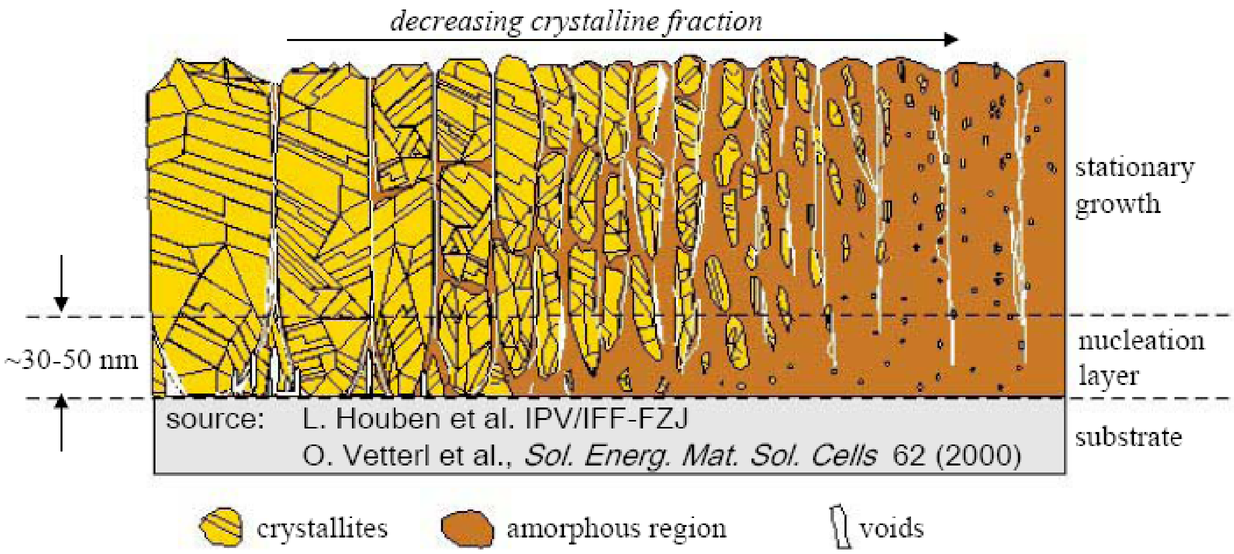
# a-Si:H / μC-Si:H Solar Cells

- Has been the main hope of a-Si:H for enhancing both efficiency and stability in recent years
- Minimal change to deposition processes: just increasing the deposition temperature to get μc-Si instead of a-Si:H
- Deposition time challenge: ~0.3 μm of c-Si takes 30 min (ideally would be at something like ~3 μm / h)
- Bandgaps match: a-Si:H = 1.7–1.8 eV (direct)
  μc-Si:H = 1.1 eV (very similar to c-Si and still indirect)
- μc-Si:H exhibits relatively poor absorption
  ⇒ light trapping structures necessary (afforded via TCO)
- Thicker absorber layers 1-3 μm ⇒ 5 – 10x thicker than a-Si:H
- Improved stability: light induced degradation improved (stable at ~10%)
- Advantage: light reduced degradation less ⇒ none or very low
- Disadvantage: low absorption ⇒ solution: textured ZnO TCO

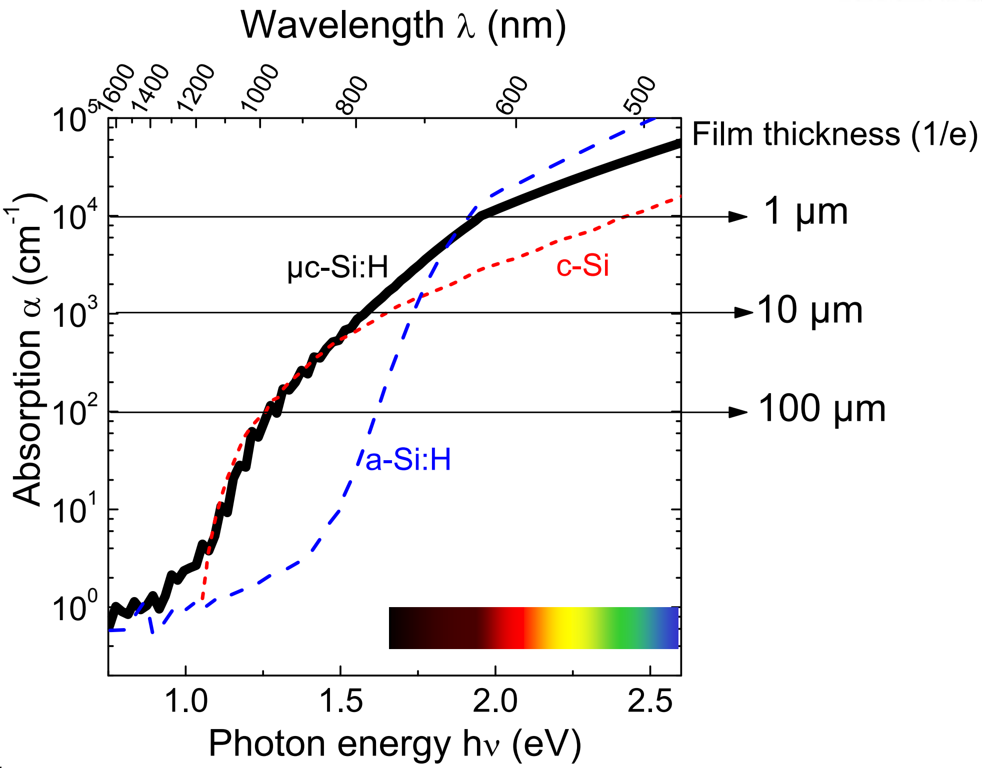


# a-Si:H / μC-Si:H Solar Cells

influence of deposition parameters: silane concentration, power, frequency, temperature, ...



# Light Absorption in μc-Si:H




*Courtesy of FZJ – IEF 5*

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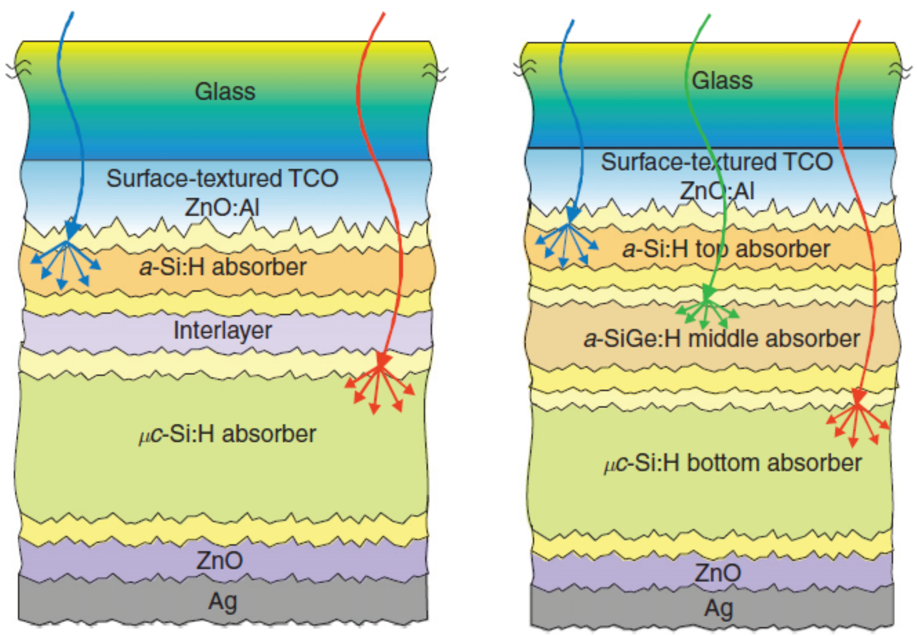
# a-Si:H / μC-Si:H Solar Cells

