“Escalamiento de celdas solares de CdTe” – proyecto SENER, Sustentabilidad Energética

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Outline

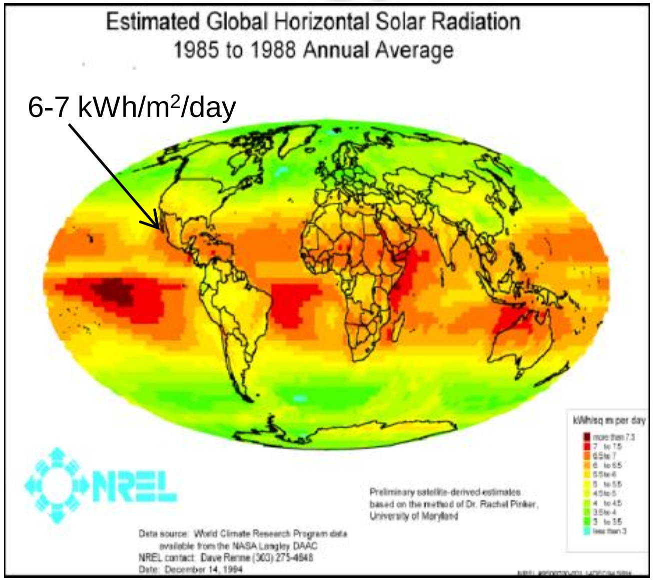
* **Introduction**
  - PV potential & actual scenario
  - Solar cells-basics
  - CdTe perspectives

* **R & D activities**
  - CdTe/CdS devices

* **CdTe issues**

* **Scale up for CdTe**
  - CSS process
  - Prototype CSS pilot plant for batch processing

PV- a technology to harness Solar Energy

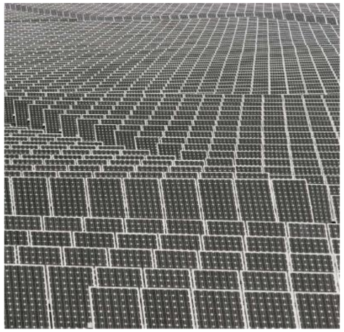


- Earth receives approximately 200,000 TW solar power

- Energy receiving each day is equivalent to the petroleum reserves of the world.
- **600TW can be utilized**
- **With 10% efficiency, 60TW on-shore production**

