CdTe/CdS Thin film solar cells.

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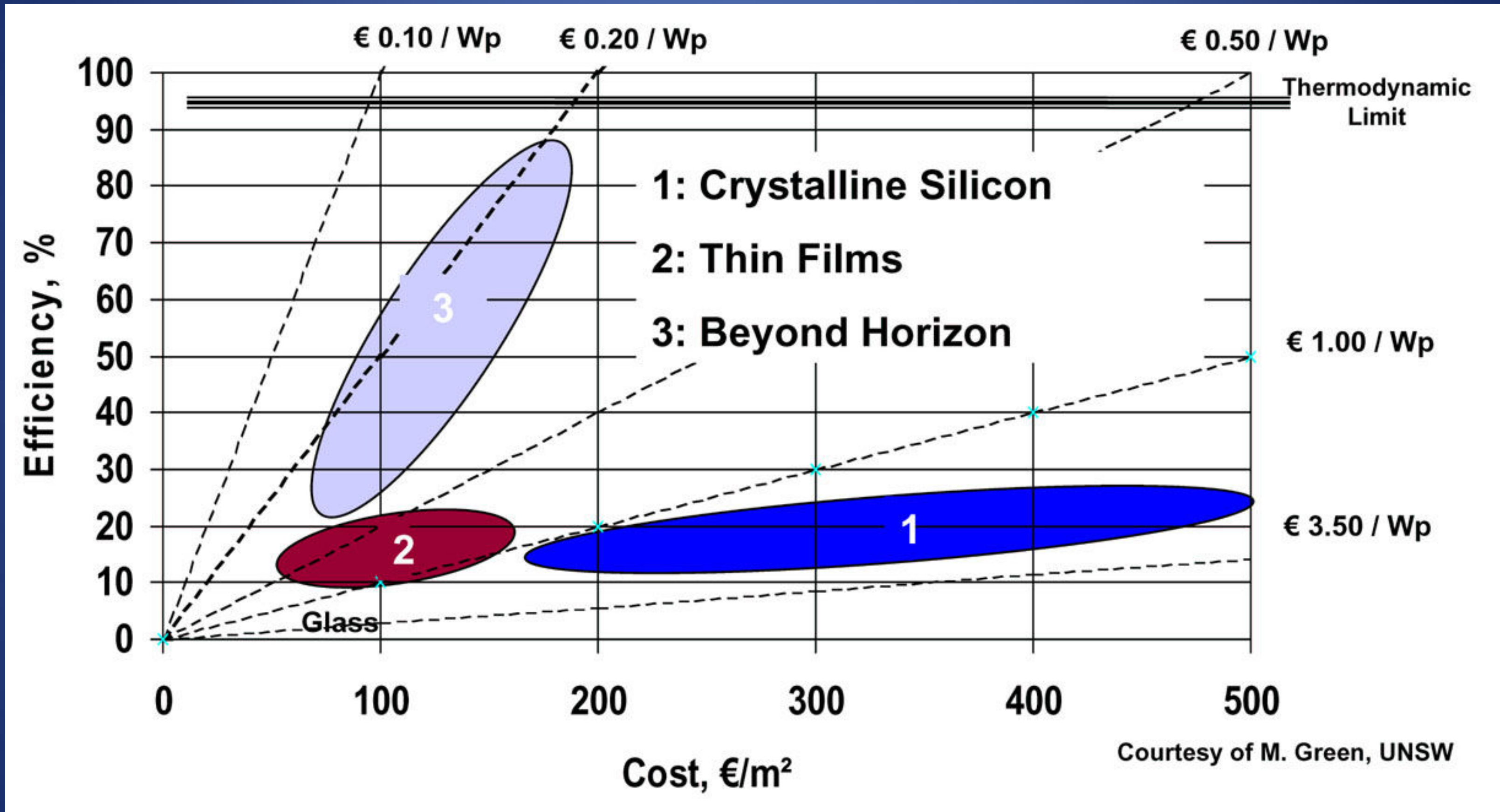
Summary

- Short Introduction
- CdTe solar cell structure
- Single layers + activation
- Bifacial cells
- The industrial process
- Flexible cells
- Environmental issues

Efficiency/costs



Thin Film PV companies

CIS

Shell Solar, CA
Global Solar Energy, AZ
Energy Photovoltaics, NJ
ISET, CA
ITN/ES, CO
NanoSolar Inc., CA
Day Star Technologies, NY/CA
MiaSole, CA
HelioVolt, Tx
Solyndra, CA

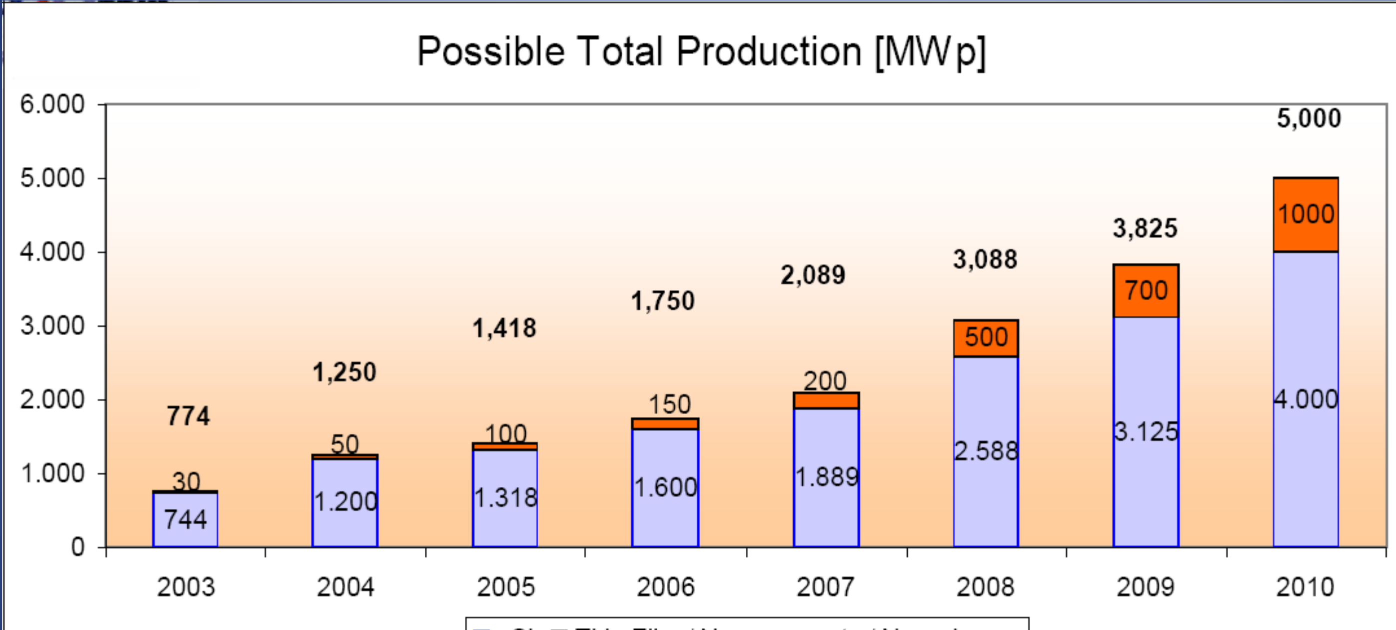
SoloPower, CA
Wurth Solar
SULFURCELL, Germany
CIS Solartechnik, Germany
Solarion, Germany
Solibro, Sweden
CISEL, France
Showa Shell, Japan
Honda, Japan

CdTe

First Solar, OH
Solar Fields, OH
AVA TECH, CO
Prime Star, CO

CANRON, NY
Antec Solar, Germany
Arendi, Italy

Motivation



Share of Thin Film of total

2003	2004	2005	2006	2007	2008	2009	2010
3.8 %	4.0 %	7.1 %	8.6 %	9.6 %	16.2 %	18.3 %	20 %

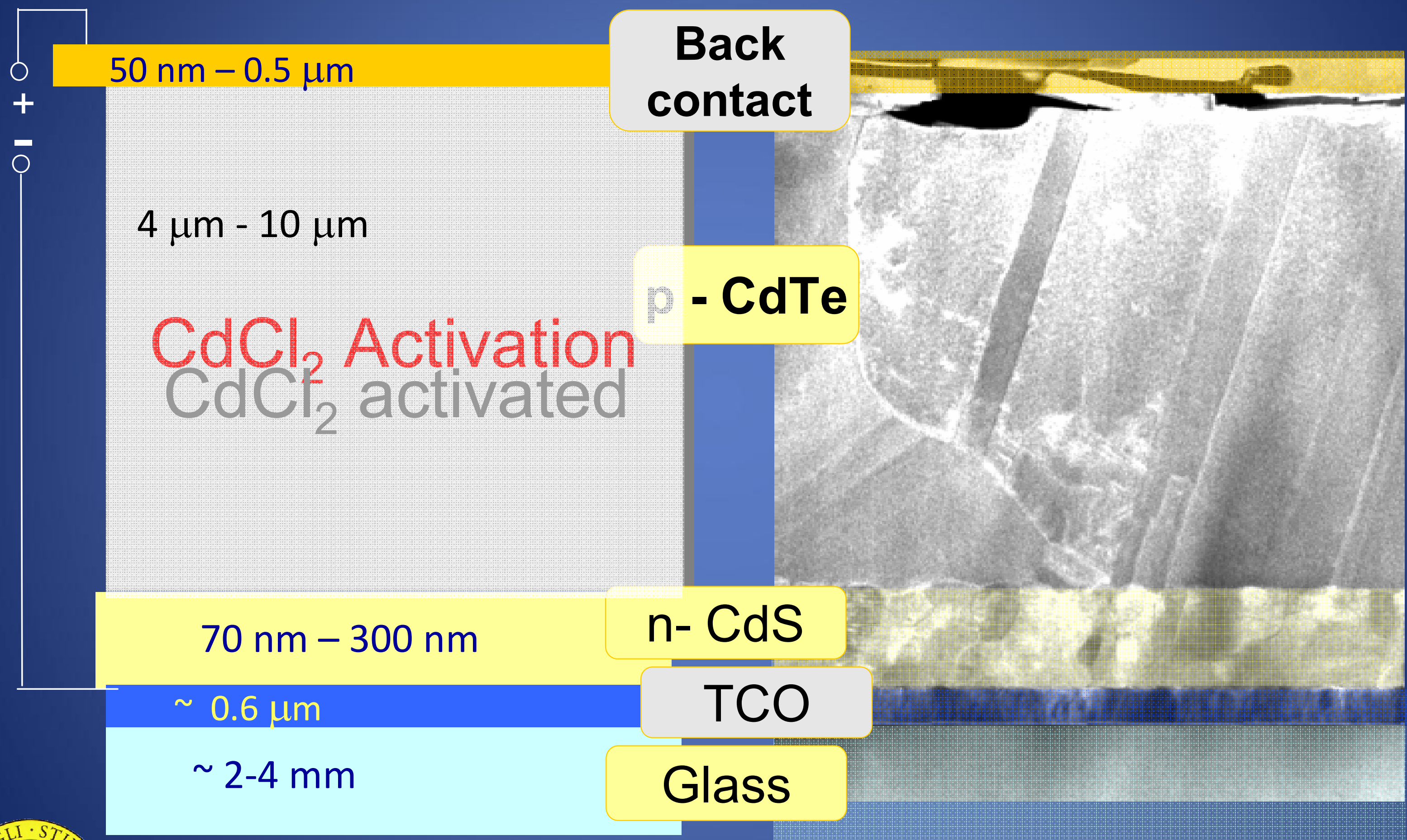
Estimation: 2020 thin films 7.5 GW (=22%) of total 34 GW,
2030 thin films 133 GW (= 28.6% = new concepts) of total 380 GW

Quelle: Marktplatz PV Anbieterseite Produktion von Solarmodulen

CdTe properties

- Band gap of 1.45eV, close to the theoretical maximum of photovoltaic energy conversion
- Direct band gap: a few microns of the material are needed for the absorption of 90% of solar light
- Simple phase diagram and stoichiometric growth at a substrate temperatures >250°C
- High efficiencies: 16.5% (Wu et Al.)

CdTe/CdS Solar Cell Structure



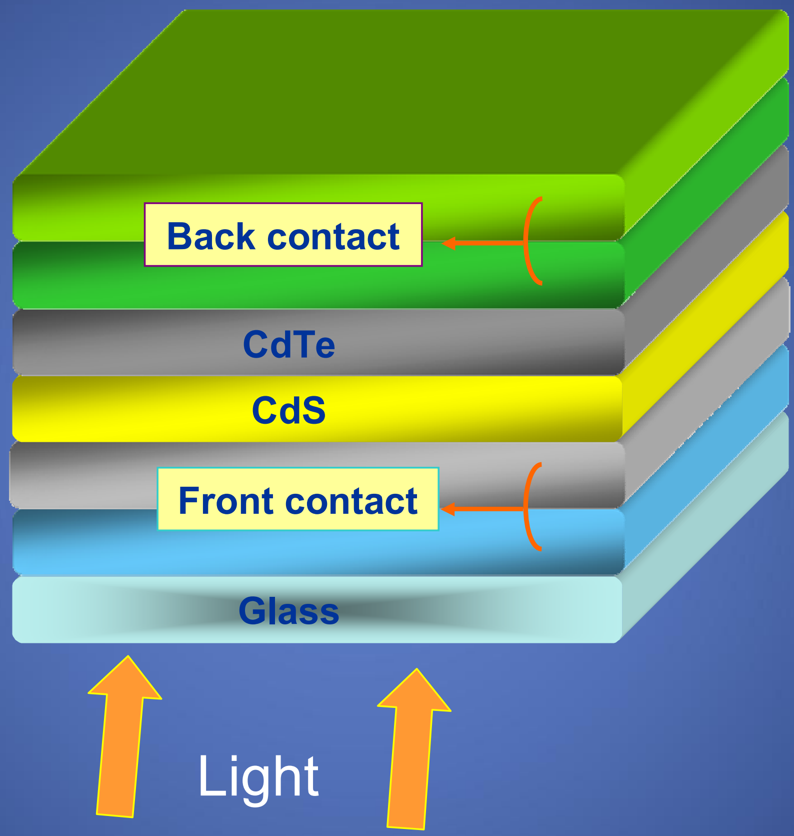
TEM graph by courtesy of M. Terheggen

Fabrication processes

- Evaporation (ETHZ-UniVerona): 12.5%
- CSS (NREL, ANTEC, First Solar, Matsushita, UniParma)
  16.5%-15.8 % (Cu free back contact)
- Sputtering (Uni-Toledo) 14 %
- Others: screen printing, electrodeposition, hot wall deposition, etc.

CdTe thin film is easy to grow.