Double- and triple-junction devices:



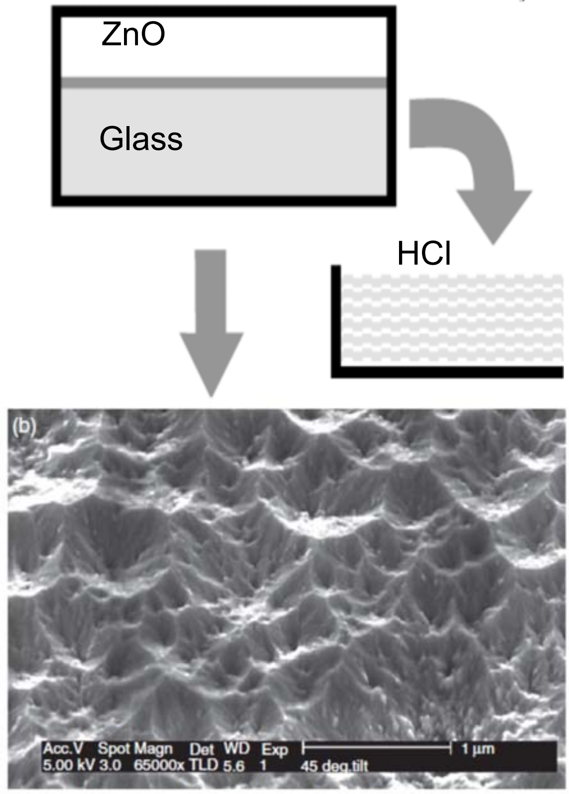

Source: http://www.sciencedirect.com/science/referenceworks/9780080878737#ancv1

# a-Si:H / µC-Si:H Solar Cells

Texturing of ZnO TCO to enhance light trapping within solar cell:

ZnO is etched in hydrochloric acid (HCl)…

… to create crater-like surface structures

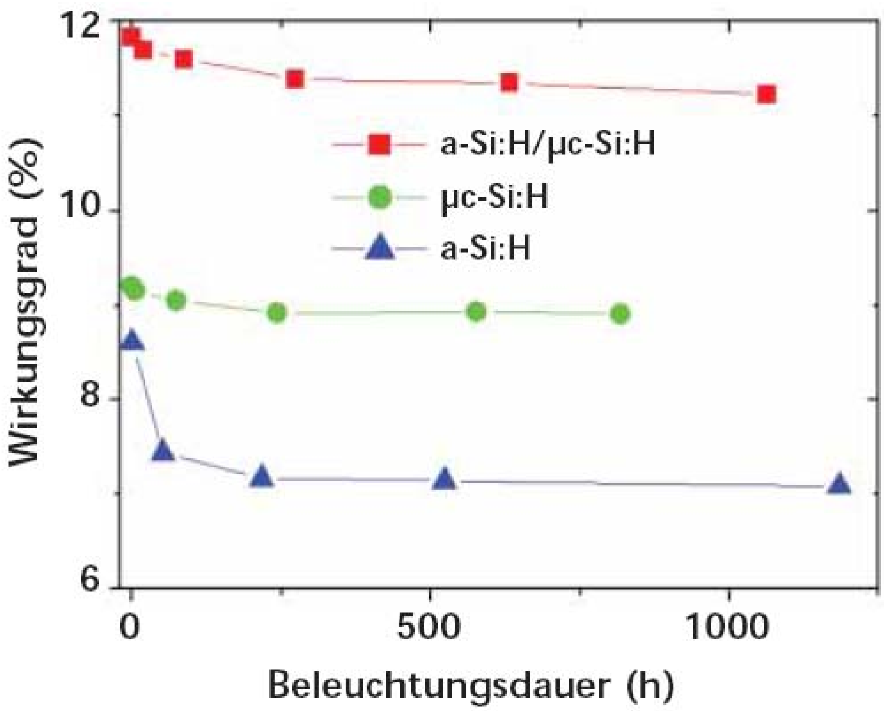



Source: http://www.sciencedirect.com/science/referenceworks/9780080878737#ancv1



# a-Si:H / µC-Si:H Solar Cells

Dependence of efficiency (Wirkungsgrad) on illumination time (Beleuchtungsdauer) for different silicon thin film solar cells



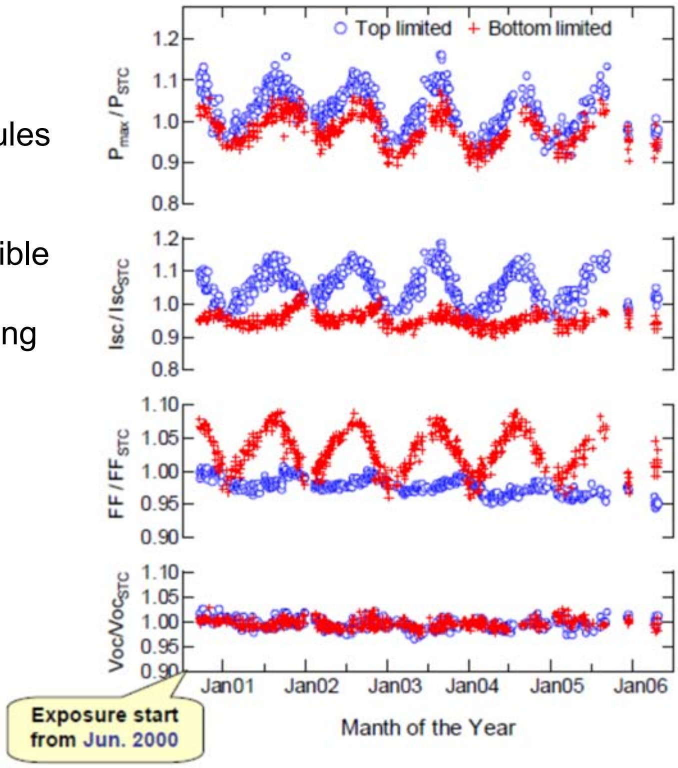
# a-Si:H / μC-Si:H Solar Cells

Comparison of outdoor performance of a-Si:H/μc-Si:H solar cells

Outdoor performance of a-Si/μc-Si modules over 7 years

Significant summer-winter effect discernible

Reason: reversible light-induced annealing of defects at elevated temperatures




Source: Kaneka



# Fabrication of a-Si:H PV Modules

Fabrication steps:

1. Glass cleaning (abrasive + washing)
2. Front contact (sputtering of 50 mm $SiO_2$, deposition 600 mm $SnO_2$:F

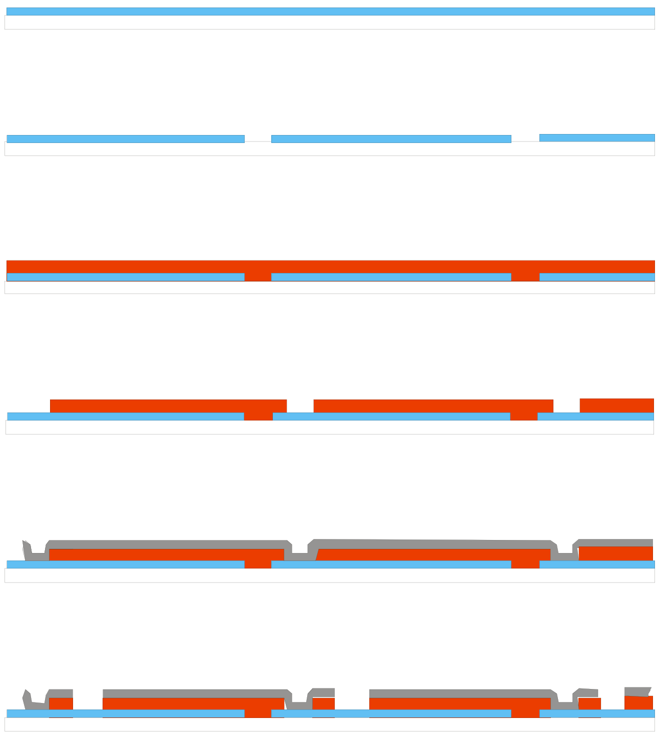
   Paste und firing (Ag busbar)
3. Structuring of front contact (laser patterning and wet chemical cleaning)
4. 20 nm *p*-type a-Si:H