- **With 10% land use this will translate into 6TW**

- A temporary problem - cost



Portugal, 52,000 paneles
11 MW capacidad

Courtesy: N.G. Dhere, FSEC, Florida

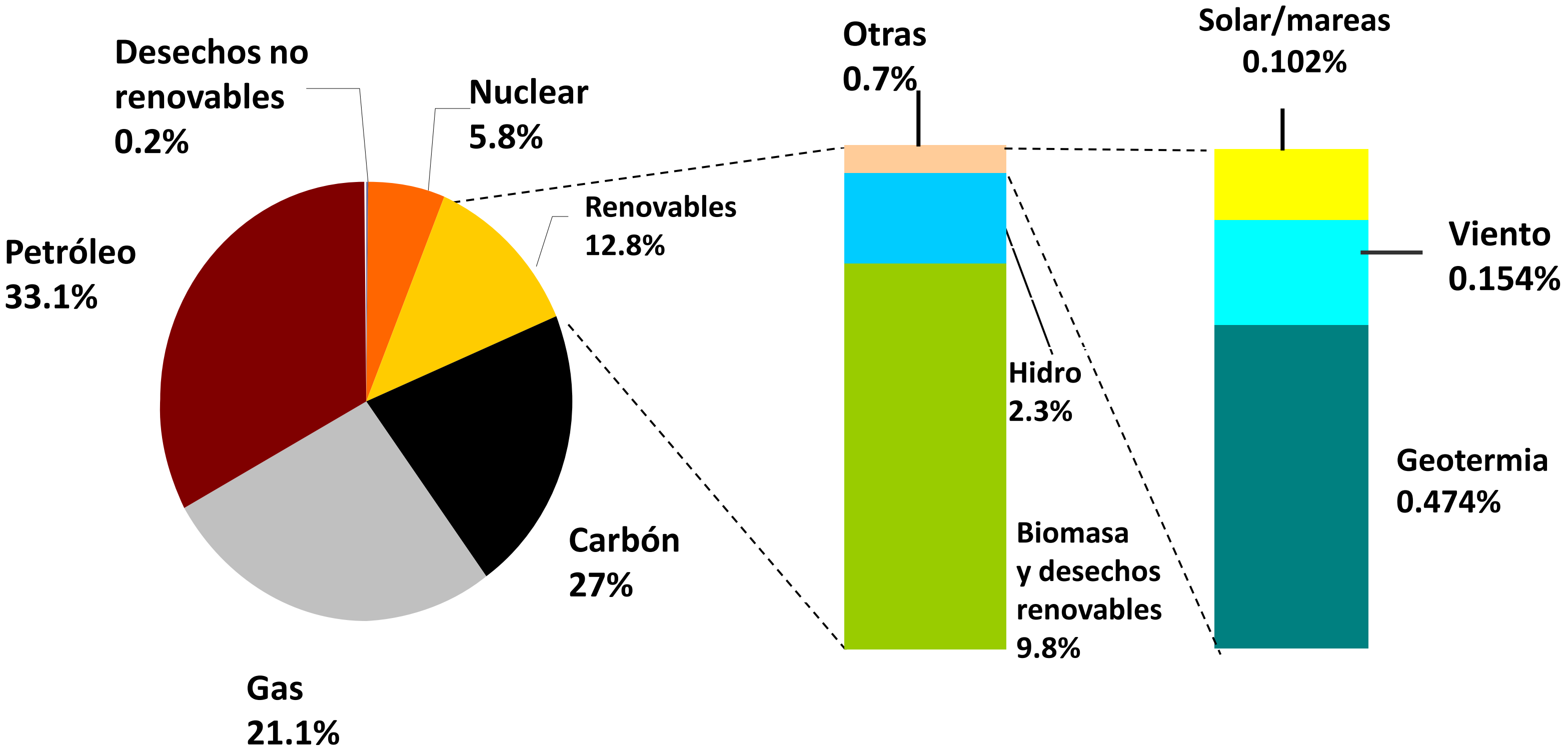
Energy is BIG business

Global Annual dollar outlays-

Energy	4T$
Agriculture	2T$
Defense	1T$ (US- 0.5T$)

Courtesy- Tim Ellison (Energy Conversion Devices Inc.), 2006

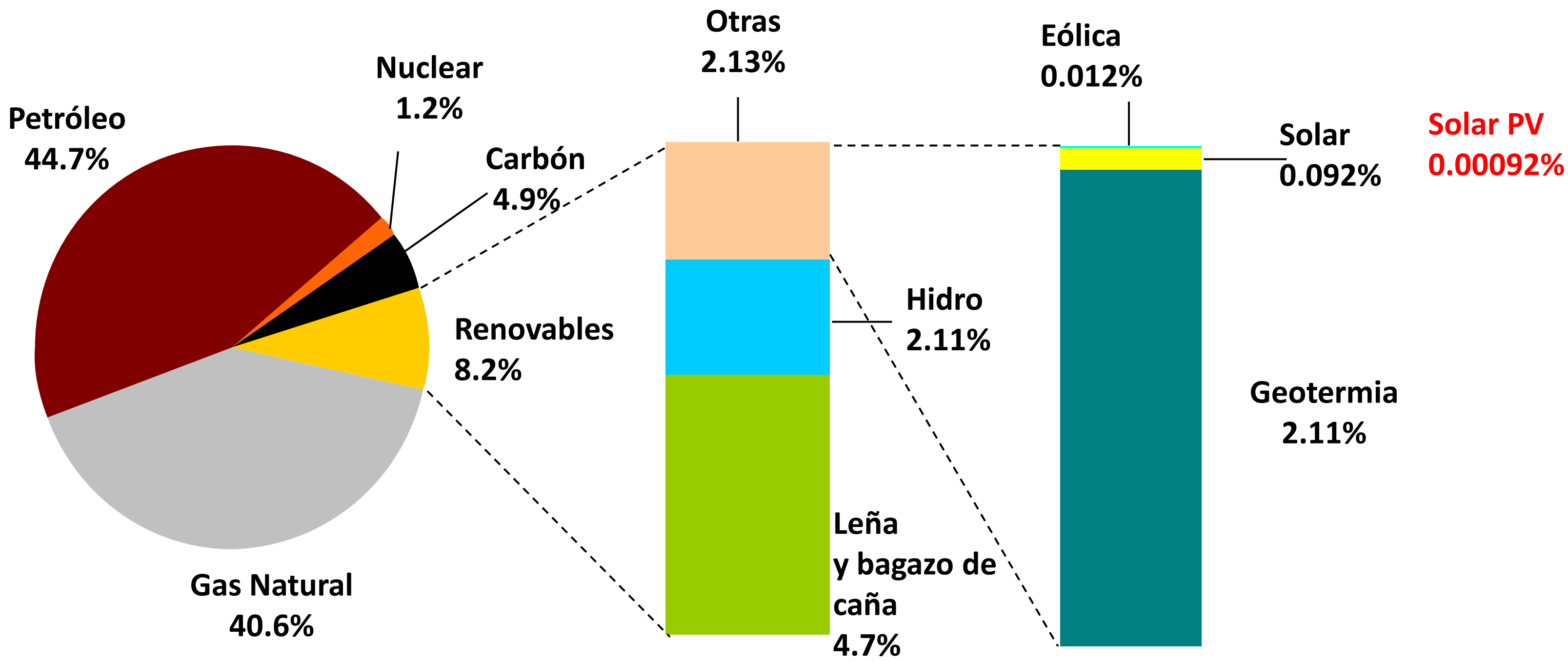
Consumo de energía primaria mundial 2008
12,264 Mtoe