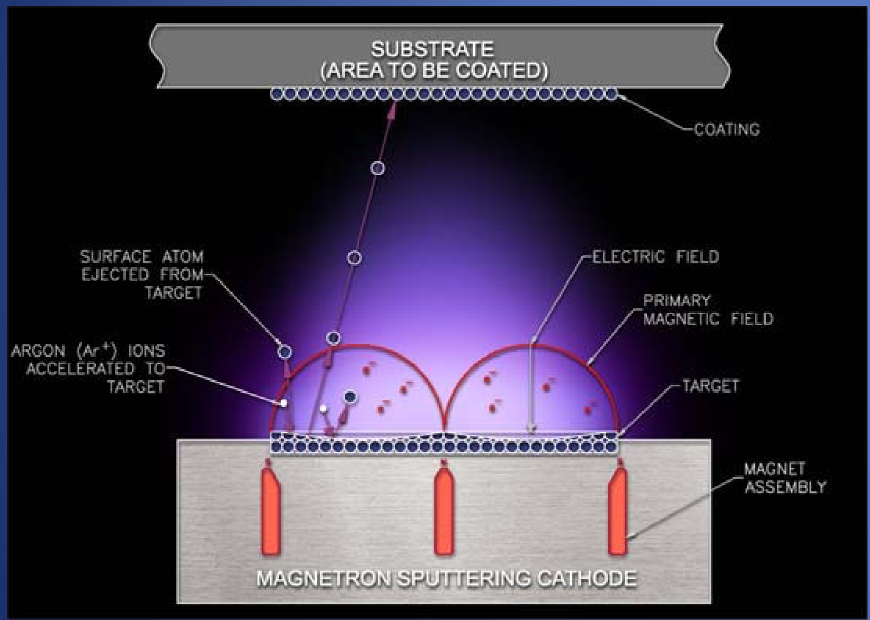
CdTe solar cell structure:

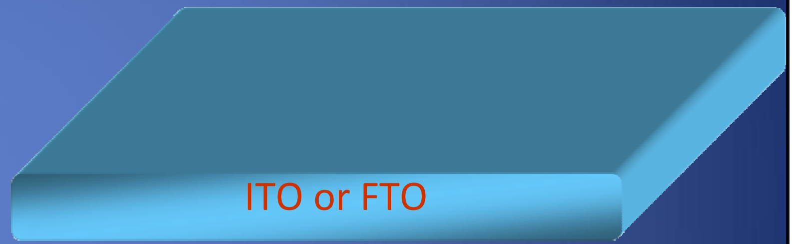


Front Contact

SnO_2 :F (FTO) ***by RF magnetron sputtering***

SnO_2 -In_2O_3 (ITO) ***per RF magnetron sputtering***



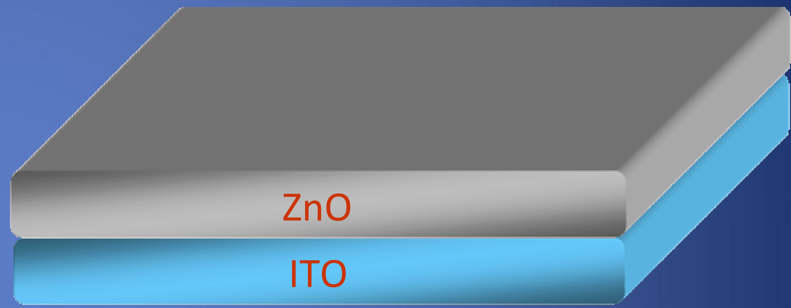


- Resistivity ⟶ $2 \cdot 10^{-4}$ ohm·cm
- Trasparency ⟶ 85 ÷ 90% in the visible

Front Contact

- *ITO:* At 400°C substrate temperature 400nm of ITO are deposited with a Deposition Rate greater than 40Å/sec by D.C. sputtering using a ceramic target.

Sheet resistance of this layer is ~5Ω·cm².



- *ZnO:* on top of the ITO layer 150nm of ZnO are deposited by D.C. reactive sputtering in an atmosphere of Ar containing 20% of O_2 with a deposition rate greater than 30Å/sec using a Zn target.

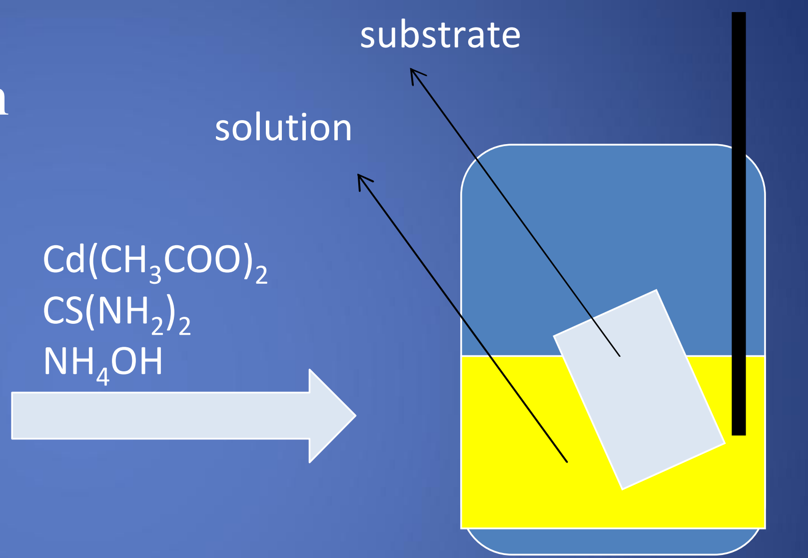
Resistivity of ZnO is ~10^3 Ω·cm .

The role of ZnO layer is both to hinder the In diffusion from ITO and to separate CdS from ITO in order to limit the effect of eventual pinholes that could be present in CdS

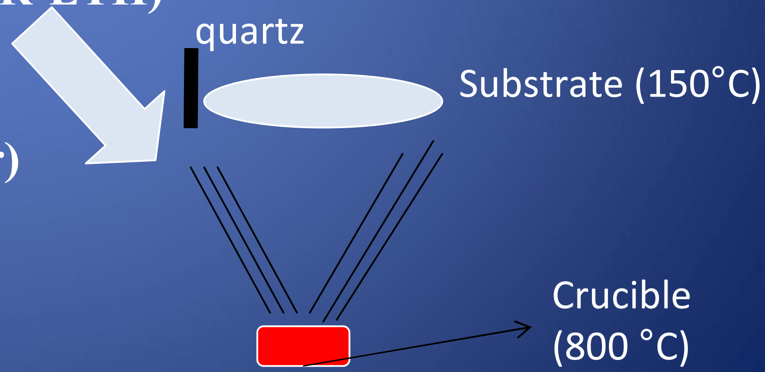
CdS layer

- ➢ thickness 80 nn-300 nm

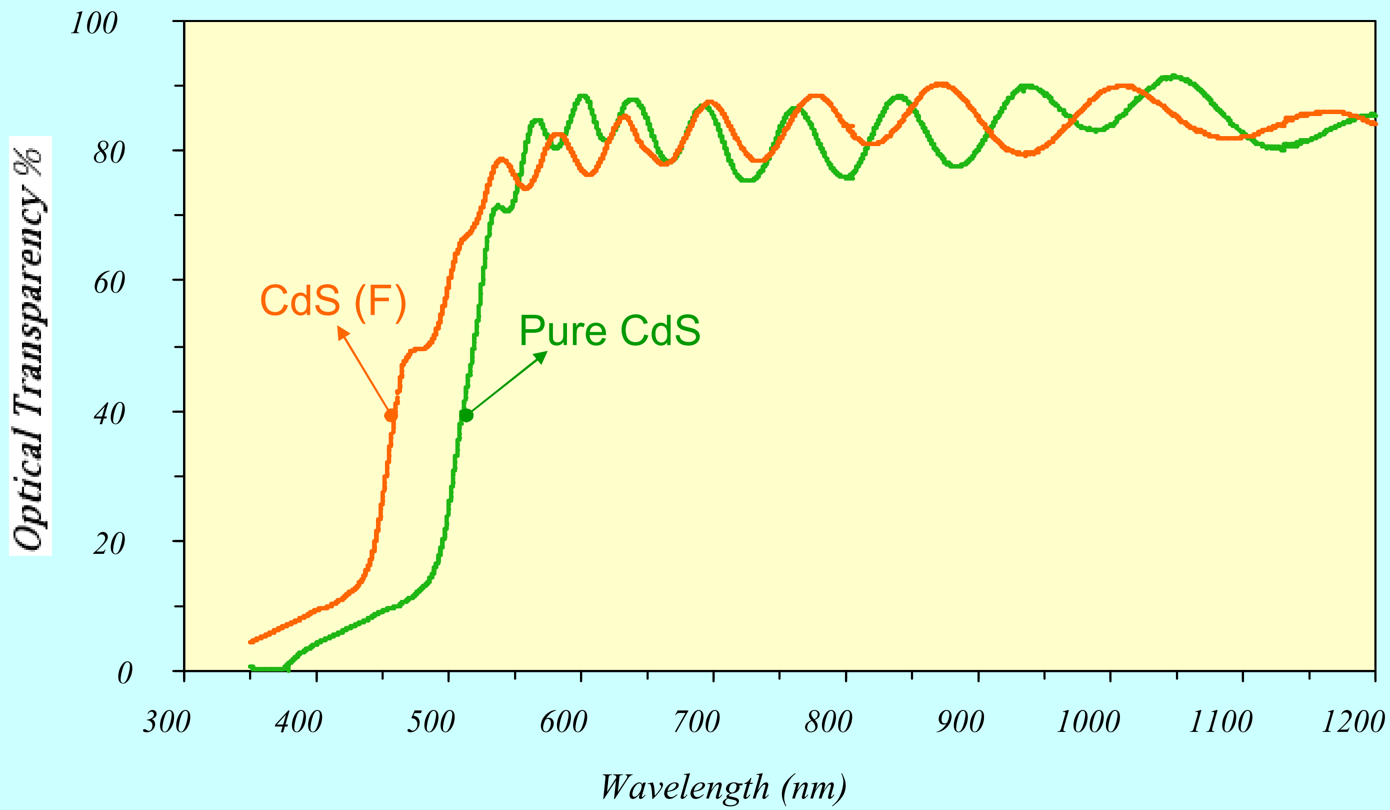
- **By sputtering (UniParma)**
- **By chemical bath (NREL)**



- **By thermal evaporation PVD (UniVR-ETH)**
- **By close space sublimation (see later)**

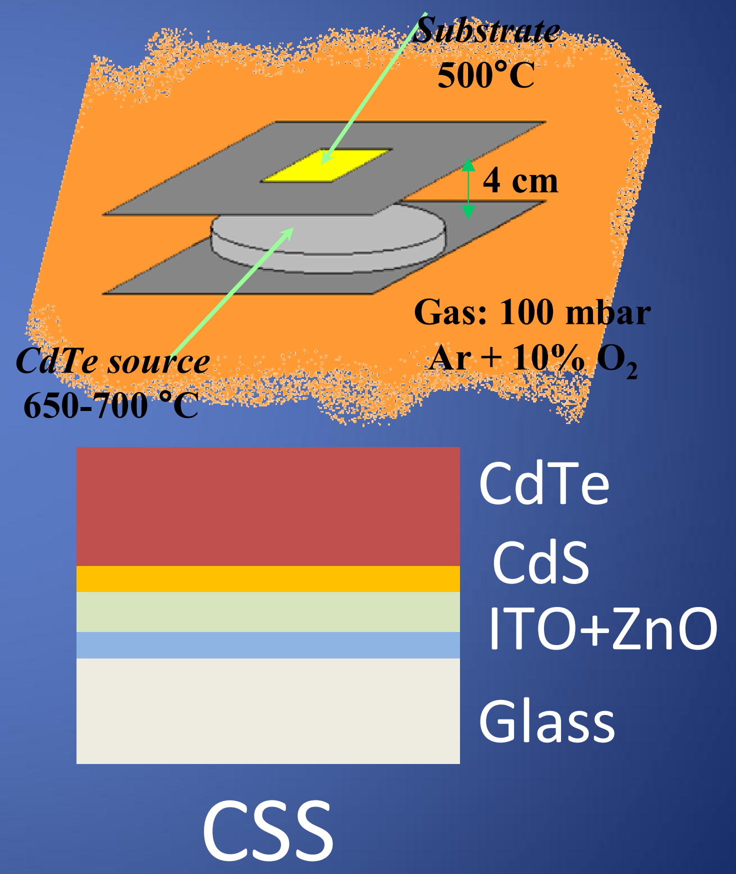


CdS layer

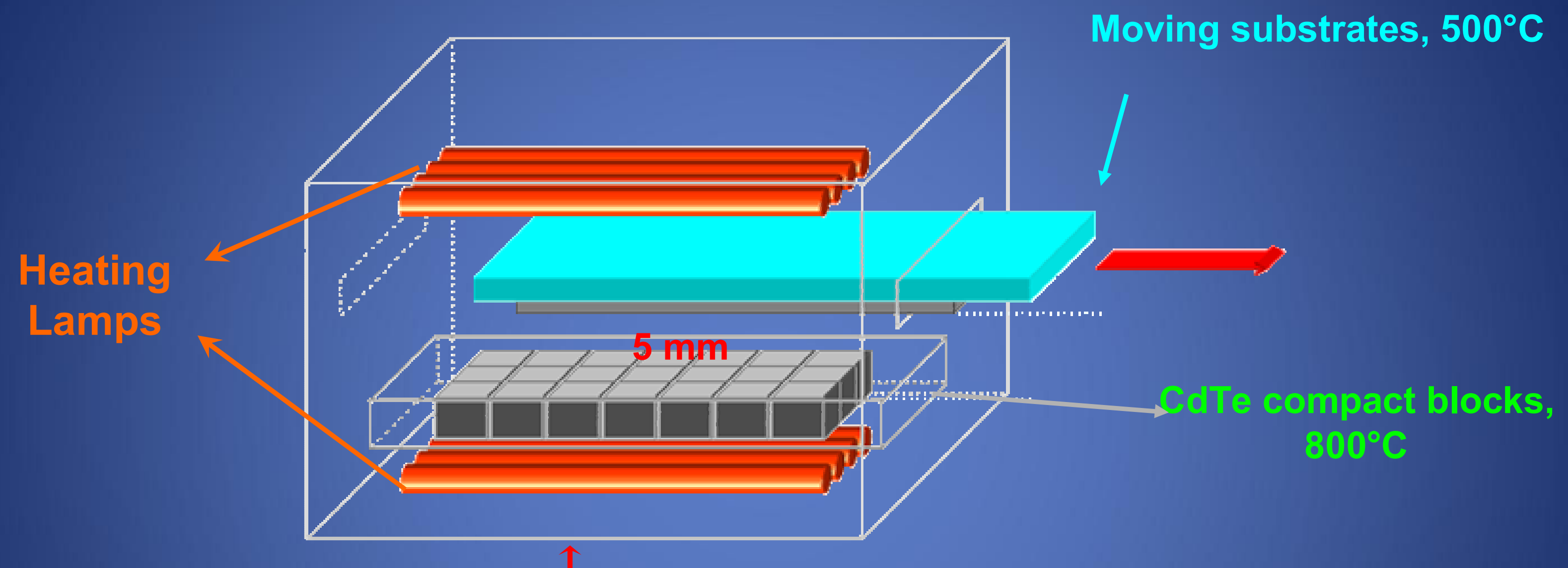


Optical Transparency %
100
80
60
40
20
0
300
400
500
600
700
800
900
1000
1100
1200
Wavelength (nm)
CdS (F)
Pure CdS