   500 nm *i*-type a-Si:H } *pin* junction

   20 nm *n*-type a-Si:H
5. Sputtering of back Al contact (or evaporation)

   Laser scribing of back contact and a-Si (or back contact TCO/metal double layer)
6. Laser welding of contact strips
7. Test and encapsulation

# Fabrication of a-Si:H PV Modules



TCO /Glass : e.g. ITO

Laser patterning

a-Si: layers

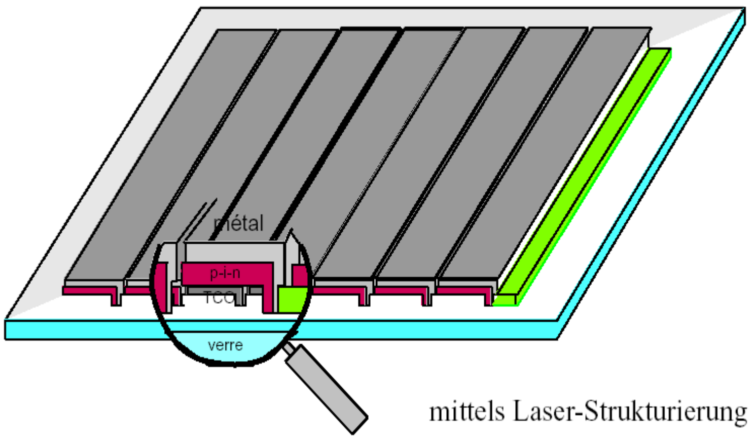
Laser patterning

Back contact e.g. Al or Ag

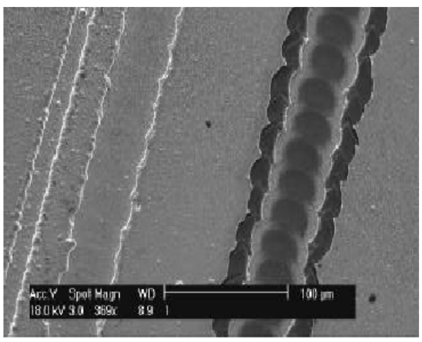
Laser patterning



# Fabrication of a-Si:H PV Modules



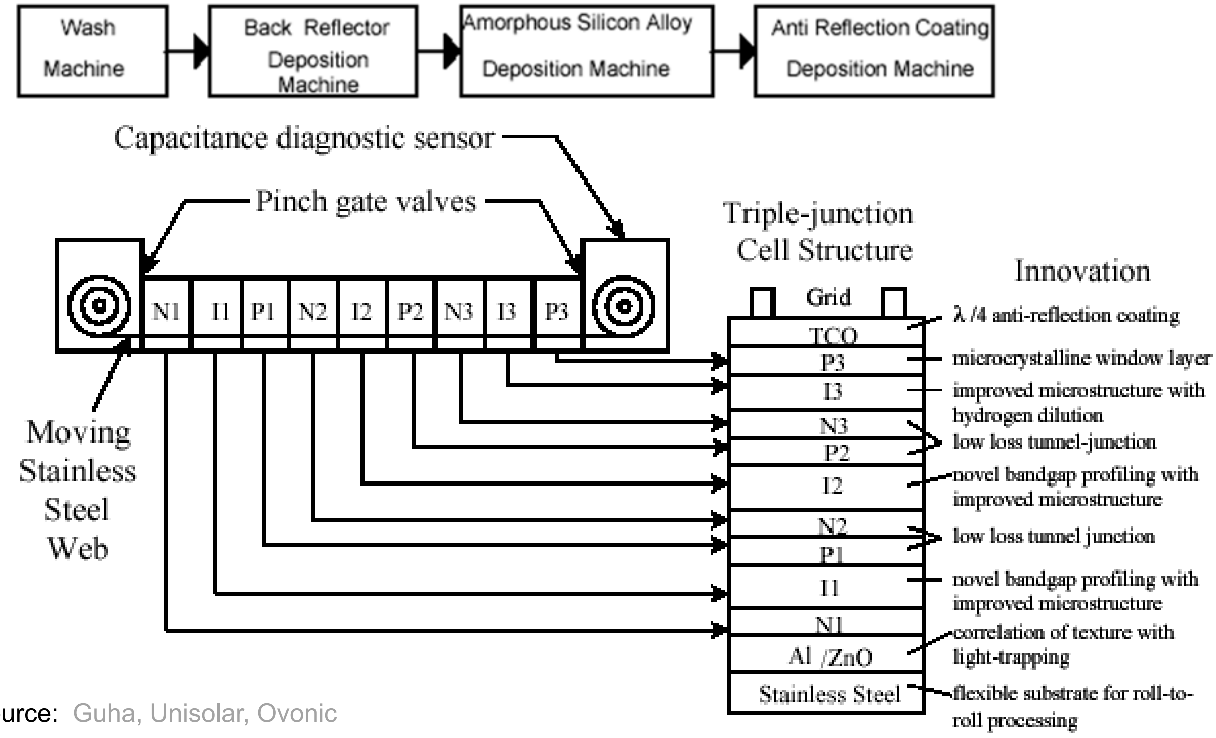

mittels Laser-Strukturierung



a-Si:H PV module

# Fabrication of a-Si:H PV Modules

Also possible via roll-to-roll technologies (e.g. Unisolar 3J):