Fuente: IEA (2010), Renewables Information 2010.

Courtesy- Genice Grande, CIE

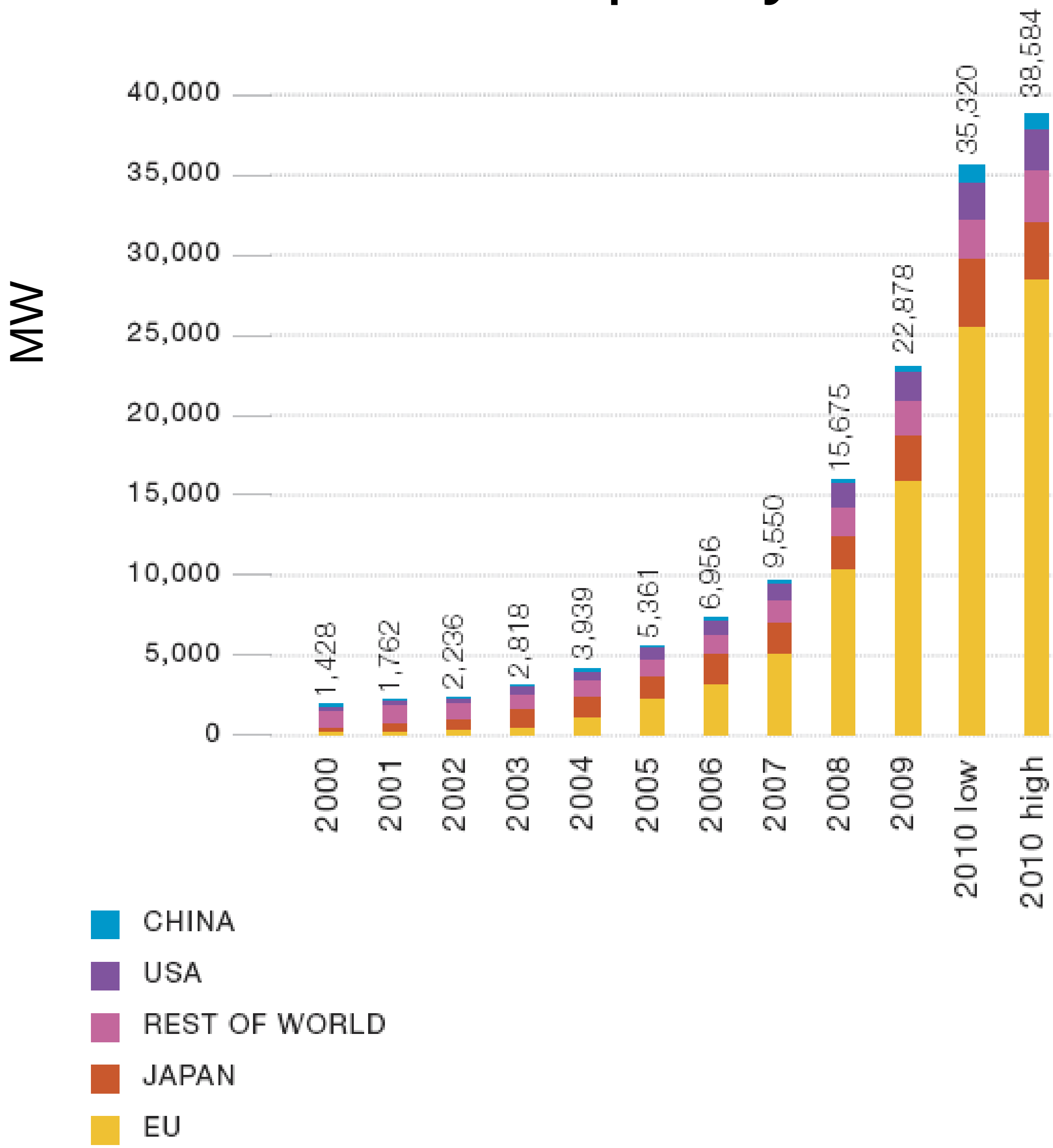
Consumo de energía primaria en México 2009
7,361 PJ