CSS- and HVE- CdTe layers

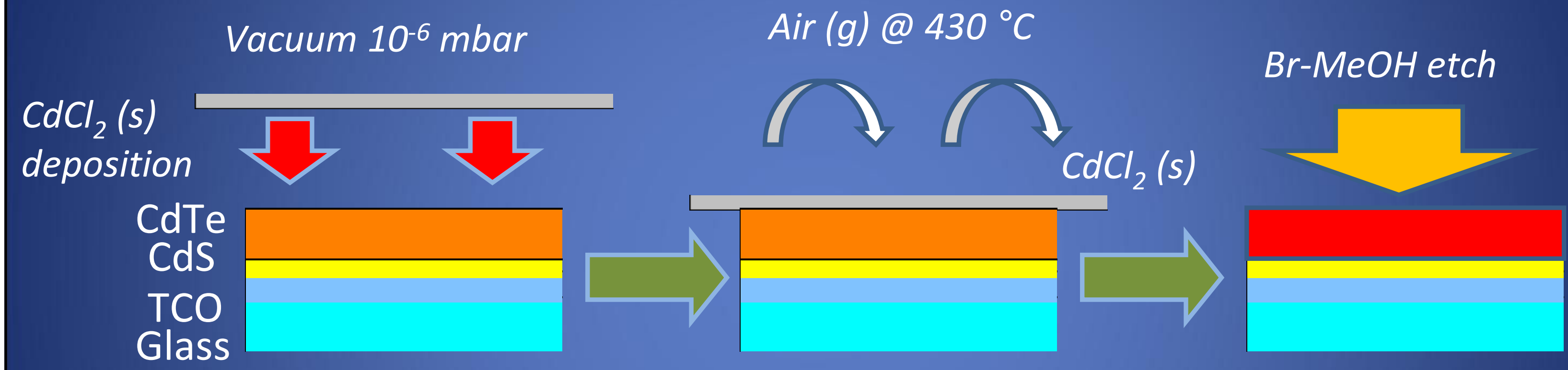


CdTe Close-Spaced sublimation (CSS)



- CdTe is deposited by CSS at a substrate temperature of 500°C in an Ar atmosphere.
- Total pressure in the deposition chamber is about 1mbar and the deposition rate is ~2μm/min.
- The thickness of the CdTe is normally 4-6 μm.

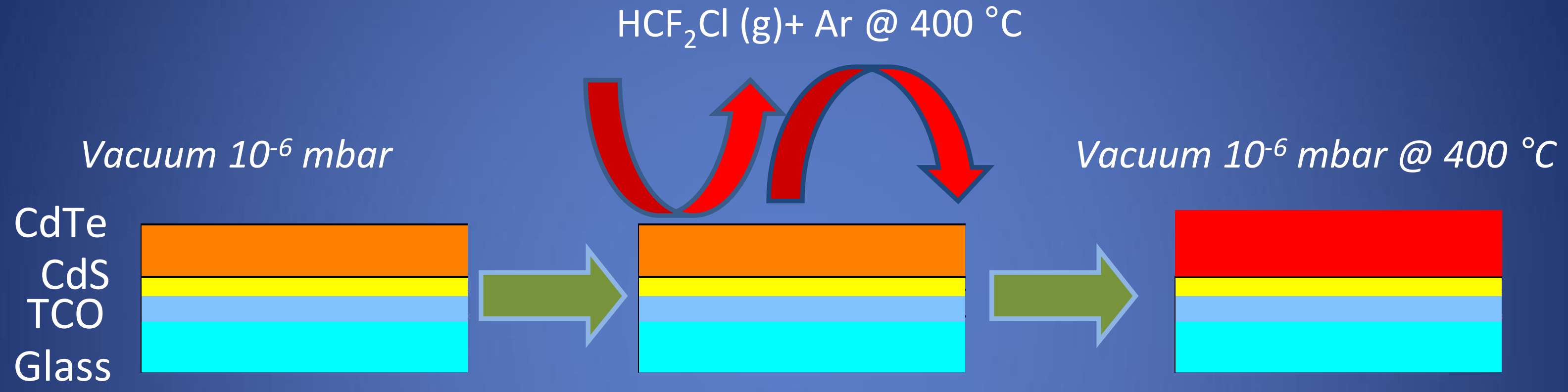
Activation processes: $CdCl_2$ treatment



$CdCl_2$ (s) + O_2 (g) + CdTe (s) <=> $TeCl_2$ (g) + 2CdO (s)

B. E. McCandless Proc. of Mat.Res. Symp. 2001, Vol 668, H1.6.1

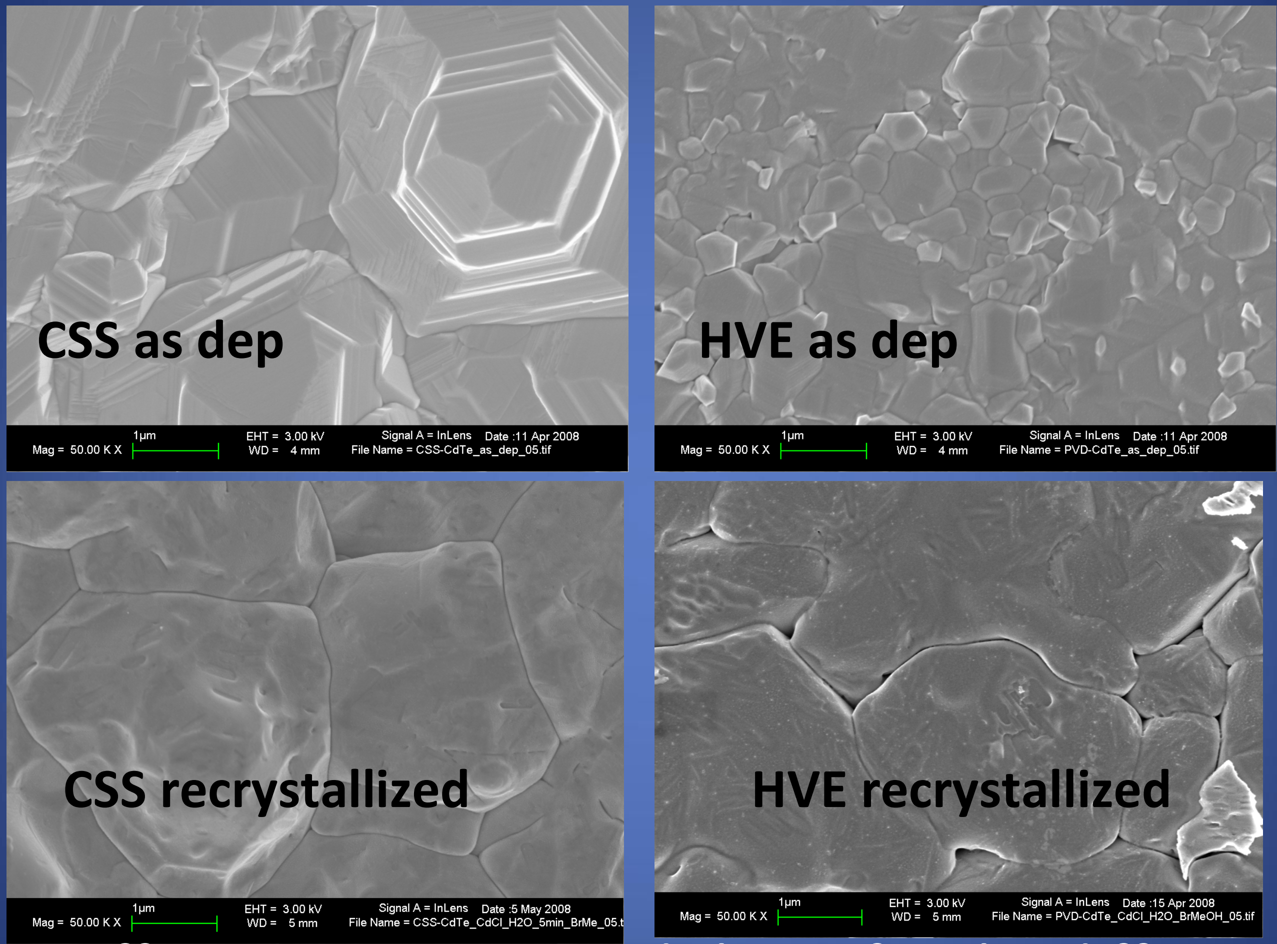
Activation processes: Freon© treatment



$$CdTe\ (s) + 2Cl_2\ (g) <=> CdCl_2\ (g) + TeCl_2\ (g)$$

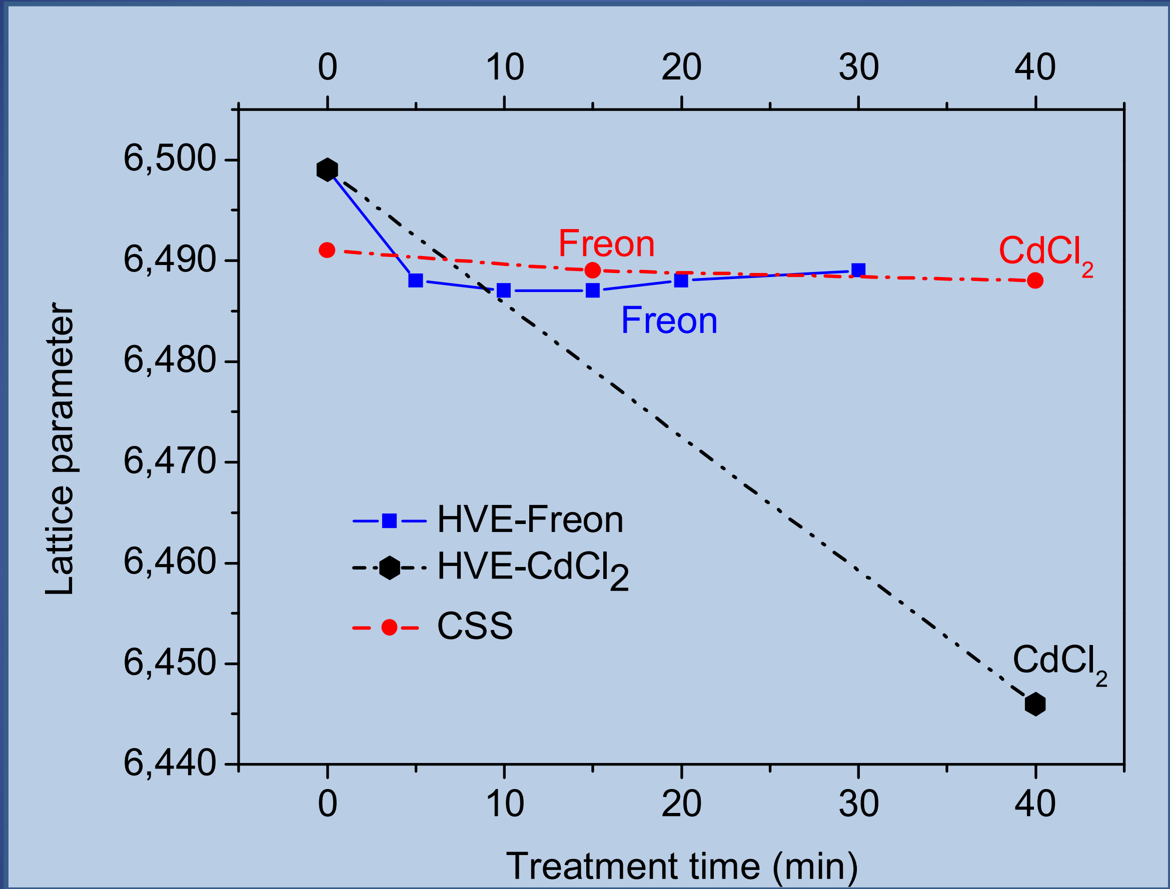
N. Romeo, A. Bosio, A. Romeo, S. Mazzamuto and V. Canevari, Proc. of the 21st Eu-PVSEC, Dresden, Germany, 2006, p. 1857.

CdTe morphology



Different grain size and shape for the different depositon methods

Nelson-Taylor plot: lattice parameters



Texture is more reduced in $CdCl_2$ treated layers

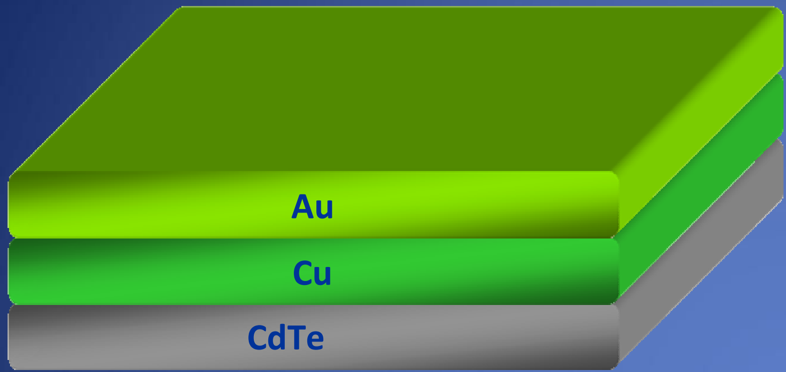
Chlorine treatment

HCF_2Cl, since it is considered an ozone belt depleting agent, will be banned within the year 2012.

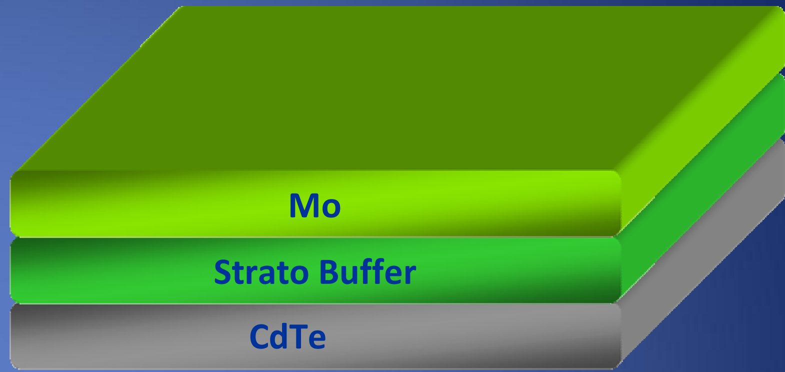
Despite this gas can be recovered in an industrial production, we found out another gas, not toxic and inert at room temperature, that will never be banned.

The use of this gas for treating CdTe is now being patented.