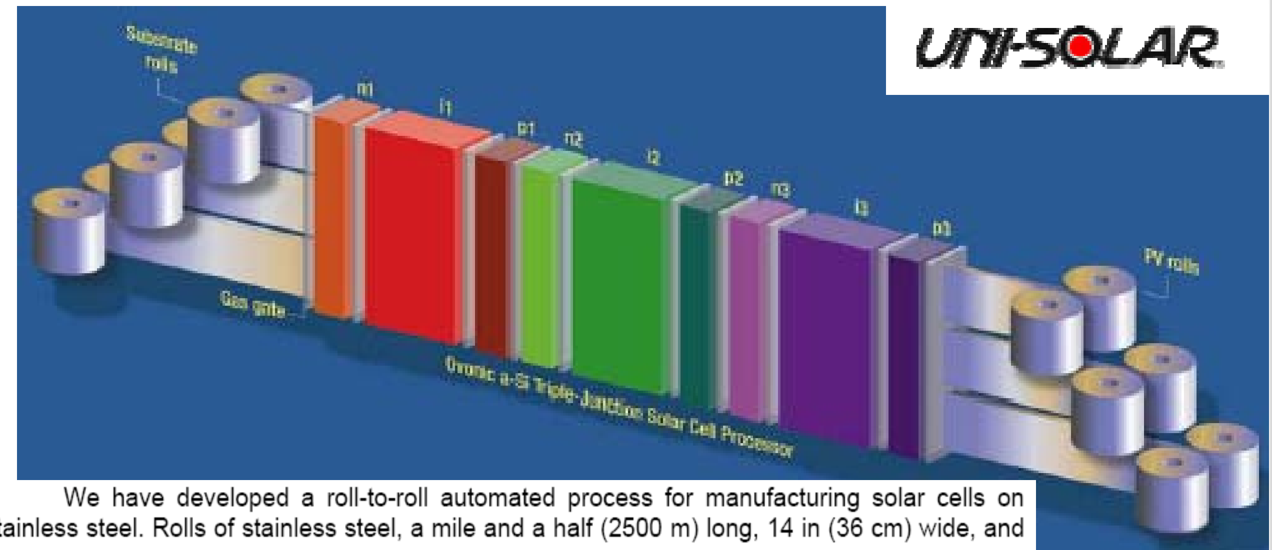



Source: Guha, Unisolar, Ovonic



# Fabrication of a-Si:H PV Modules

Canon – Unisolar – Ovonic triple-junction a-Si:H roll-to-roll




We have developed a roll-to-roll automated process for manufacturing solar cells on stainless steel. Rolls of stainless steel, a mile and a half (2500 m) long, 14 in (36 cm) wide, and 5 mil (125 μm) thick, move in a continuous manner in four machines to complete the solar cell fabrication. The machines are (Fig. 2): 1) The wash machine that washes the web one roll at a time; 2) the back reflector machine that deposits the back reflector by sputtering Al and ZnO on the three rolls of washed webs at a time; 3) the triple junction amorphous silicon alloy processor that deposit the nine layers of a-Si and a-SiGe alloy layers on six rolls of back reflector coated stainless steels at a time; and 4) the anti-reflection coating machine that deposits indium tin oxide (ITO) on top of the three rolls of stainless steel at a time.

# Fabrication of a-Si:H PV Modules

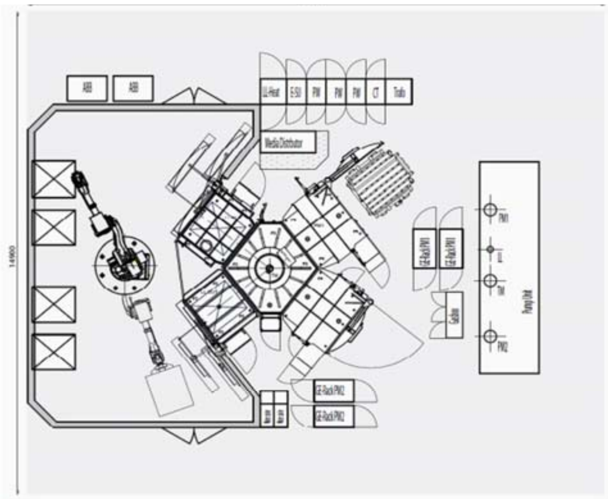
Fig. 8 Amorphous silicon processor for the 25MW plant.

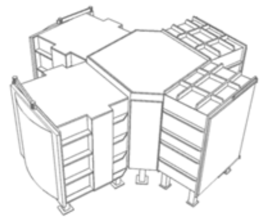


# Fabrication of a-Si:H PV Modules

# Fabrication of a-Si:H PV Modules

Industrial Thin-Film Si PECVD systems – Oerlikon Solar





Images

The KAI 1200 cluster batch system simultaneously processes 28 $m^2$ of solar modules in a single production run.>

*Source: Oerlikon solar website & marketing material*

# Fabrication of a-Si:H PV Modules

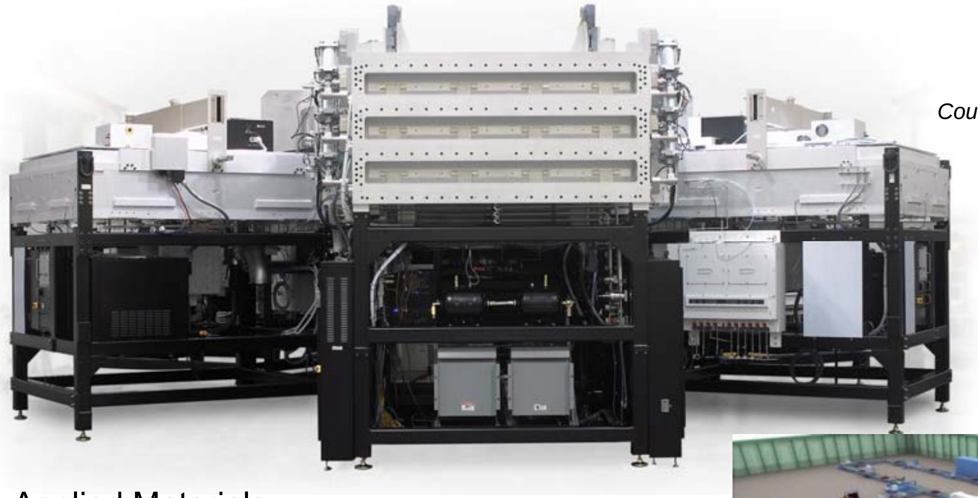
Industrial Thin Film Si PECVD systems – Oerlikon Solar KAI 1200

- KAI 1200 with Plasma Box® reactor
  - 40 MHz for highest rate and quality
  - 28$m^2$ of 40 MHz deposition area
  - Amorph & microcrystaline PIN layers
  - Single chamber processing
  - insitu-clean after every step
- Result
  - Proved best in class TF silicon modules
  - High throughput
  - High system flexibility & utilization