Fuente: SENER (2010), Balance Nacional de Energía 2009.

Courtesy- Genice Grande, CIE

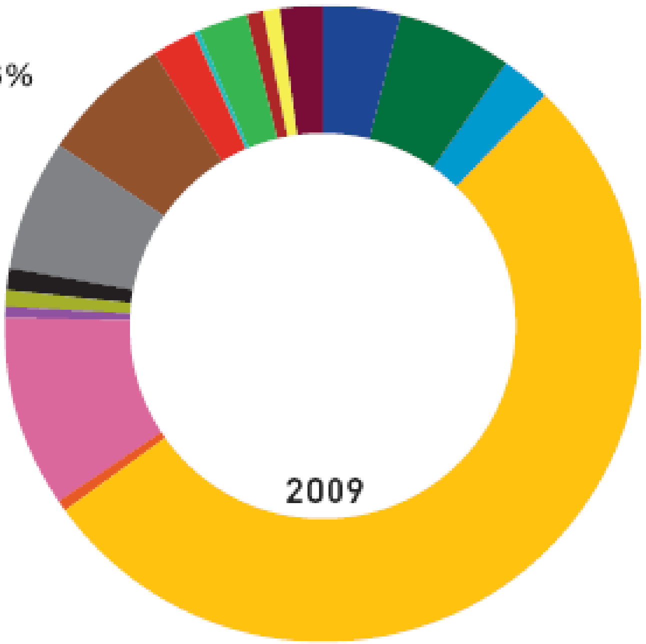
PV installed capacity-Global



source: Global Market Outlook for Photovoltaics until 2014, EPIA, May 2010.

THE WORLD PV MARKET IN 2009

- BELGIUM 4%
- CZECH REPUBLIC 6%
- FRANCE 3%
- GERMANY 53%
- GREECE 0.5%
- ITALY 10%
- PORTUGAL 0.5%
- SPAIN 1%
- REST OF EU 1%
- JAPAN 7%
- USA 7%
- CHINA 2%
- INDIA 0.5%
- SOUTH KOREA 2%
- CANADA 1%
- AUSTRALIA 1%
- REST OF WORLD 2%



source: EPIA.

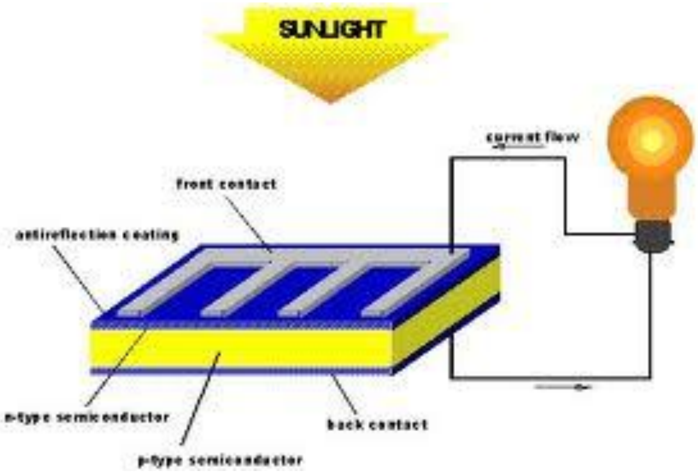
World PV Production 2009

World PV Production in 2009 by technologies

- c-Si: 8.678 GW 81%
- a-Si:H: 796 MW 7%
- CdTe: 1.019 GW 10% (2010 data >1.5GW)
- CIGS: 166 MW