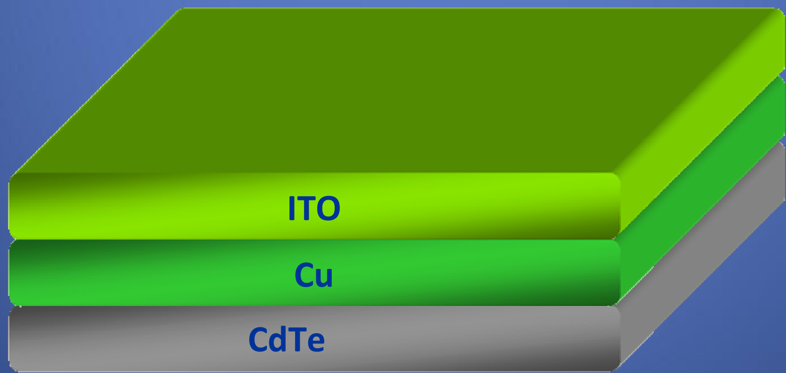
The Back contact



Efficient but not stable

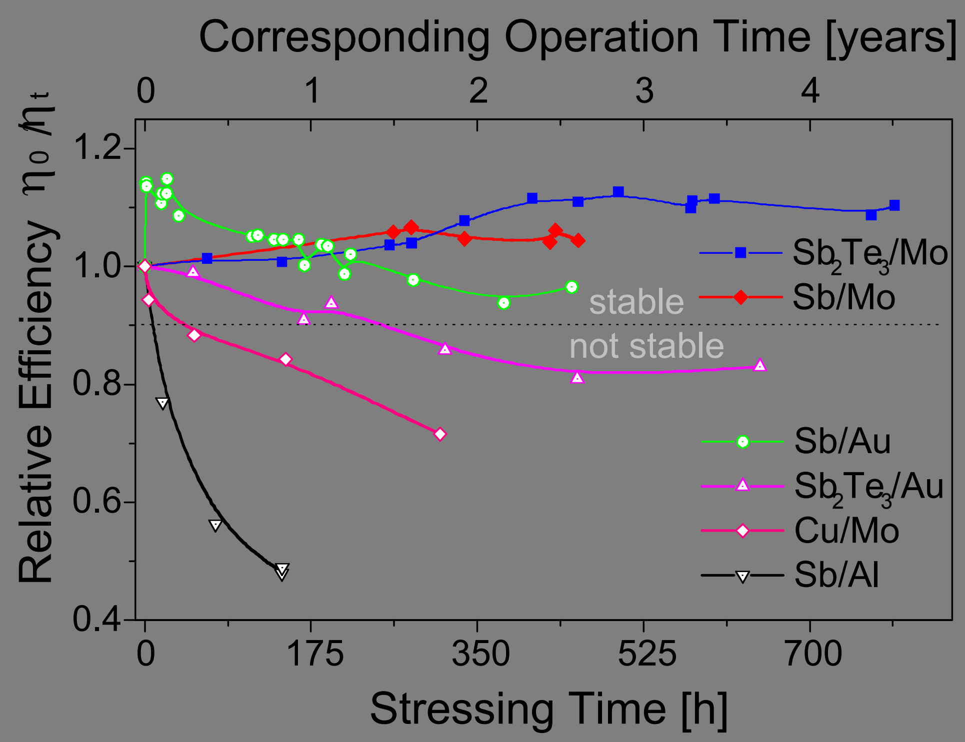


Stable



Transparent: Bifacial cells

Stability tests: stressing



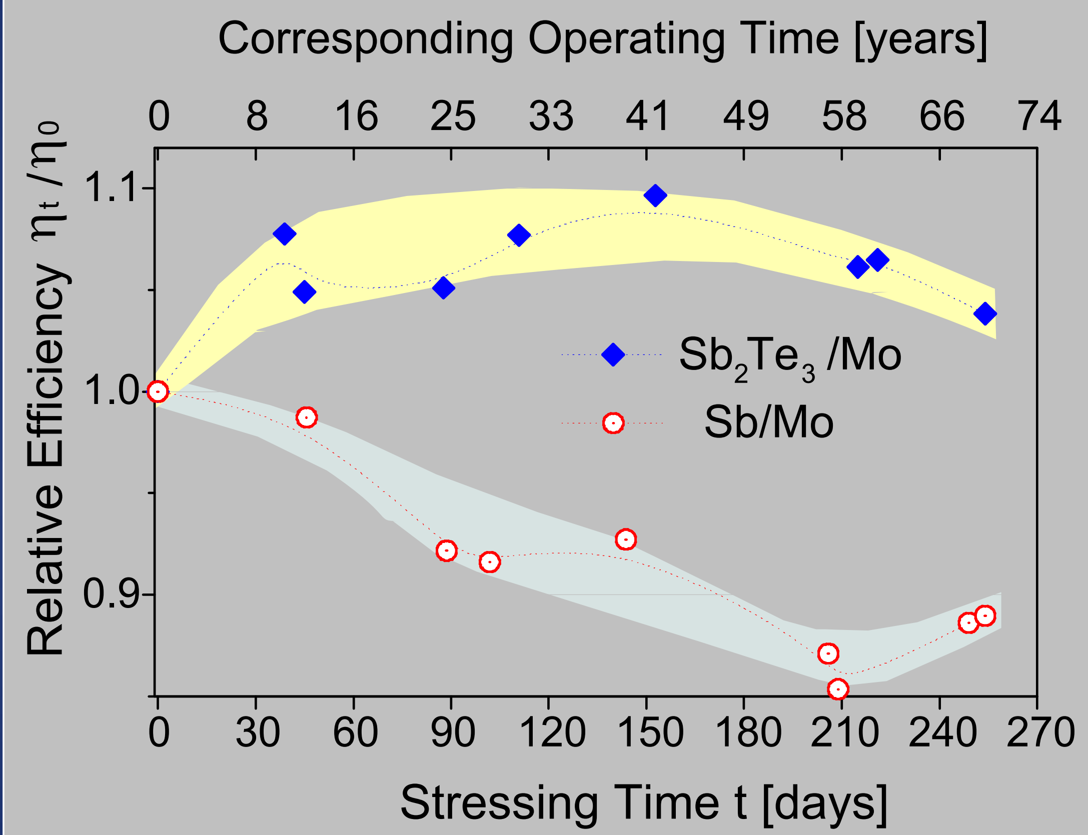
Annealing
@ ~200°C, 30 min

Light soaking
@ ~65°C, 1 sun

Stable cells only with:

Mo metallisation
and Sb or Sb_2Te_3 buffer layer

Stable Cells: Sb/Mo & Sb_2Te_3/Mo back contacts



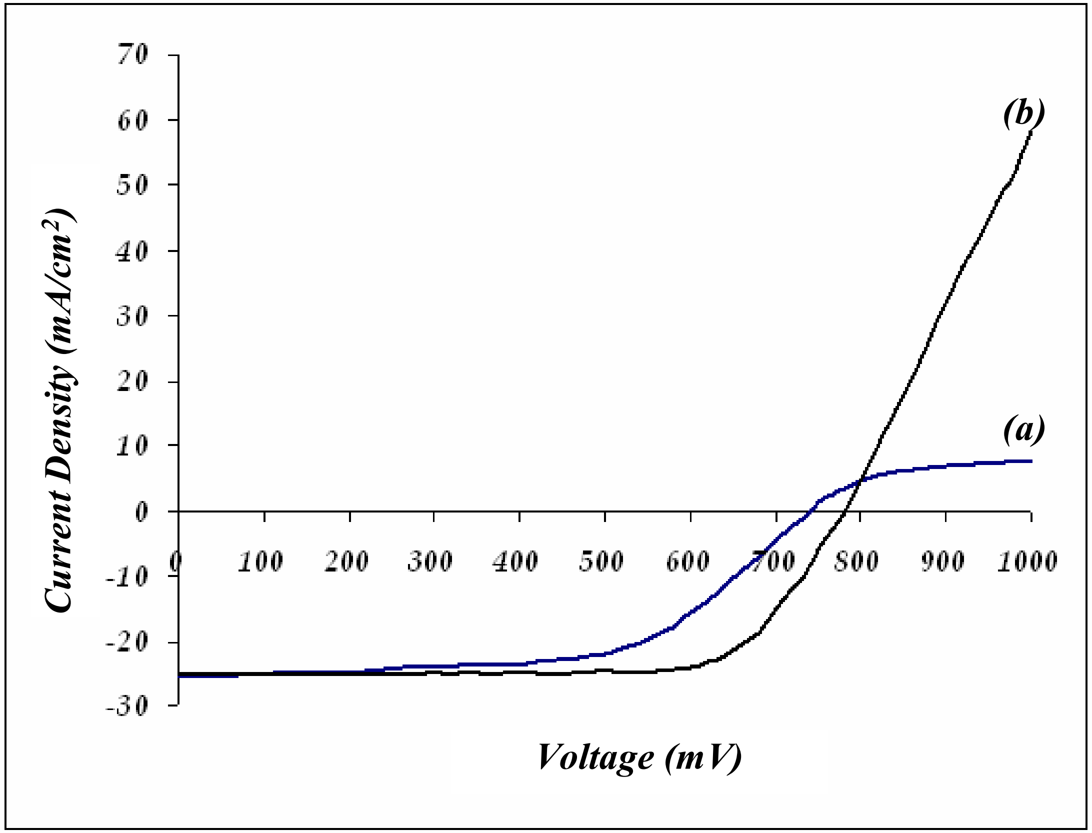
Light soaking @ ~80°C, 1 sun

accelleration factor:100

Sb_2Te_3 buffers show best stability

Sb buffers show acceptable stability

The AS_2Te_3 Back Contact: J-V characteristics



J-V characteristics of CdTe/CdS solar cells in which the back contact is deposited with different substrate temperatures:

(a) As_2Te_3+Cu both deposited at RT
ff = 0.57

(b) As_2Te_3+Cu both deposited at 200°C
ff = 0.7

N.Romeo et al. Proceedings of 22° Photovoltaic Solar Energy Conference

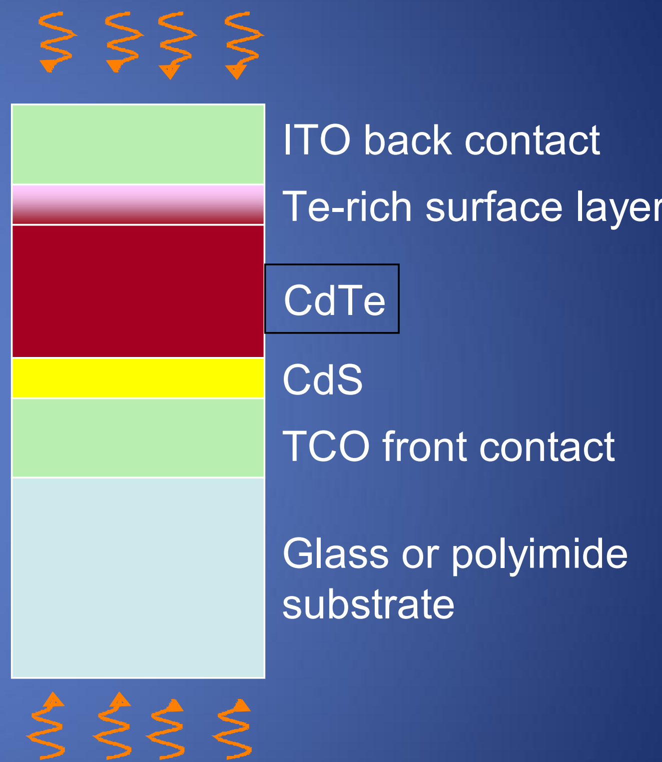
Novel strategy for back contact on p-CdTe

TCO is used as an ohmic contact on p-CdTe

A. Romeo et al Solar Energy Materials and Solar cells (91)2007

Advantages of bifacial solar cell

- Illumination from front and back side:
  Added value to the efficiency and novel applications
- Suitable for tandem solar cells:
  ITO is stable and compatible with several semiconductors
- Stable back contact.
- CdTe thickness reduction:
  Light trapping concepts, including back reflecting mirror



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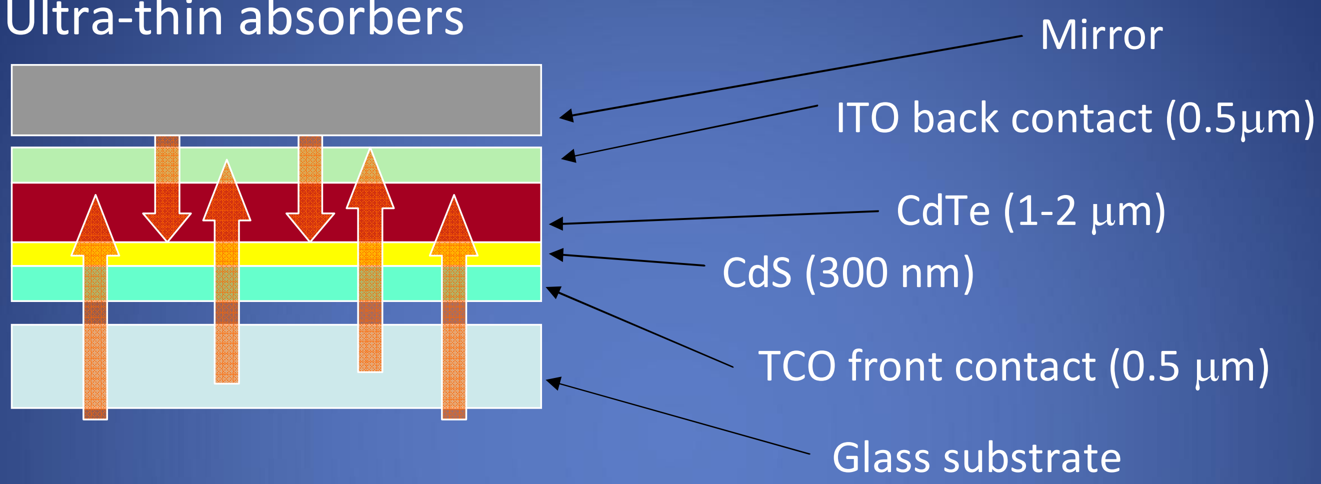
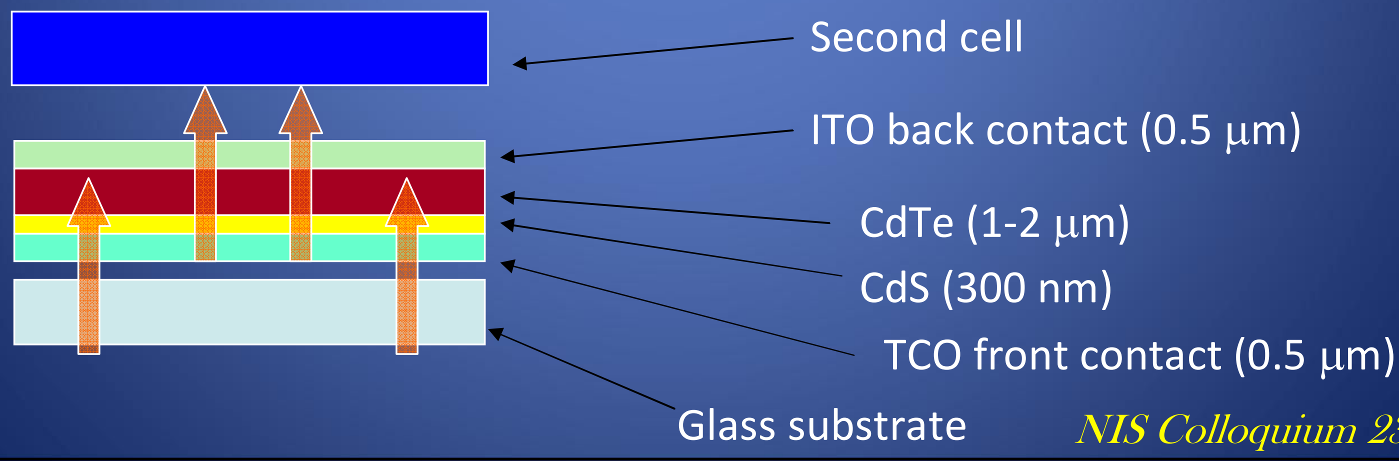
Transparent back contact: applications