Clean ▸ TCO ▸ Laser ▸ **PECVD a-Si/µc-Si** ▸ Laser ▸ TCO ▸ Laser ▸ Assembly

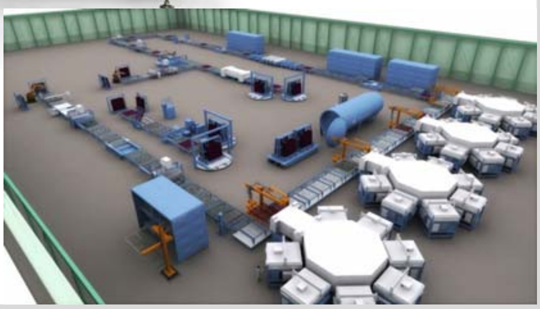
# Fabrication of a-Si:H PV Modules

Industrial Thin-Film Si PECVD systems - Applied Materials



*Courtesy of Applied Materials*

Applied Materials
Gen 8.5 (**5.7m² !!**)
PECVD Cluster system

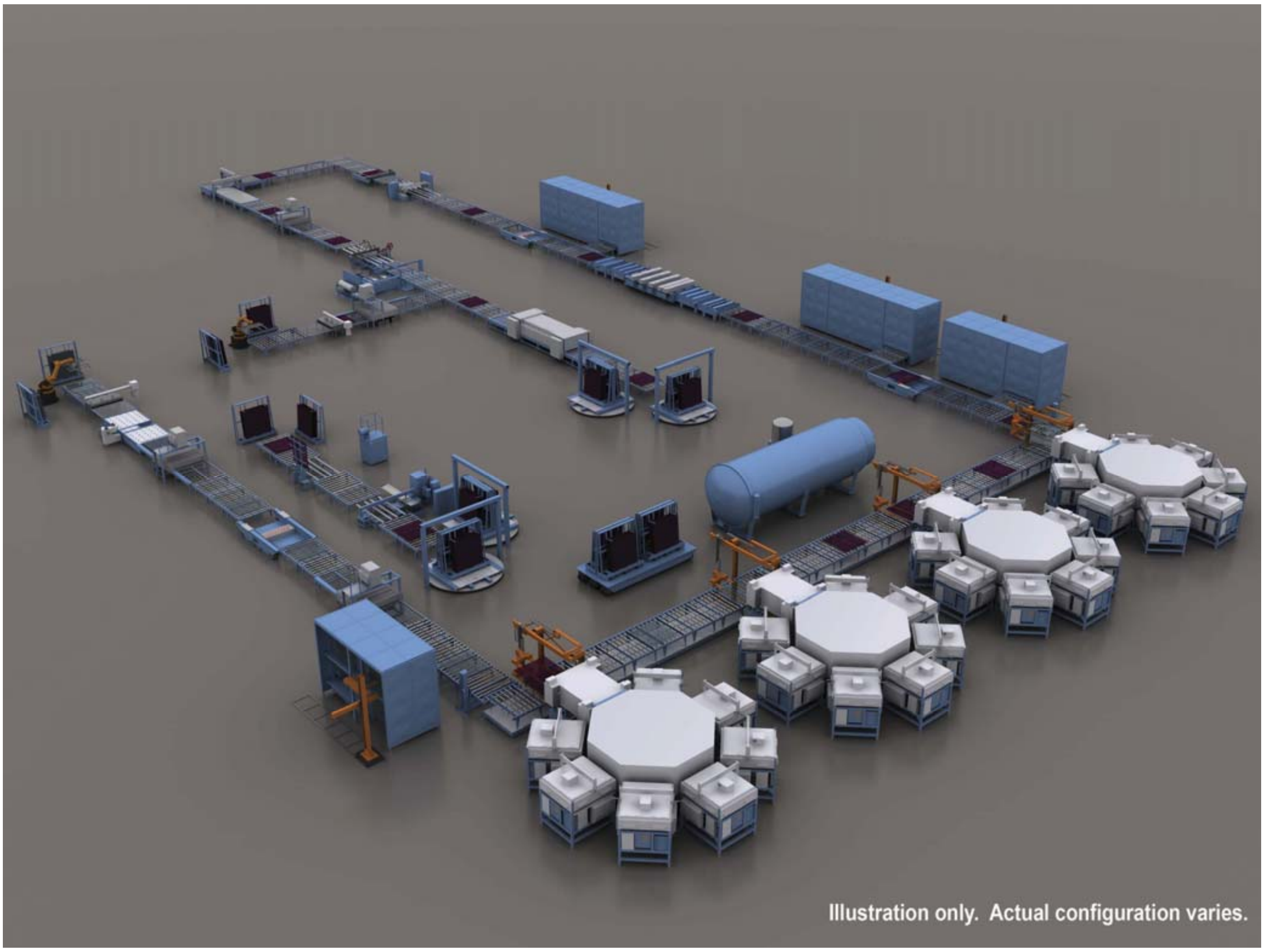


Layout of Applied Materials SunFab



# Fabrication of a-Si:H PV Modules


Source:
Applied Materials




# a-Si:H PV Modules

- The entry of big equipment manufacturers (which have been serving the semiconductor and display market) into the a-Si:H / c-Si solar technologies contributed to a boom from 2007 to 2010
- Billions of € invested
- Since then, c-Si has become very cheap, and lower efficiency (e.g. a-Si:H with $\eta$ < 12%) will find it very tough and may only survive in a few niche markets

**Example:**

- **SCHOTT Solar, Jena (a-Si/a-Si, 1.4m²):**
  Initial η = 9.4% (aperture area), production capacity **127 Wp** of PV module with 71% FF. Typical light induced degradation of -16…-18%, so a typical PV module producing initially 120W is then only rated at 99W (for a 1.4$m^2$ product)

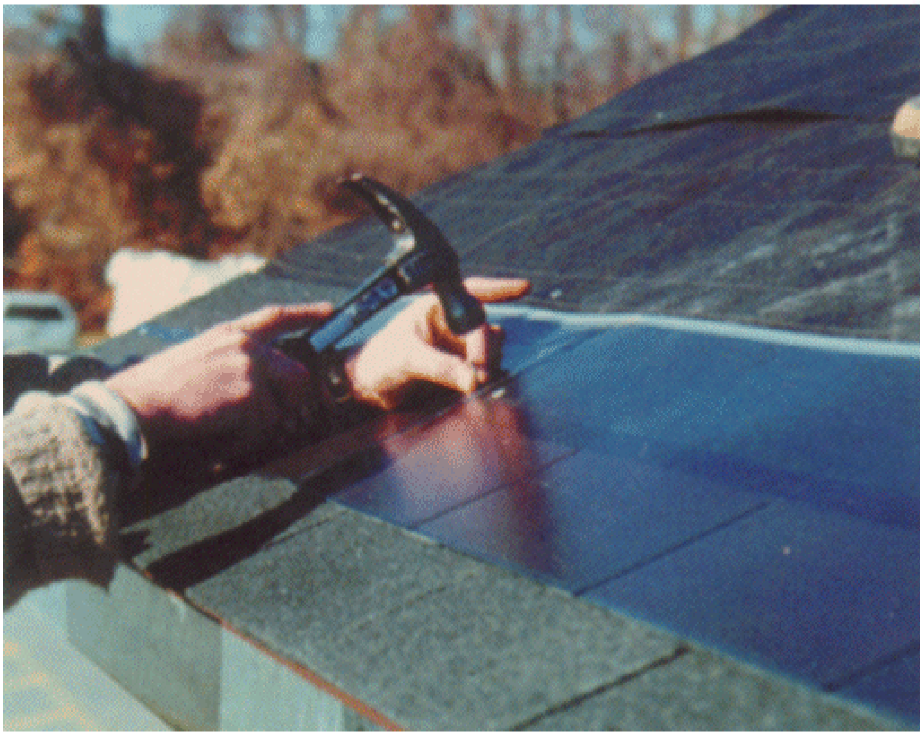
- Already seeing a merger of the a-Si:H technology together with c-Si wafer –based technologies (e.g. these are the high efficiency heterojunction Si solar cells mentioned in Dr. Jan Goldschmidt's lecture)

**Example:**

- **Inventux Technolgies AG, Berlin (**a-Si/µc-Si, 1.4m$^2$):
  In-house CVD-deposited ZnO; Since Aug 2009 producing PV modules with >120 Watt stable, η(stable, total area) = 8.6%, Recordmodule: **145.2 Wp**, η(initial, aperture) = 11.1%, 11.83mA/cm2), stable at 125W

Source: Inventux





Unisolar

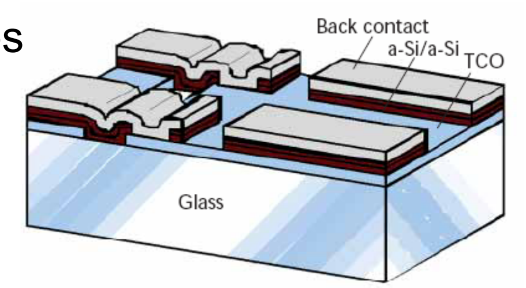
# a-Si:H PV Modules

a-Si:H PV module with integrated LEDs (Sharp)




# a-Si:H PV Modules

Semitransparent a-Si:H PV modules




RWE Schott Solar

Semitransparent roof top

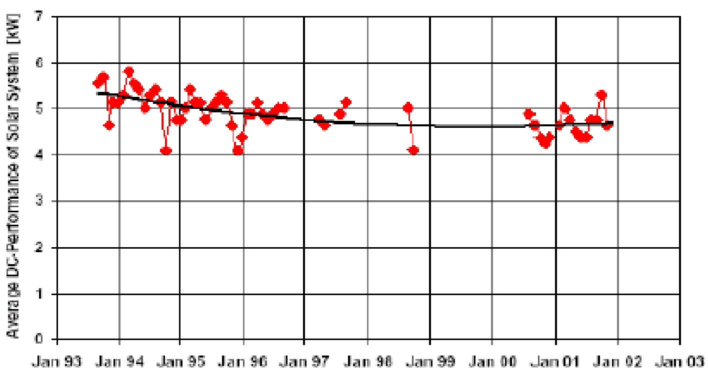
# a-Si:H PV Modules

Iowa Thin Films
a-Si roll-to-roll, Polyimide, 13“ wide up to 2400 feet long



# a-Si:H PV Modules

long term monitoring of the power supply of an ASI®-Fassade (Bavarian ministry for environment protection)