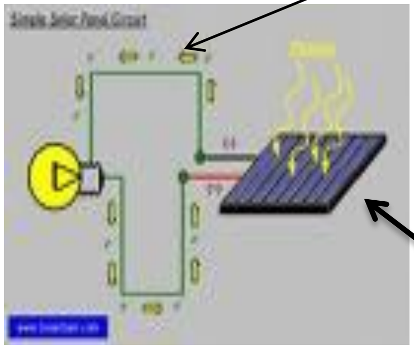
Courtesy: N.G. Dhere, FSEC, Florida

Solar cells-basics

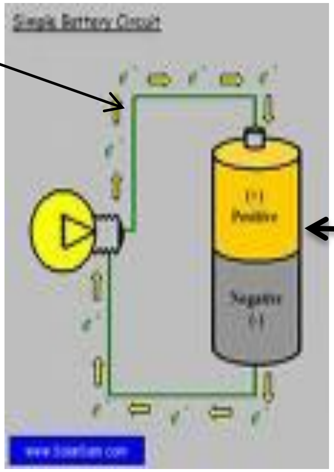


¿Qué son las celdas solares?

Carga



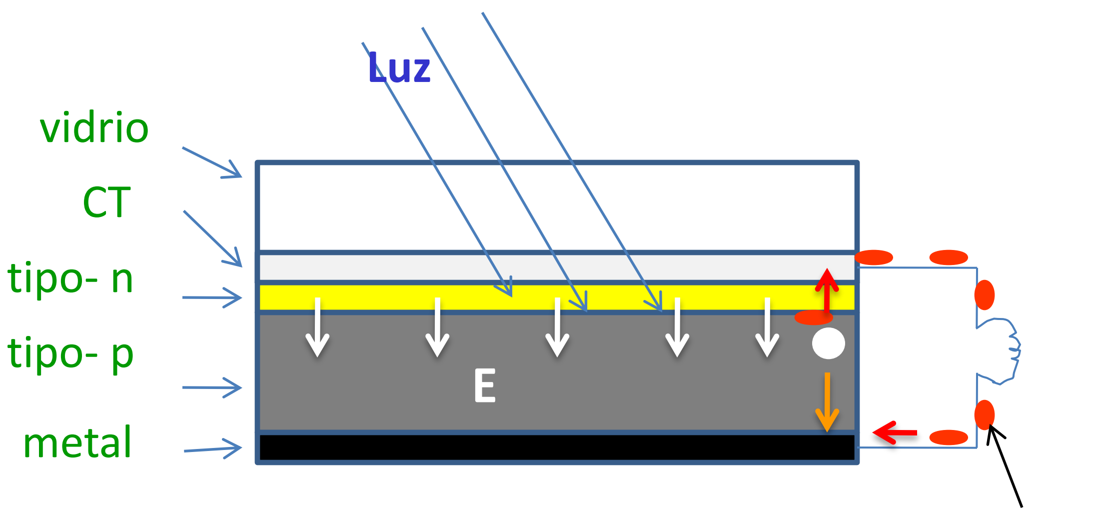
Celda solar



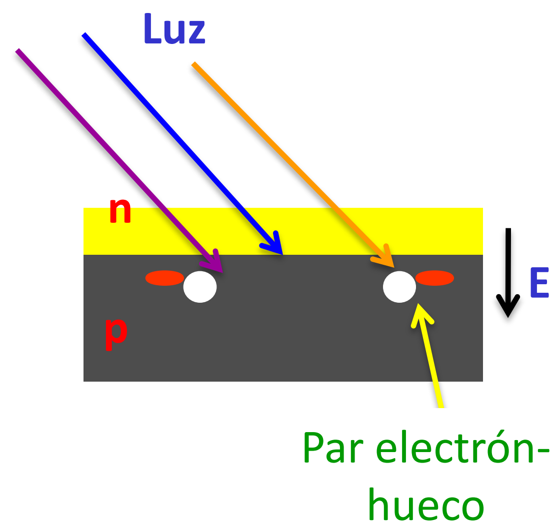
Pila

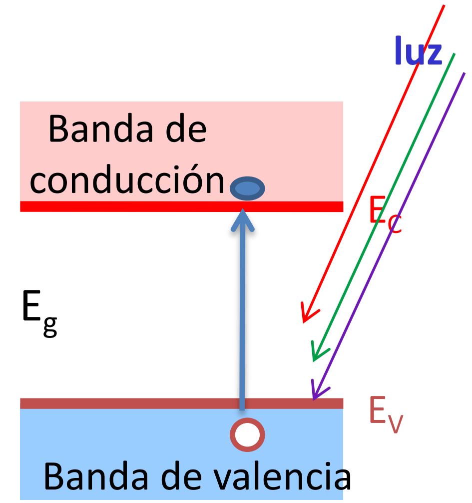
La celda solar es un pila que trabaja con el SOL