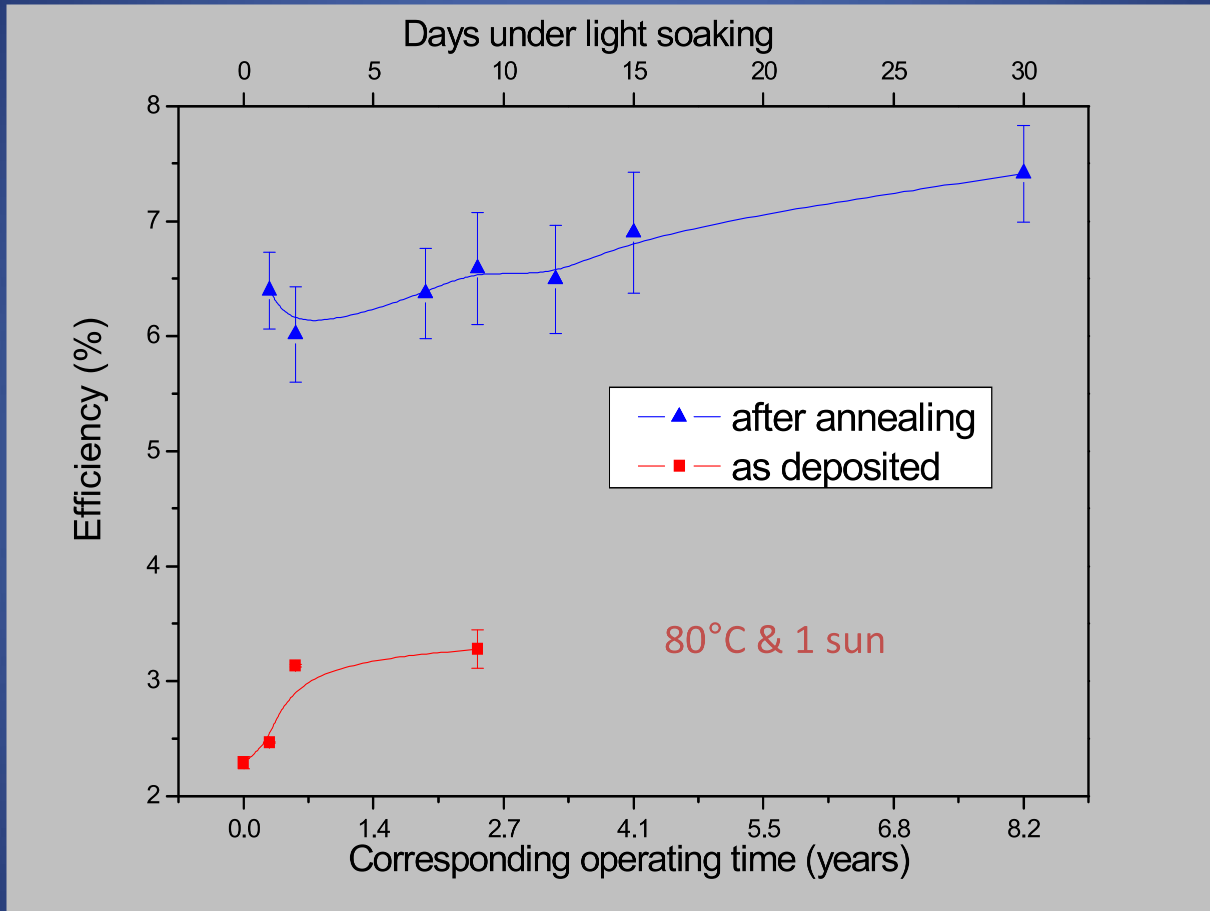
Ultra-thin absorbers



Tandem cells



Stability of ITO back contacted solar cells

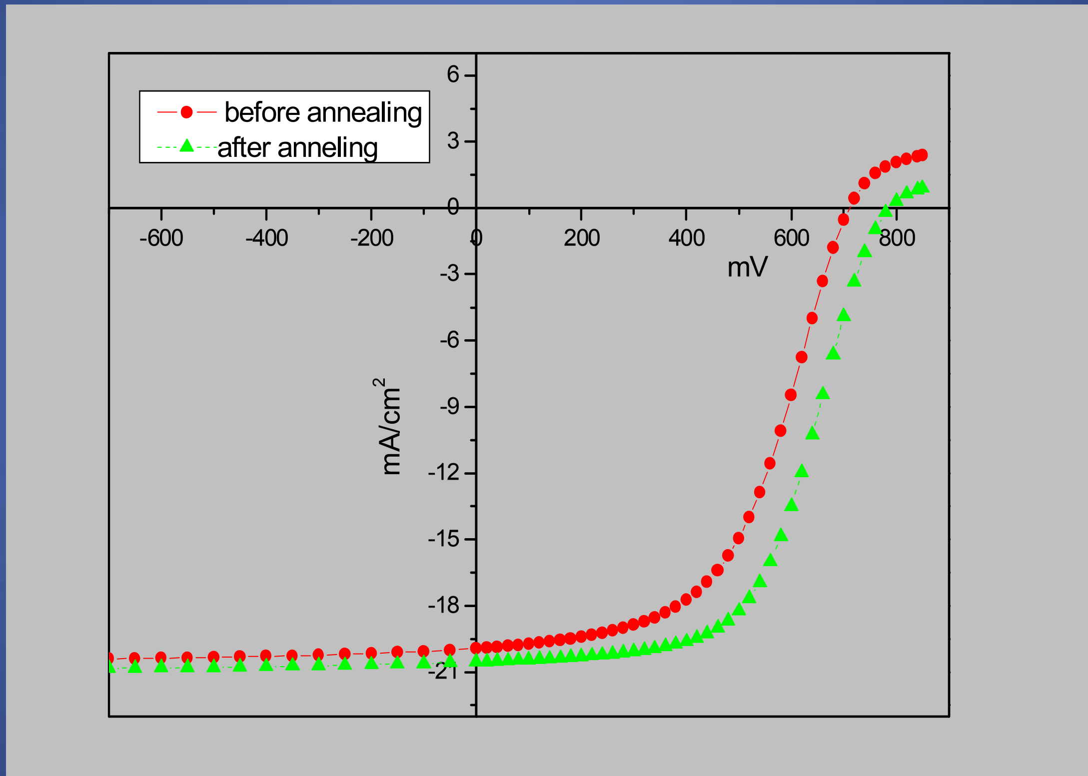


Very good stability also after annealing

Adding copper to the ITO back contact

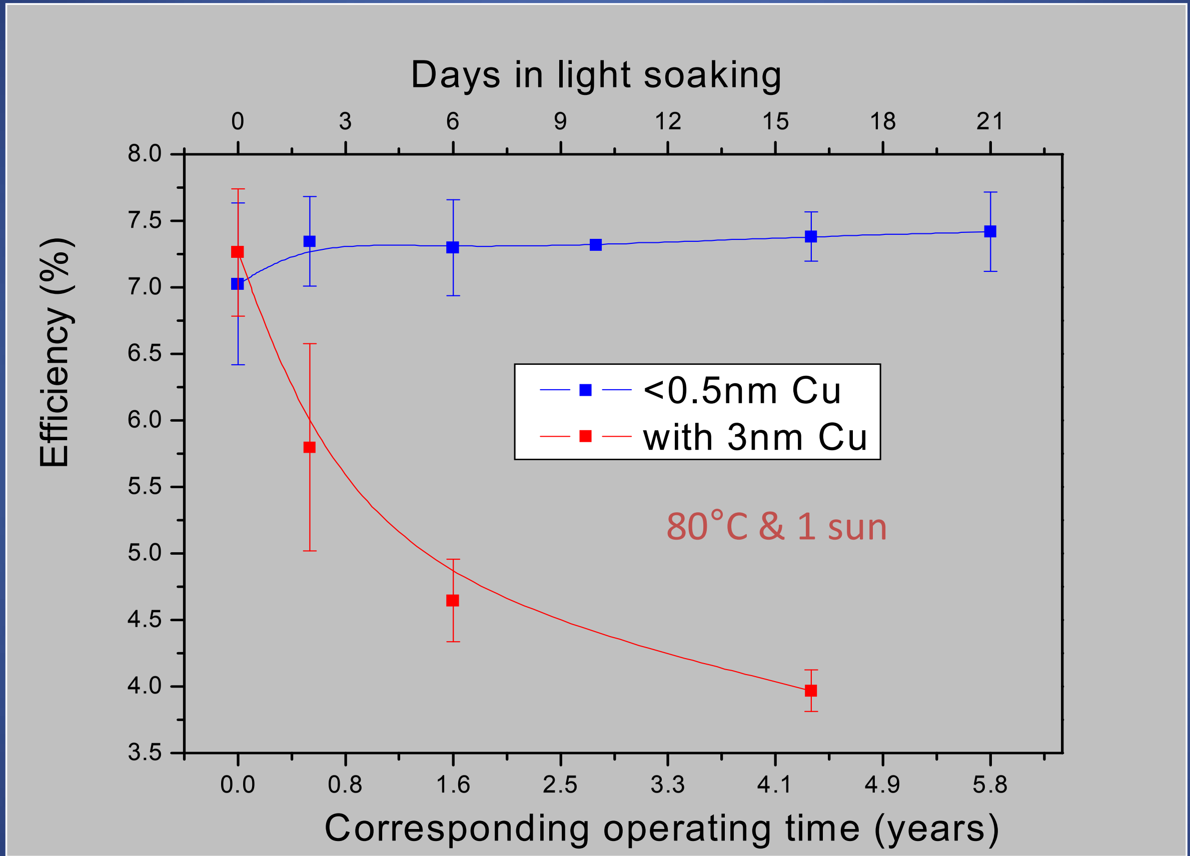
Transparency of the back contact kept if Cu is low

Performance of ITO/Cu/CdTe/CdS/FTO solar cells



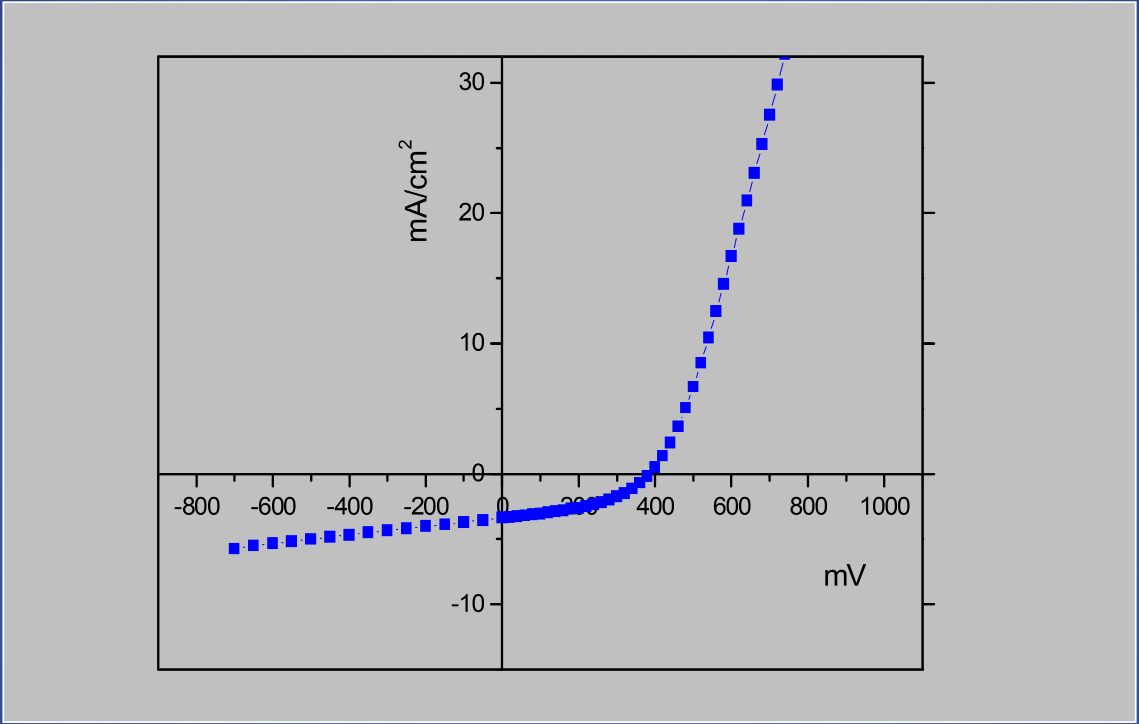
before annealing (V_{oc}=710 mV, J_{sc}=19.9 mA/cm2, F.F. =53.3%, η=7.5 %)
after annealing (V_{oc}=787 mV, J_{sc}=20.5 mA/cm2, F.F.=56.8 %, η=9.2%)

Stability of ITO/Cu back contacted solar cells



If copper is "controlled" the solar cell is stable.