# a-Si:H PV Modules

- Efficiency of small-area laboratory a-Si:H solar cells (note, no single junction)

**Table 12.4** Efficiency of small-area solar cells fabricated in different laboratories

| Structure | Initial $\eta$ [%] | Stable $\eta$ [%] | Organization | References |
|---|---|---|---|---|
| a-Si/a-SiGe/a-SiGe | 15.2 | 13.0 | United Solar | [8] |
| a-Si/a-SiGe/a-SiGe | 11.7 | 11.0 | Fuji | [157] |
| a-Si/a-SiGe/a-SiGe | 12.5 | 10.7 | U. Toledo | [158] |
| a-Si/a-SiGe/a-SiGe | | 10.2 | Sharp | [159] |
| a-Si/a-SiGe | 11.6 | 10.6 | BP Solar | [160] |
| a-Si/a-SiGe | | 10.6 | Sanyo | [161] |
| a-Si/μc-Si | | 12.0 | U. Neuchatel | [162] |
| a-Si/μc-Si | 13.0 | 11.5 | Canon | [163] |
| a-Si/poly-Si/poly-Si | 12.3 | 11.5 | Kaneka | [164] |
| a-Si/a-SiGe/μc-Si | 11.4 | 10.7 | ECD | [165] |
| a-Si/a-SiGe | | 12.4 | United Solar | [166] |

Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus



a-Si:H PV Modules

- Efficiency of small-area a-Si:H PV modules

**Table 12.5** Stabilized efficiency of a-Si PV modules manufactured by various companies

| Structure | Stable $\eta$ [%] | Size [$m^2$] | Company | Reference |
|---|---|---|---|---|
| *R&D modules* | | | | |
| a-Si/a-SiGe/a-SiGe | 10.5 | 0.09 | United Solar | [186] |
| a-Si/a-SiGe | 9.1 | 0.08 | BP Solar | [160] |
| a-Si/a-SiGe | 9.5 | 0.12 | Sanyo | [192] |
| *Large-area modules* | | | | |
| a-Si/a-SiGe | 9.3 | 0.52 | Sanyo | [193] |
| a-Si/a-SiGe/a-SiGe | 9.0 | 0.32 | Fuji | [160] |
| a-Si/a-SiGe | 8.1 | 0.36 | BP Solar | |
| a-Si/a-SiGe/a-SiGe | 7.9 | 0.45 | United Solar | |
| a-Si/a-Si/a-SiGe | 7.8 | 0.39 | ECD | [185] |
| a-Si/poly-Si | 10.0 | 0.37 | Kaneka | [194] |

Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

# a-Si:H PV Modules

- Outdoor performance comparison of 9 different PV modules in The Netherlands in 2000
- N.B. only one non-Si based module!

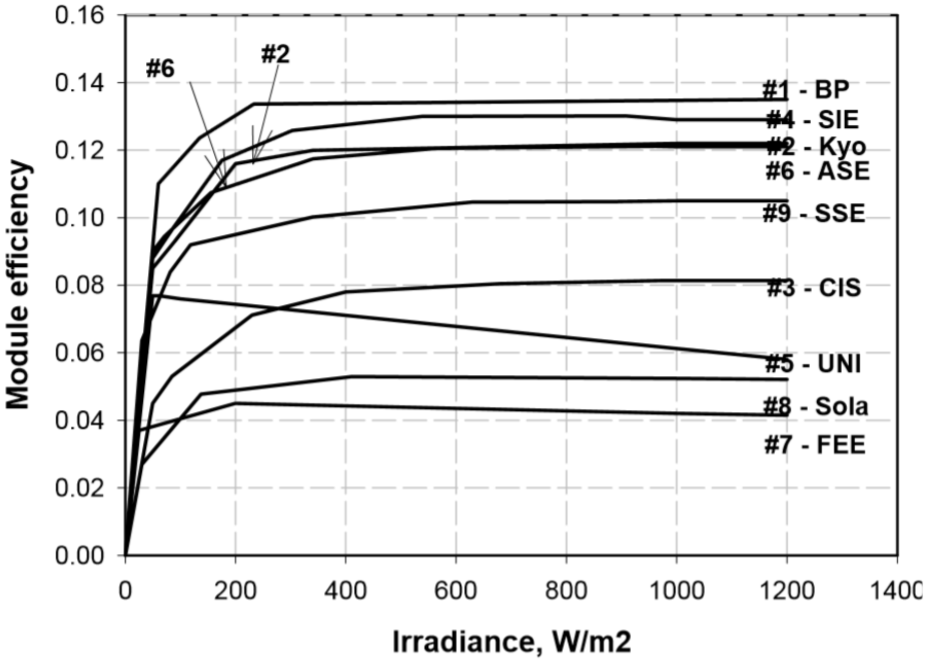
| Number | Manufacturer | Code | Technology | Area, $m^2$ |
|---|---|---|---|---|
| 1 | BP Solarex | BP 585 | Mono-Si, LGBG | 0.6303 |
| 2 | Kyocera | KC60 | Multicrystalline Si | 0.4911 |
| 3 | Siemens | S30 | CIS | 0.2458 |
| 4 | Siemens | SM-55 | Mono-Si | 0.4274 |
| 5 | United Solar Systems | US-32 | Amorphous Si (triple stack) | 0.5222 |
| 6 | ASE | ASE-100 | EFG Si sheet | 0.8262 |
| 7 | Free Energy Europe | A13P | Amorphous Si | 0.2880 |
| 8 | BP Solarex | MST 43 | Amorphous Si (double stack) | 0.8210 |
| 9 | Shell Solar Energy | RSM 75 | Multicrystalline Si | 0.7113 |

Source: https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-C--00-067



# a-Si:H PV Modules

- Outdoor performance comparison of 9 different PV modules in The Netherlands




Source: https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-C--00-067

# a-Si:H PV Modules

| Number | Manufacturer | DC yield kWh/kWp | Sunmaster 2500 PV inverter | | |
|---|---|---|---|---|---|
| | | | AC yield, kWh/kWp | AC yield, $kWh/m^2$ | Performance ratio |
| 1 | BP Solarex (c-Si) | 977 | 868 | 117 | 0.80 |
| 2 | Kyocera (mc-Si) | 964 | 856 | 105 | 0.79 |
| 3 | Siemens (CIS) | 930 | 824 | 67 | 0.76 |
| 4 | Siemens (m-Si) | 963 | 855 | 110 | 0.79 |
| 5 | UniSolar (a-Si) | 1164 | 1038 | 64 | 0.95 |
| 6 | ASE (Si) | 966 | 857 | 104 | 0.79 |
| 7 | FEE (a-Si) | 1084 | 961 | 40 | 0.88 |
| 8 | BP Solarex (a-Si) | 1001 | 888 | 47 | 0.81 |
| 9 | Shell Solar Energy (mc-Si) | 961 | 853 | 90 | 0.78 |

Table 6 - DC and AC annual yields for all modules under test, determined for typical Dutch meteorological conditions (TRY) and roof-integrated PV modules