Performance of ITO/Cu: back illumination

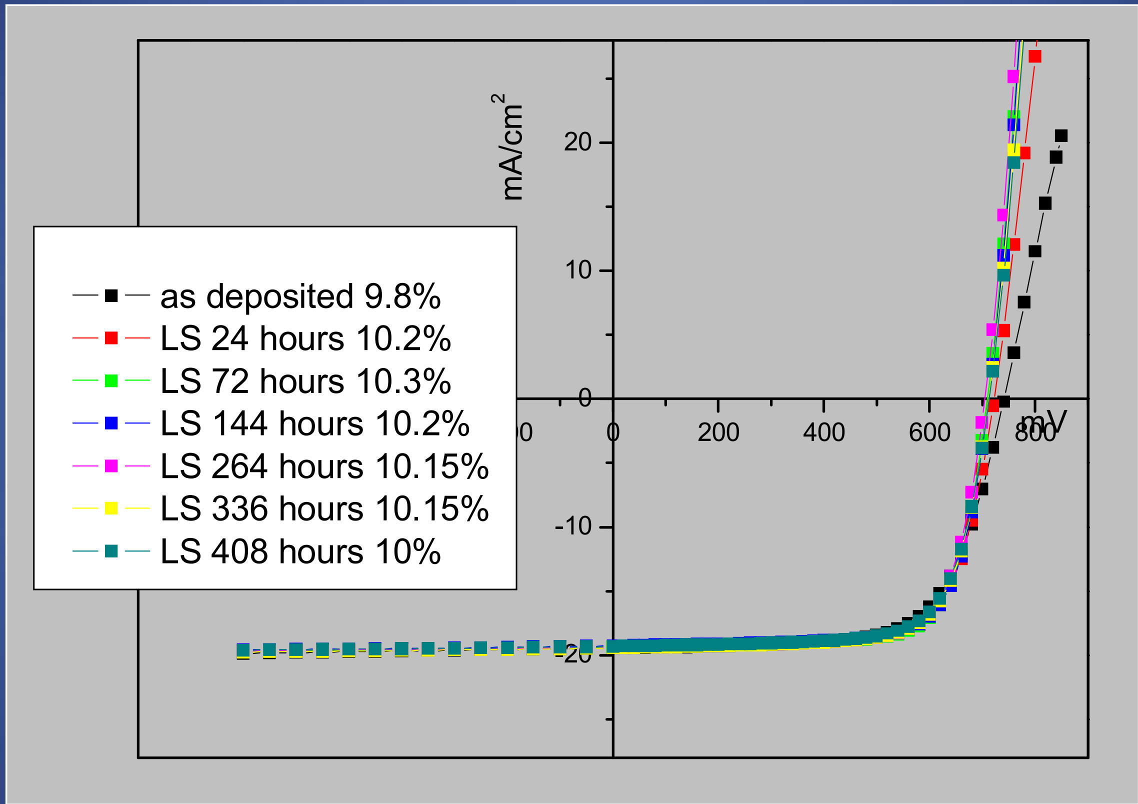


Back illuminated: Voc=384 mV, Jsc=3.4 mA/cm^2 , F.F.= 44 , h= 0.57 %

Thin absorber solar cells

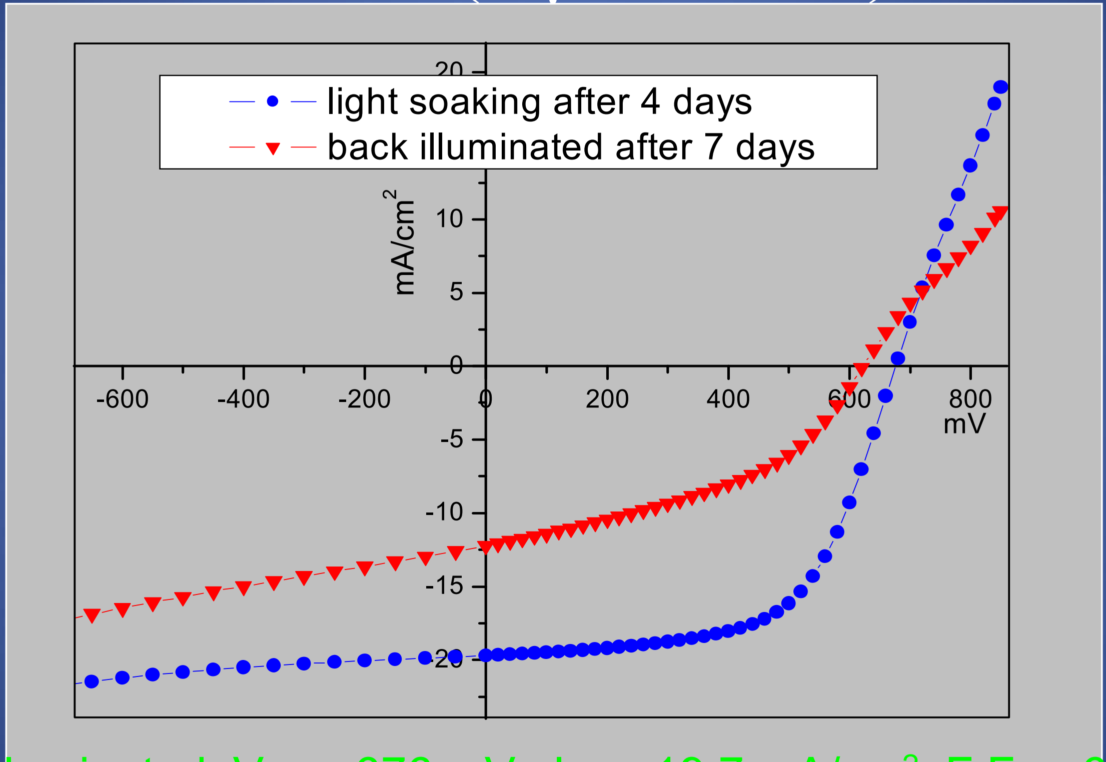
A. Romeo et al Solar Energy Materials and Solar cells (91)2007

Performance of ITO/Cu thin absorber (2.5 μm) solar cells



Front illuminated: Voc= 710 mV, Jsc= 19.4 mA/cm^2, F.F. = 74.6, η= 10.3%

Performance of ITO/Cu very thin absorber solar cells (1 μm CdTe)



Front illuminated: Voc= 676 mV, Jsc= 19.7 mA/cm^2, F.F. = 60.5 %, η= 8%

Back illuminated: Voc=622 mV, Jsc=12.2 mA/cm^2 , F.F.= 43%, η= 3.2 %

The Italian CdTe industrial project:

A new company, with the aim of building a production line with a capacity of 15 MW/year, has been constituted. The name of the company is ARENDI and the production line will be set near Milan.

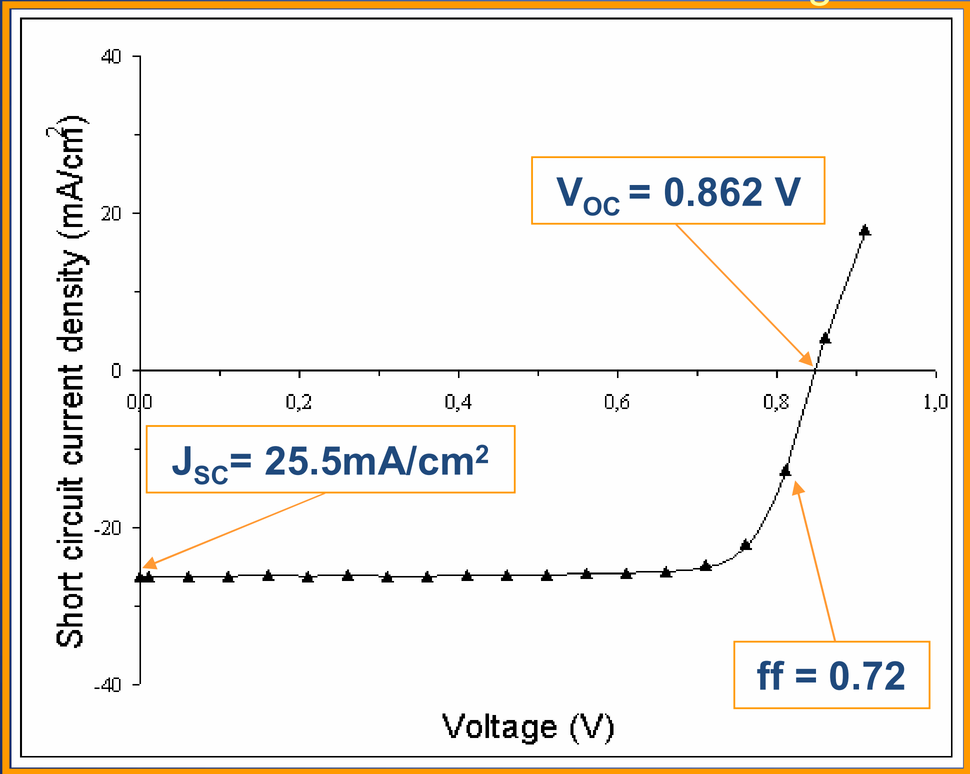
Soda-lime glass with a size of 0.6x1.2 m^2 are planned to be used in the in-line system.

A module each 2 min. will be processed.

With three shifts, the line has the capacity to produce 15MW/year.

Laboratory results :

Efficiencies larger than 14% are routinely obtained with this process on an 1 inch^2 soda-lime glass substrate.

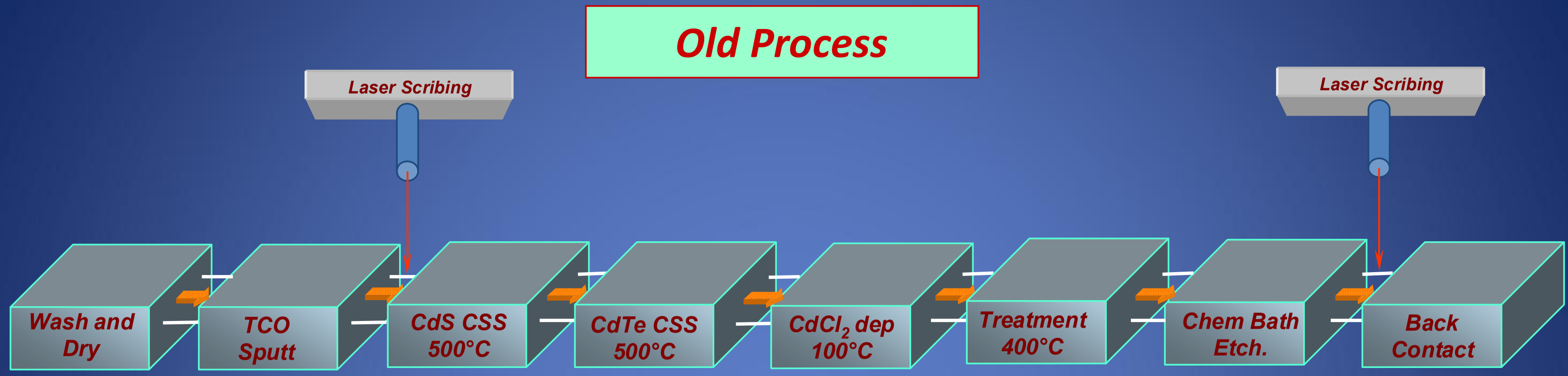


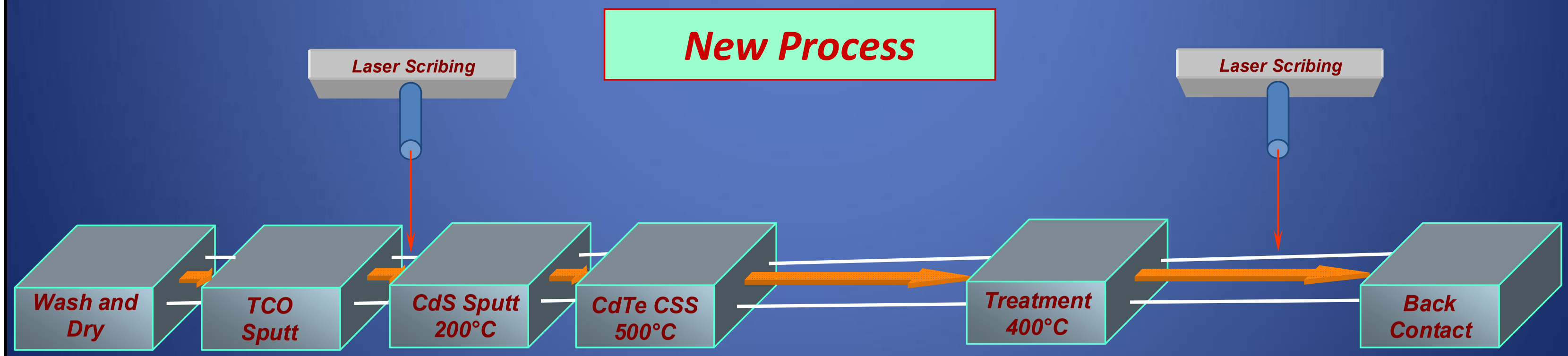
Best efficiency is 15.8% with:

- *V_{OC} = 0.862 V*
- *J_{SC}= 25.5mA/cm^2*
- *ff = 0.72*
- *Area= 1cm^2*

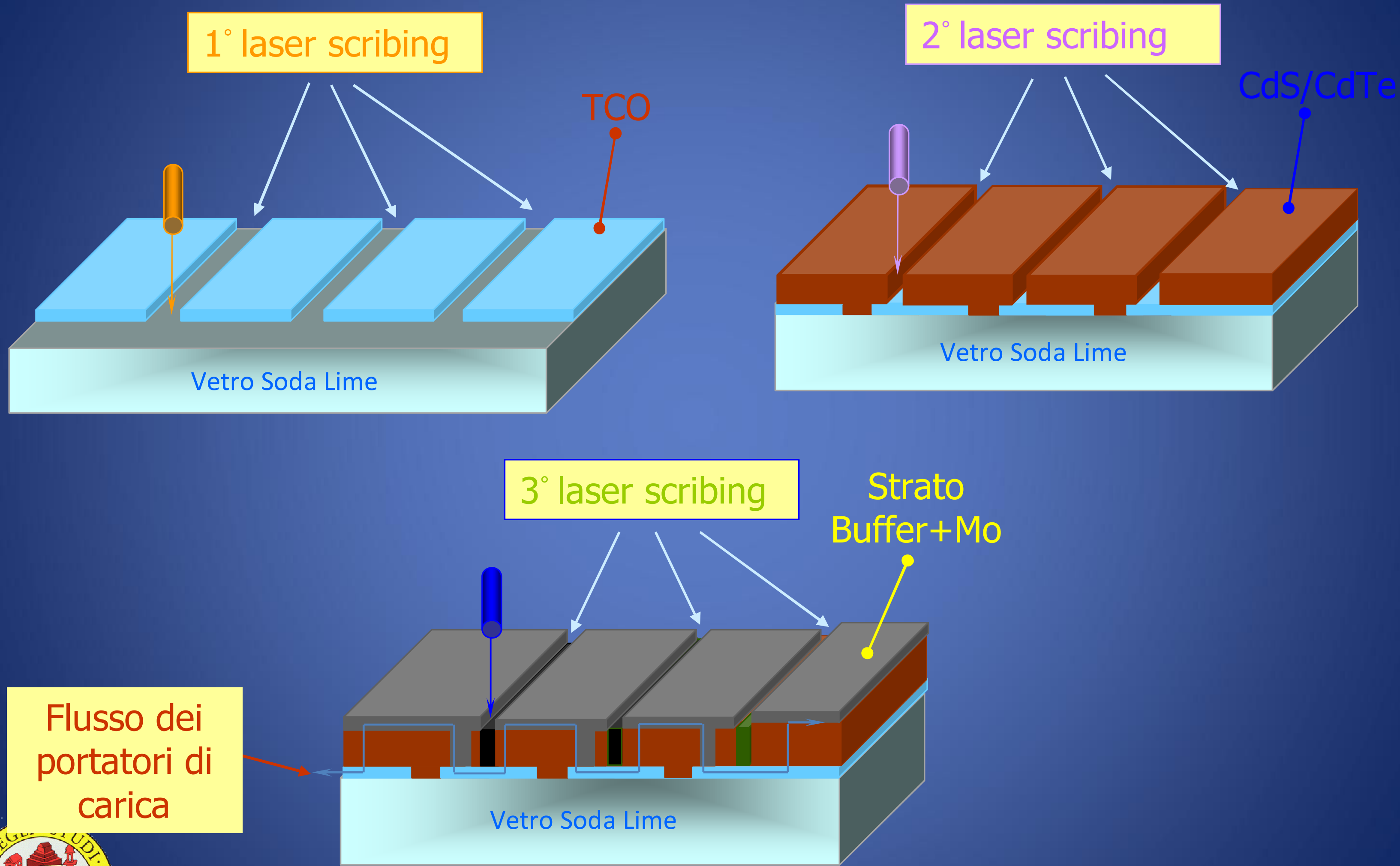
The parameters of the cell have been measured under AM 1.5, 100mW/cm^2 simulated solar light.