Source: https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-C--00-067



# a-Si:H PV Modules

- While $\eta$ of a-Si:H based modules are low, evident that a-Si:H show high yields in terms of installed nominal power. Caused by several factors:
- First, low light level efficiency is relatively high compared to STC efficiency. $\Rightarrow$ in Dutch (and German) climate, where low light levels can be found during all seasons, this is especially important
- From the a-Si:H PV modules the UniSolar has highest $\eta$ , both at STC as and lower light levels. This, together with the special shape of the efficiency curve and the positive temperature coefficient (e.g. +0.5% per °C) with respect to a-Si, accounts it very high annual yield (kWh/kWp)
- Trends different for other a-Si:H modules, e.g. the FEE module shows constant efficiencies at almost all light levels $\Rightarrow$ also scores well
- a-Si:H often claim better performance under cloudy skies that c-Si. This is partly true and is linked to i) the efficiency under low irradiance being surprisingly good sometimes, as well as ii) there being more blue light scattered $\Rightarrow$ favours solar cells with higher bandgaps

# a-Si:H PV Modules

- Building integrated photovoltaic (BIPV) systems – combination of power generation with daylighting

**Paul-Löbe-Haus**

**part of the German parlament's buildings in Berlin**

- Grid connected since April 2001
- 123 $kW_p$



# a-Si:H PV Modules

# a-Si:H PV Modules

„Bierzelt für den Bayerischen Markt“



# a-Si:H PV Modules

Solarpark Buttenwiesen
First project of GP Solarpark, operating since September 2004.
Was then world‘s largest thin film PV system with 1 $MW_P$ a-Si:H from Mitsubishi Heavy Industries

Red/brown colour indicates that it is single-junction a-Si:H

Source: Phönix SonnenStrom AG


# a-Si:H PV applications

Schweißschutzmaske
*welding mask*

Funk-Raumthermostat
*ambient thermostat – radio controlled*

Briefwaage
*letter scale*

Funk Display
*remote disply*

Armbanduhr
*wrist watch*

SCHOTT solar

# a-Si:H PV Modules


Spannungsprüfer
*voltage meter*


Thermometer
*thermometer*


Tastatur
*keyboard*


Raumspray
*airfresh spray*


Wasserhahn mit Sensor
*lavatory faucet with sensor*



# a-Si:H PV Modules


Teichpumpe
*pond pump*


EZ View® Hausnummer
*EZ View® house nummber*


Wandlampe
*wall lamp*


Gartenlampe
*garden lamp*


Bewässerungscomputer
*water computer*

# a-Si:H PV Modules

## Special applications for flexible a-Si:H modules

**Consumer Electronics**
* Portable CD Player charger
* GameBoy® charger
* Radios
* Cell phone chargers
* PDA chargers
* Flashlights

**Outdoor and Recreation**
* Camping Equipment
* Marine
* Automotive

**Remote and Military**
* Military field communication
* GPS units
* Emergency Power
* Highway/Transportation

**Building Integrated**
* Metal-based roofing products
* Elastomer-based roofing products
* Windows

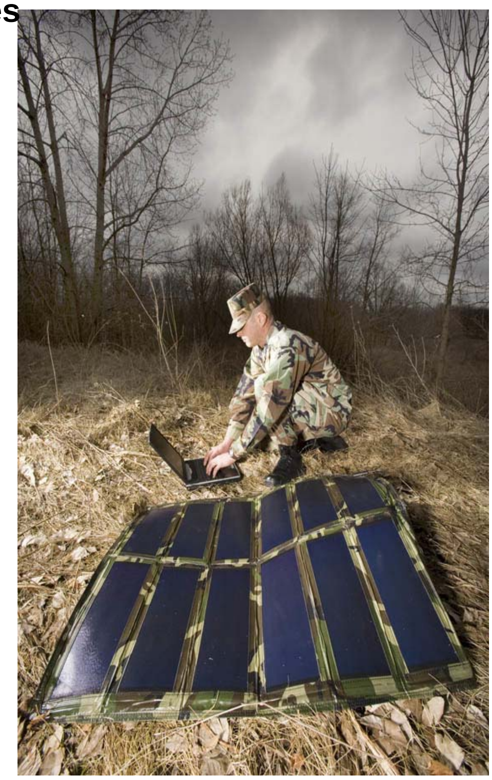
**Applications for Remote Use**
* Remote Sensors and Transmitters
* Outbuildings
* Decorative Lighting
* Warning / Safety Lights
* Water Pumping Systems
* Roadway Indicators



# a-Si:H PV Modules

## Special applications for flexible a-Si:H modules

Roof of General Motors in Zaragoza



## Applied Materials stops selling 'SunFab' thin-film lines: focus on c-Si solar and LED technology

21 July 2010 | By Mark Osborne | News > Thin Film, Silicon TF

In a significant change of direction, Applied Materials has revealed that it will stop selling its turnkey a-Si thin-film technology under the SunFab name to potential new customers, shifting emphasis away from thin-film altogether and focusing on crystalline silicon (c-Si) and LED manufacturing equipment and technology. Applied has not been as active in the growing LED market as other equipment suppliers, primarily from the semiconductor industry. Leading semiconductor foundry, TSMC is entering the LED market as it pushes into energy markets, including solar. The restructuring of Applied's Energy and Environmental Solutions (EES) division was said to cost the company between US$375 million and US$425 million.

"While Applied has delivered significant innovations with our SunFab production line and made substantial progress on our technology roadmap, the thin-film market has been negatively impacted by several factors, including delays in utility-scale solar adoption, solar panel manufacturers' challenges in obtaining affordable capital, changes and uncertainty in government renewable energy policies, and competitive pressure from crystalline silicon technologies," said Mike Splinter, chairman and CEO of Applied Materials. "Led by Mark Pinto, EES will focus on our industry-leading crystalline silicon solar business and on pursuing other opportunities in advanced energy technologies like LED lighting."

As for the equipment that makes up the SunFab line, Applied said that it would be continue to offer individual tools for sale to thin-film solar manufacturers, including CVD and PVD equipment. R&D efforts to improve thin-film efficiency levels and high-productivity deposition would continue for existing customers.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AC-DC conundrum: Latest PV power-plant ratings follies put focus on reporting inconsistency (update)

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Home » News » Inventux saved by South American investors

## Inventux saved by South American investors

06. AUGUST 2012 | INDUSTRY & SUPPLIERS, MARKETS & TRENDS | BY: SANDRA ENKHARDT

The insolvent, Germany-based Inventux has been saved. More than half of the company's workforce will be retained.



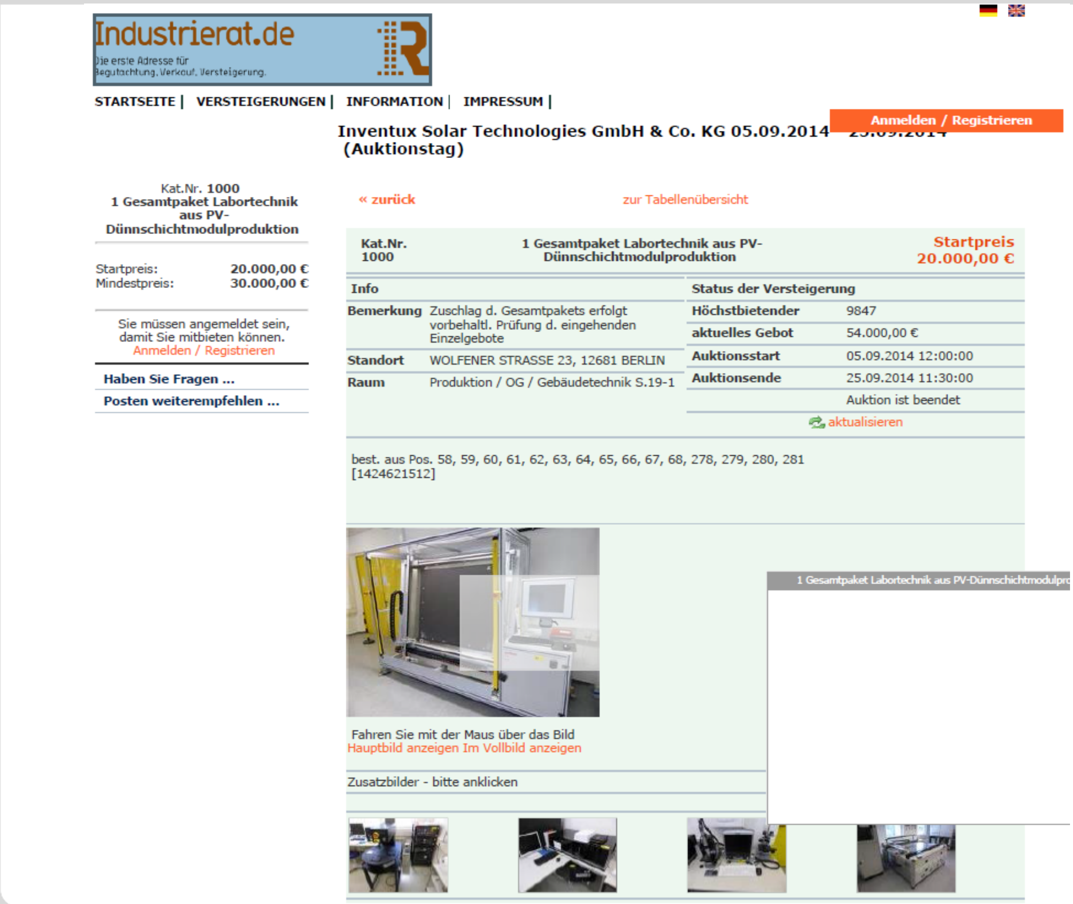
The South American investors want to permanently continue with production in Berlin.
*Inventux Technologies AG*

Some good news for the currently beleaguered photovoltaics industry: an unnamed South American investor group has taken over Inventux Technologies AG, which filed for insolvency on May 22.

Liquidator, Ralf Rattunde from law firm Leonhardt said around 100 of the 170 jobs will be retained.

Karlsruher Institut für Technologie

„Am 18. Mai 2012 wurde über die Inventux Technologies AG ein vorläufiges Insolvenzverfahren beim Amtsgericht Charlottenburg eingeleitet. Mithilfe von neuen Investoren aus Südamerika wurde das Unternehmen ab August 2012 als Inventux Solar Technologies GmbH weitergeführt und produziert weiterhin am Standort Berlin-Marzahn.
Am 1. Mai 2014 wurde über die Inventux Solar Technologies GmbH ein Insolvenzverfahren beim Amtsgericht Charlottenburg eröffnet. Die Gesellschaft wurde daraufhin bereits am 12. Mai 2014 aufgelöst."






# Summary

- The concept of a-Si:H is good and builds on some of the advantages of c-Si (non-toxic, earth abundant) and even overcomes some of the disadvantages of c-Si (weak absorption requiring thick abosrber layer, a negative temperature coefficient)
- Also, the energy yield (kWh/kWp) from such technologies is typically good
- Good possibilities for using flexible substrates due to low temperature processes… size of this niche market?
- However, today, the record lab-scale cells are 13.4% stabilised and the best modules in the 11% range
- Huge investments in the mid-2000s from large equipment manufacturers (Oerlikon, Applied Materials)
- Market crash in 2009 – many thin-film manufacturers
- Market share of a-Si:H getting smaller and smaller over time
- Best hope for a-Si:H today lies in a marriage with c-Si wafers – the high efficiency a-Si:H / c-Si heterojunction device (25.6% record efficiency)

# Announcements

- Upcoming Lectures
  - #9: Thin Film Solar Cells – Inorganic – CIGS and CdTe
  - #10: Thin Film Solar Cells – Excitonic #1
    (Dr. Ian Howard, IMT)
- Excursion to Fraunhofer Institute for Solar Energy Systems in Freiburg on 22nd January – leaving ~8:30am arriving back ~5:30pm – a small financial contribution from each student is expected by the Faculty

**Areas of Business**

In its twelve business areas, Fraunhofer ISE carries out applied research to develop new technologies, processes and solutions:

**Energy Efficient Buildings**
- Building Energy Concepts
- Smart Home Technologies
- Building Management and Operation
- Façades and Windows
- Lighting Technology
- Electrically and Thermally Driven Heatpumps
- Heat Transfer in Building Energy Systems
- Cooling and Air-Conditioning in Buildings

**Silicon Photovoltaics**
- Feedstock, Crystallization and Wafering
- Crystalline Silicon Thin-Film Solar Cells
- Characterization of Process Materials and Silicon Materials
- Doping and Diffusion
- Surfaces: Conditioning, Passivation and Light-Trapping
- Metallization and Patterning
- High-Efficiency Cell Fabrication and Analysis
- Pilot Processing of Industrial Solar Cells
- Metrology and Production Control
- Module Integration
- Amorphous Silicon Multi-Junction Solar Cells
- Technology Assessment

**III-V and Concentrator Photovoltaics**
- III-V Epitaxy and Solar Cells
- Concentrator Assemblies
- Concentrator Optics
- High-Concentration Systems (HCPV)
- Low-Concentration Systems (LCPV)
- Silicon Concentrator Solar Cells

**Dye, Organic and Novel Solar Cells**
- Dye and Perovskite Solar Cells
- Organic Solar Cells
- Photon Management
- Tandem Solar Cells on Crystalline Silicon

**Photovoltaic Modules and Power Plants**
- Module Development
- Module Characterization
- Service Life of Modules and Materials
- Module Testing
- Photovoltaic Power Plants
- Building Integrated Photovoltaics

**Hydrogen and Fuel Cell Technology**
- Hydrogen Production by Water Electrolysis
- Thermochemical Processes for Hydrogen Production
- Fuel Cell Systems
- Biomass for Materials
- Power-to-Liquid

**Solar Thermal Technology**
- Thermal Solar Systems
- Service Life of Collectors and Components
- Heat Transfer and Heat Transport
- Solar Cooling and Refrigeration
- Solar Process Heat
- Solar Thermal Power Plants
- Solar Thermal Façades
- Decentralized Water Purification Systems

**System Integration and Grids – Electricity, Heat, Gas**
- Operation of Energy Supply Systems
- Smart Energy Cities
- District Concepts and Heat Grids
- Power Distribution Grids and Operating Equipment
- ICT for Components in Smart Grids
- Power-to-Gas
- Biomass for Energy
- Autonomous Power Supplies and Mini-Grids
- Solar Desalination

**Energy Efficient Power Electronics**
- Grid-connected Inverters and Storage Systems
- Off-Grid Energy Systems
- Electromobility
- New Devices and Applications
- Electricity Grids

**Zero-Emission Mobility**
- Charging Infrastructure for Electric Vehicles
- Battery Systems for Mobile Applications
- Grid Integration of Electric Vehicles
- Fuel Cell Electric Vehicles
- Hydrogen Infrastructure
- Thermal Management in Vehicles

**Storage Technologies**
- Battery Systems
- Redox Flow Batteries
- Latent Heat Storage
- Cold Storage
- Storage for Low Temperature Solar Thermal
- High Temperature Storage
- Membrane Electrolyzers and Hydrogen Storage Systems

**Energy System Analysis**
- Techno-Economic Assessment of Energy Technologies
- Market Analysis and Business Models
- Planning and Operating Strategies of Power Plants
- National and Regional Energy Supply Concepts
- Modeling of Energy Supply Scenarios