Comparison between the Old & the New Process





The laser scribing



Why flexible solar cells ?

More than 90 % of the weight is from the glass substrate

Very high specific power (power/weight) if glass is substituted with lightweight flexible substrates

Thin film superstrate (a-Si, CdTe, CIGS)
- Glass- 5 mil
- Thin film PV

337 g/m²

Thin film substrate (CIGS)
- Cover glass- 5 mil
- Encapsulant- 3 mil
- Thin film PV
- Substrate- 5 mil

746 g/m²

Ref: F.S. Fairbanks et al (Boing Space Co. USA) Proc. 26th IEEE PV Conf, 1997, p979

Solar cells on polyimide: 53 - 60 g/m²

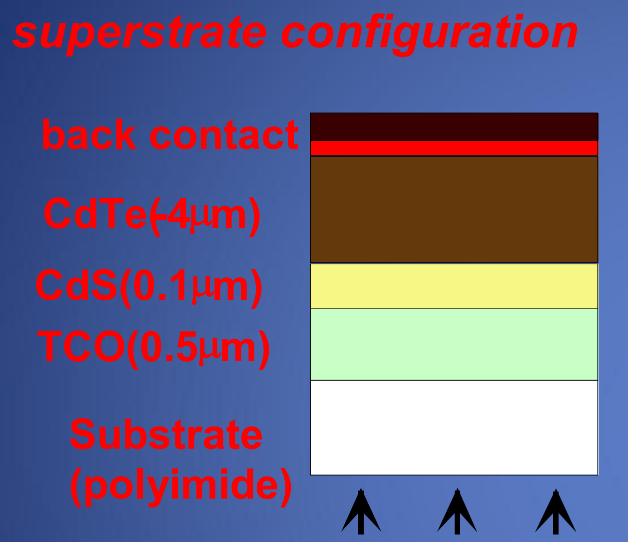
6 to 12 times lighter than conventional thin film PV modules

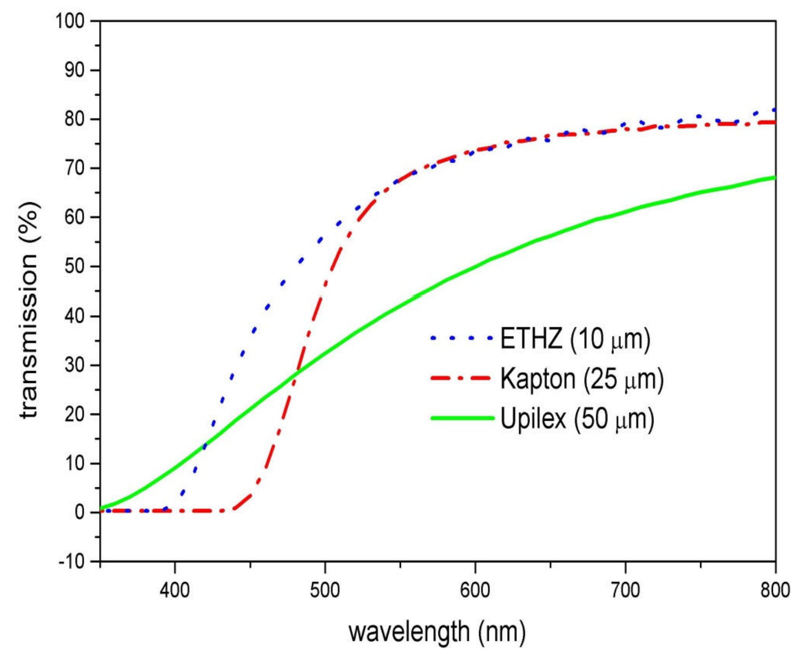
Space applications: satellites cheaper to put in orbit

solar cells easy to deploy in space

Terrestrial applications: integration in buildings (roofs, facades, etc.) consumer electronics (smart cards, solar boats, etc.)

Flexible CdTe solar cell superstrate configuration



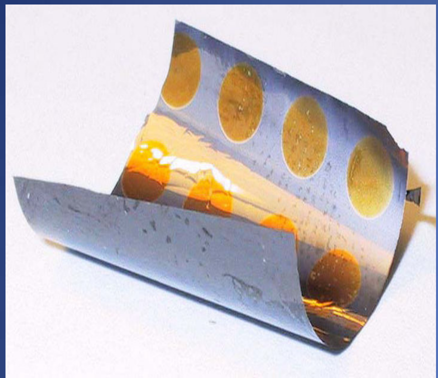


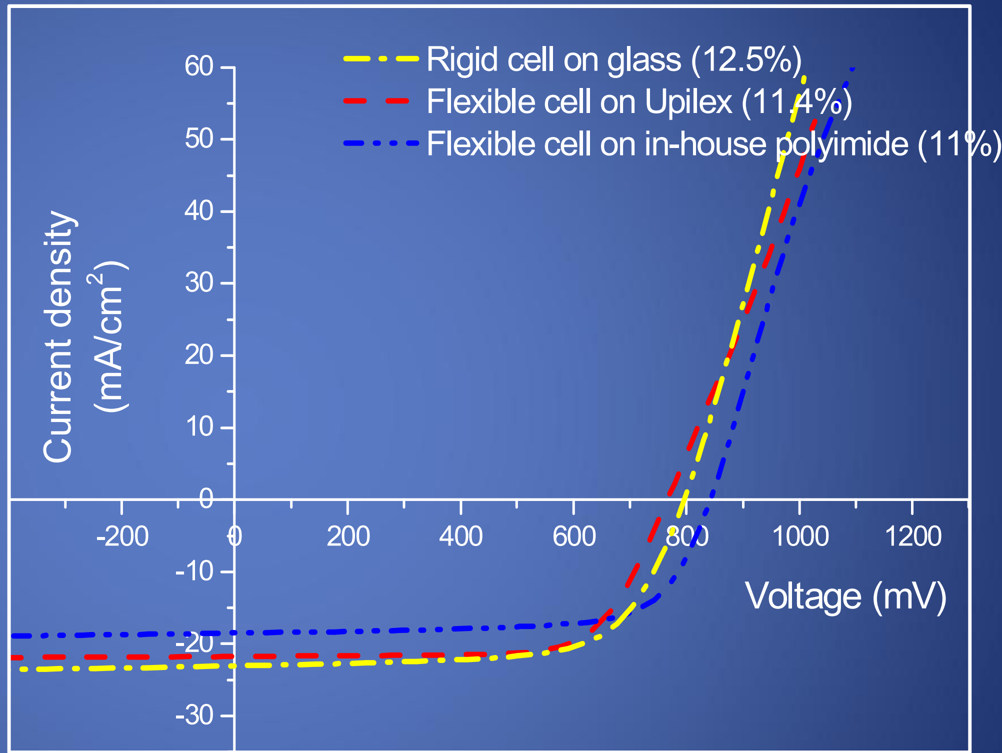
Substrate temperature (450 °C)

Transparency

Transmission strongly depends on the polyimide thickness

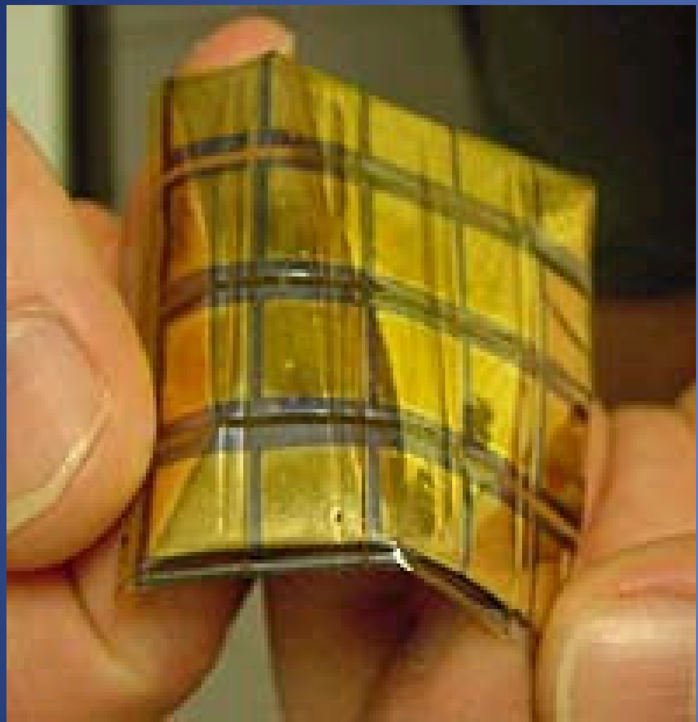
I-V performance of CdTe flexible cells

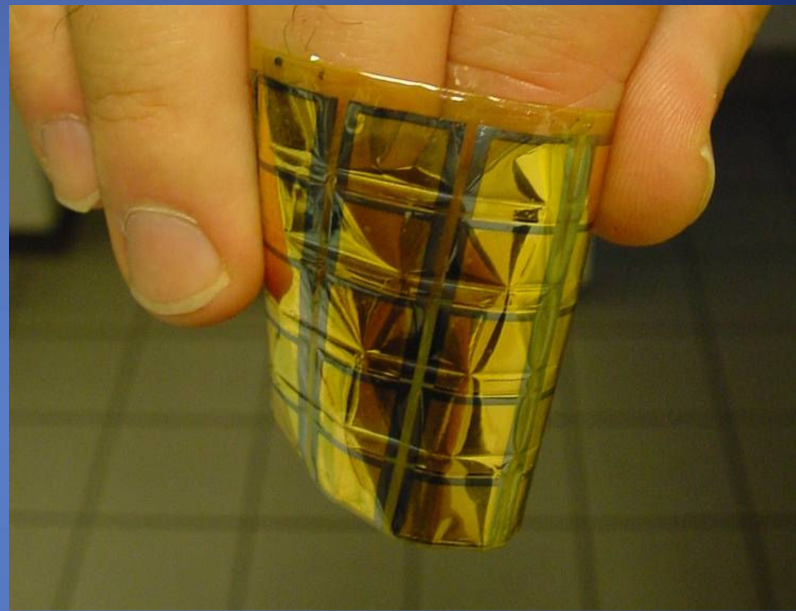




11.4 % record efficiency flexible CdTe

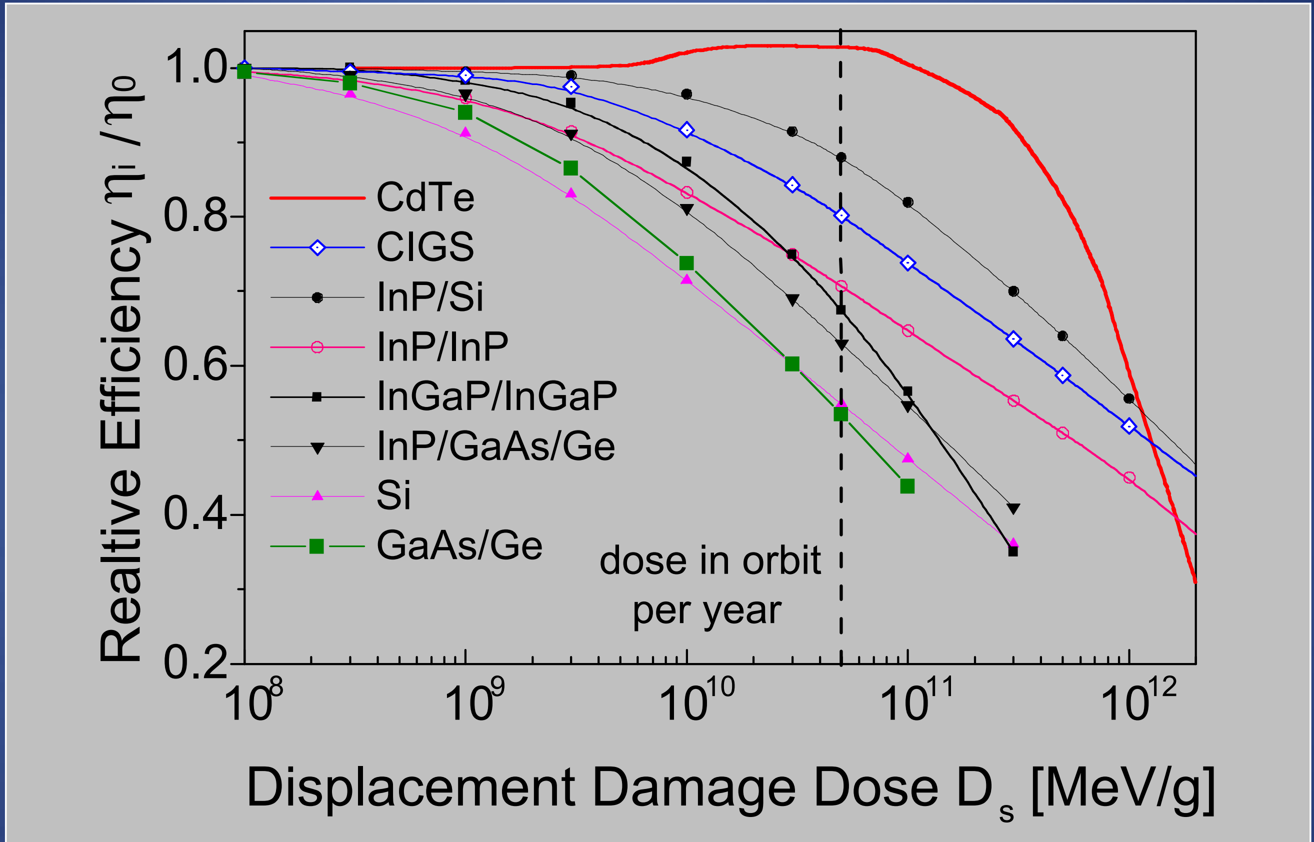
5x5 cm mini-modules





Shadow mask-made mini-modules have performed 3.5% efficiency

Stability under irradiation (e- & p-)

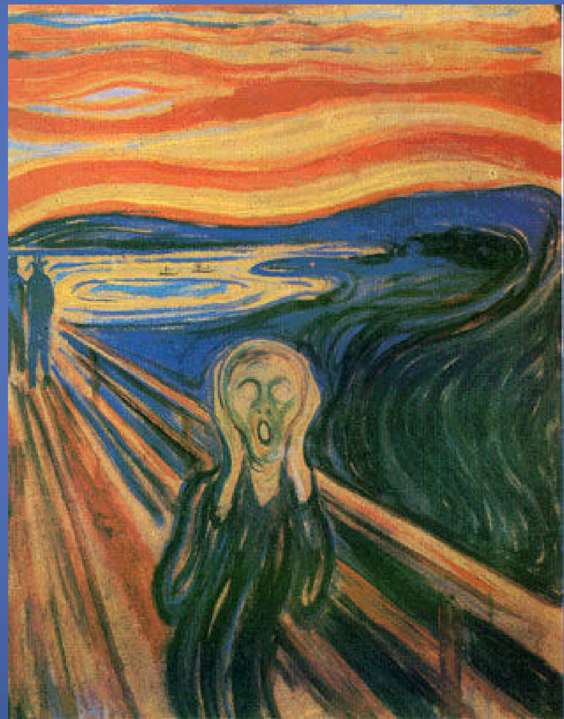


CdTe has superior stability

(except CdTe, other data are from G.P. Summers, S.R. Messenger, Tutorial at 29th IEEE PVSC, New Orleans 2002)

Environmental issues

Cadmium Telluride is really polluting ?

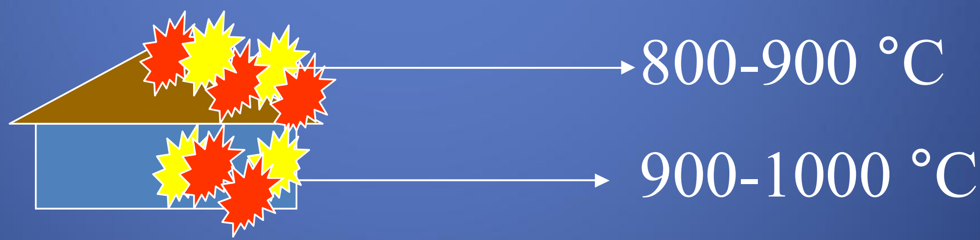


$CdTe/CdS$ solar cells pollution issues

$CdTe$: Melting point @ 1041 °C

Evaporation starts @ 1050 °C

Sublimation @ 800°C is 2.5 Torr



In case of fire the covering glass melts encapsulating any compound

Alsema et al. Report nr 96074 Utrecht University 1996

Cadmium is a by-product of zinc, lead, and copper mining.

- Its major feedstock, sphalerite (ZnS), contains only 0.25% cadmium.
- Zn is produced in large quantities (8 million metric tons in 1999): substantial amounts of cadmium are produced as a by-product

(irrespective of the Cd used in the PV industry).

Reference :
K. Zweibel, V. Fthenakis, NCPV Program Review Meeting: http://www.nrel.gov/cdte/

Cadmium is a by-product of zinc, lead, and copper mining.

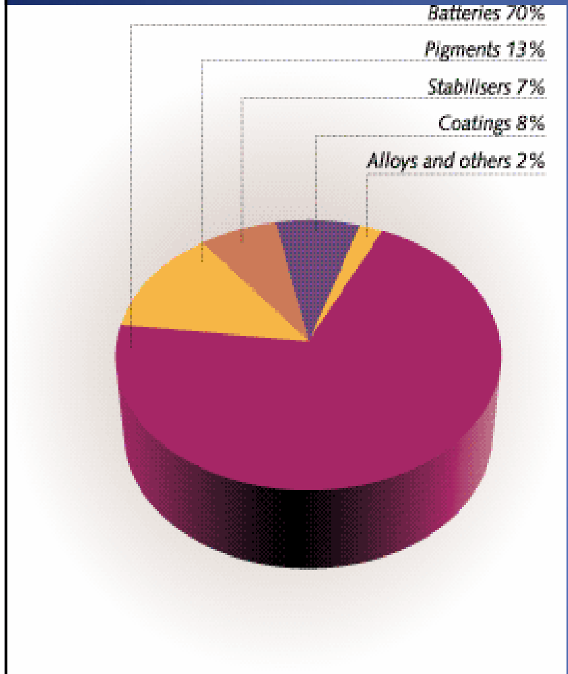
- This cadmium by-product can be put to beneficial use in PV modules.
  Otherwise it is discharged into the environment.

- When Cd generated by metal smelters/refiners is not used in the market:
  1. cemented and buried
  2. stored for future use
  3. disposed of in landfills as hazardous waste

Reference :

K. Zweibel, V. Fthenakis, NCPV Program Review Meeting: http://www.nrel.gov/cdte/

Hypothetical Cd consumption



Cadmium world consumption in the last 30 years: 16 to 20 thousands tons per year

Quantity of cadmium used per power generated:*

10 MWp = 7 tons of cadmium

100 MWp= 70 tons of cadmium

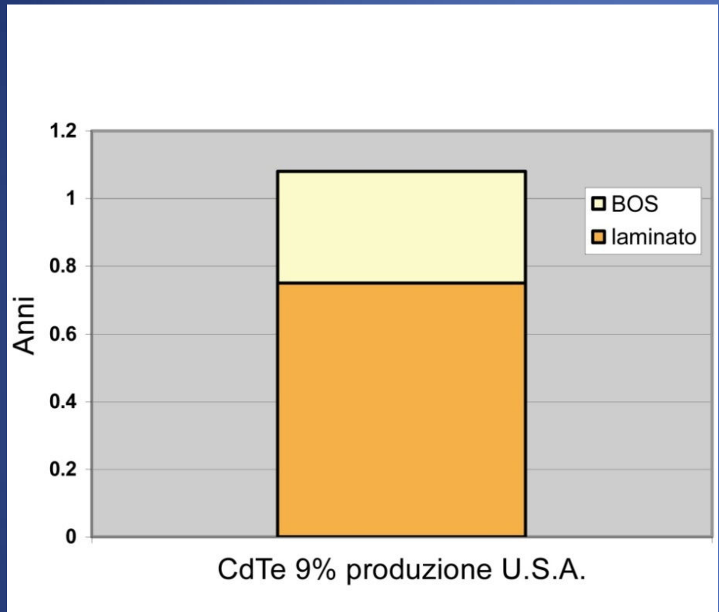
1000 MWp= 700 tons of cadmium

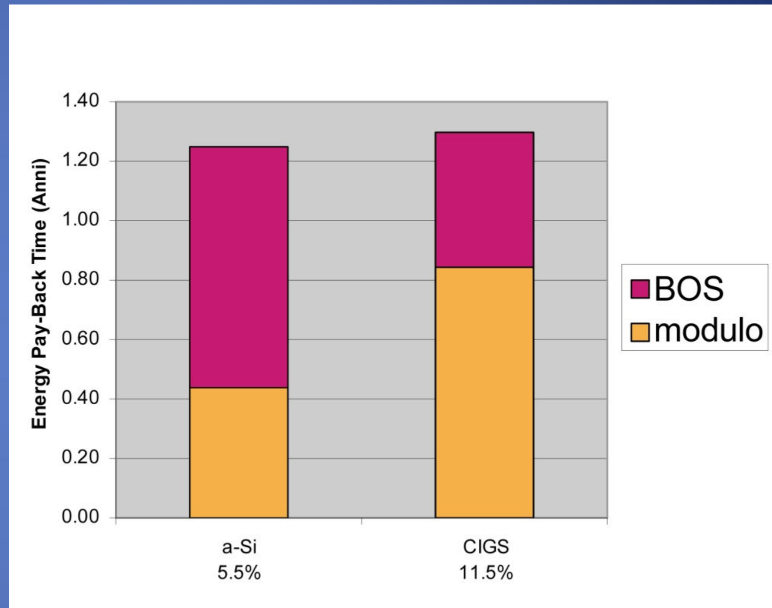
700 tons over 16 thousand tons is 4 %

(in case of extreme Cd concentrations)

* With 10 % efficiency module and supposing a density of 70 g/m^2 (maximum density of cadmium found in a CdTe module: quantity of cadmium per m^2 may vary: 6 to 66 g/m^2 in 4 different modules reported by Steinberger et al. (13th European Photovoltaic Solar Energy Conference, Nice, October 1999))

Energy Pay-back time: thin films





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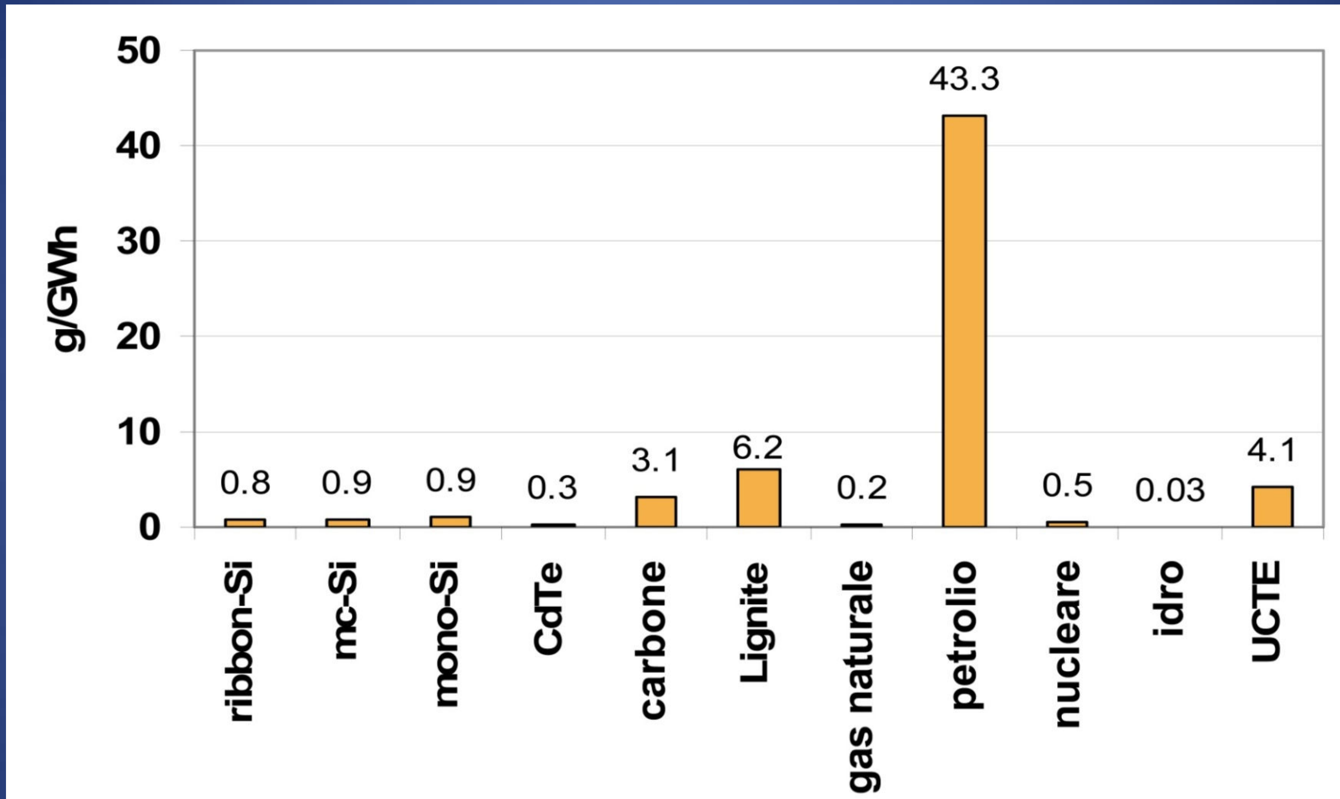
Cadmium emission



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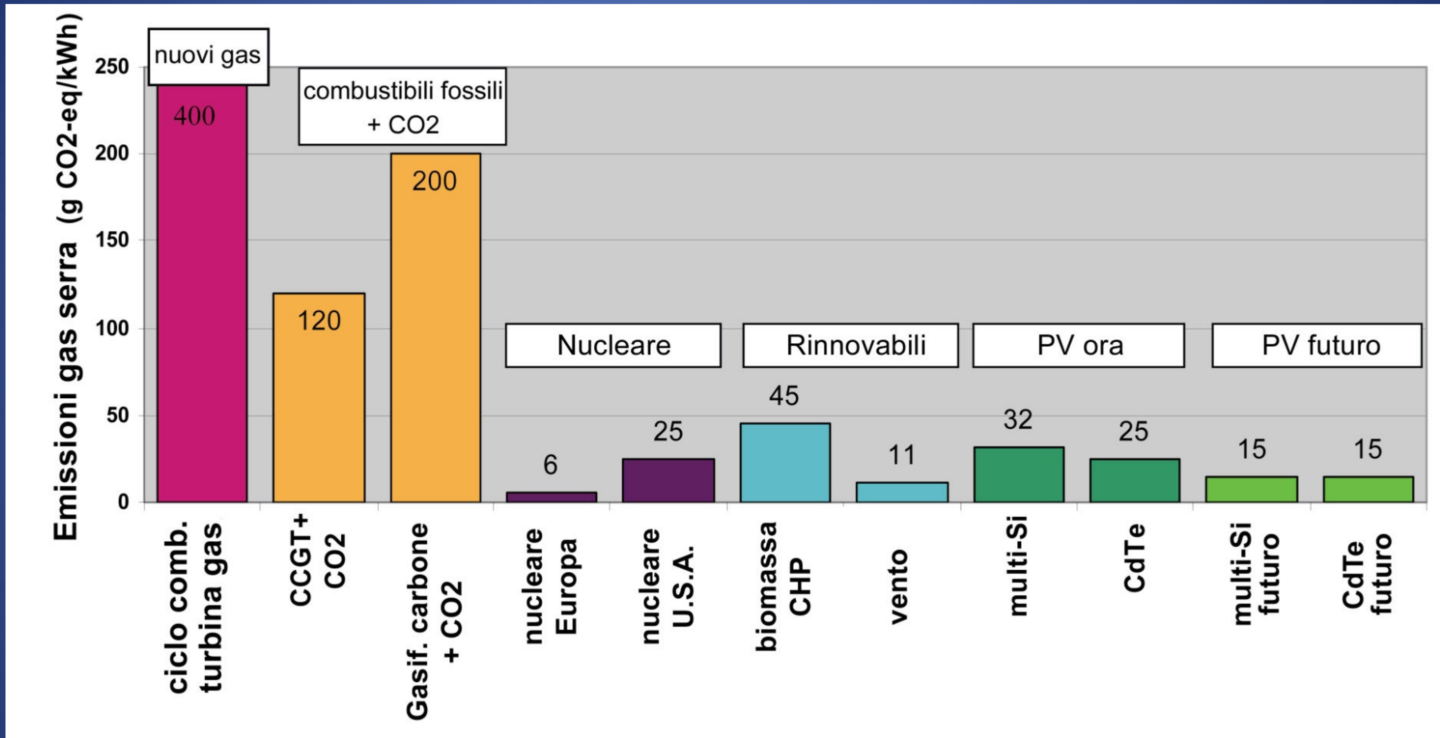
CO_2 emissions



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Summary and conclusions

- CdTe cells are easy to produce and perform high efficiency
- High efficiency flexible CdTe solar cells have been obtained
- Stable back contacts have been developed
- First CdTe bifacial cells have been achieved
- First Italian CdTe production plant
- Extreme radiation hardness demonstrated ⇒ space application
- CdTe solar modules are not polluting the environment

Thank you for your attention !!!