Esquema de una celda solar



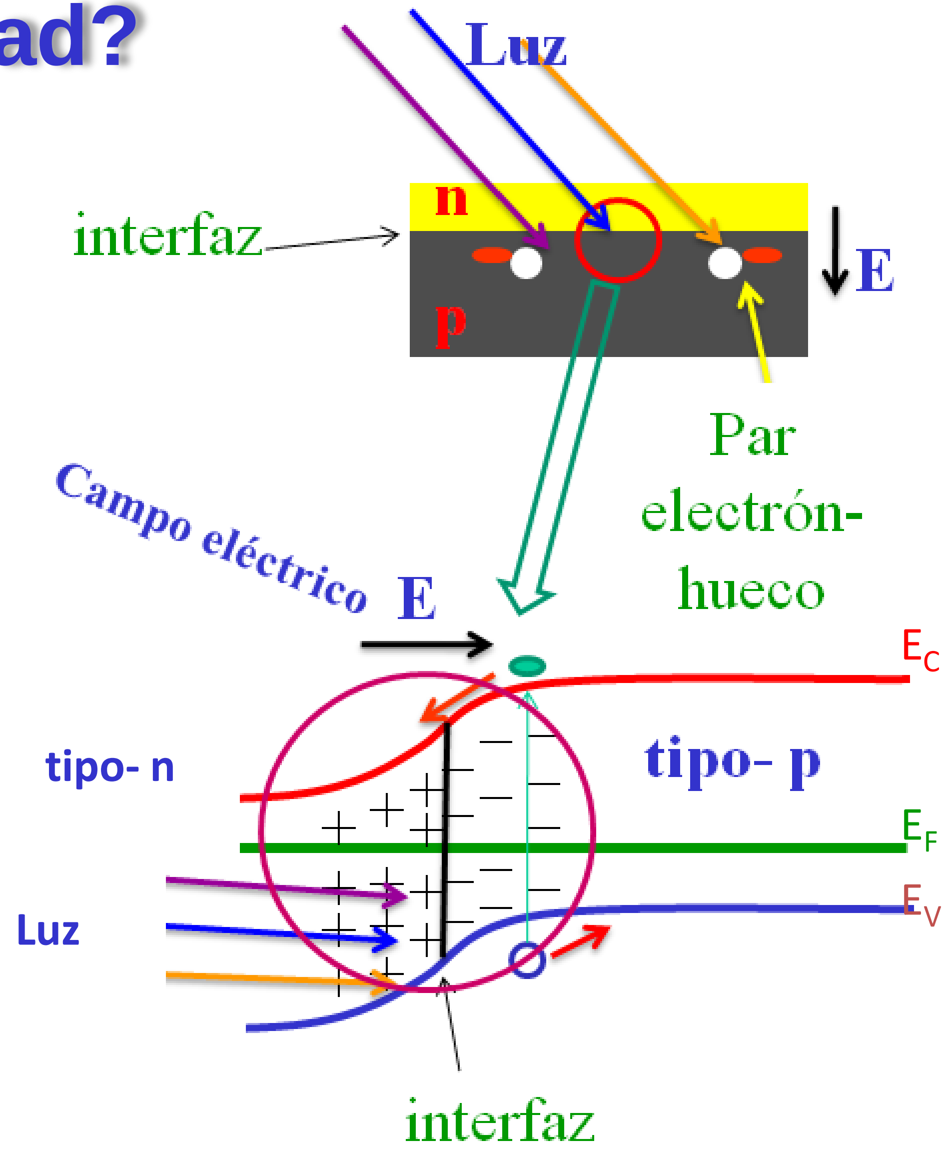
CT= conductor transparente





Los electrón-hueco pares generados en el campo eléctrico del unión p-n va mover en direcciones opuestos. Así creando una corriente.

¿Como una celda solar produce la electricidad?



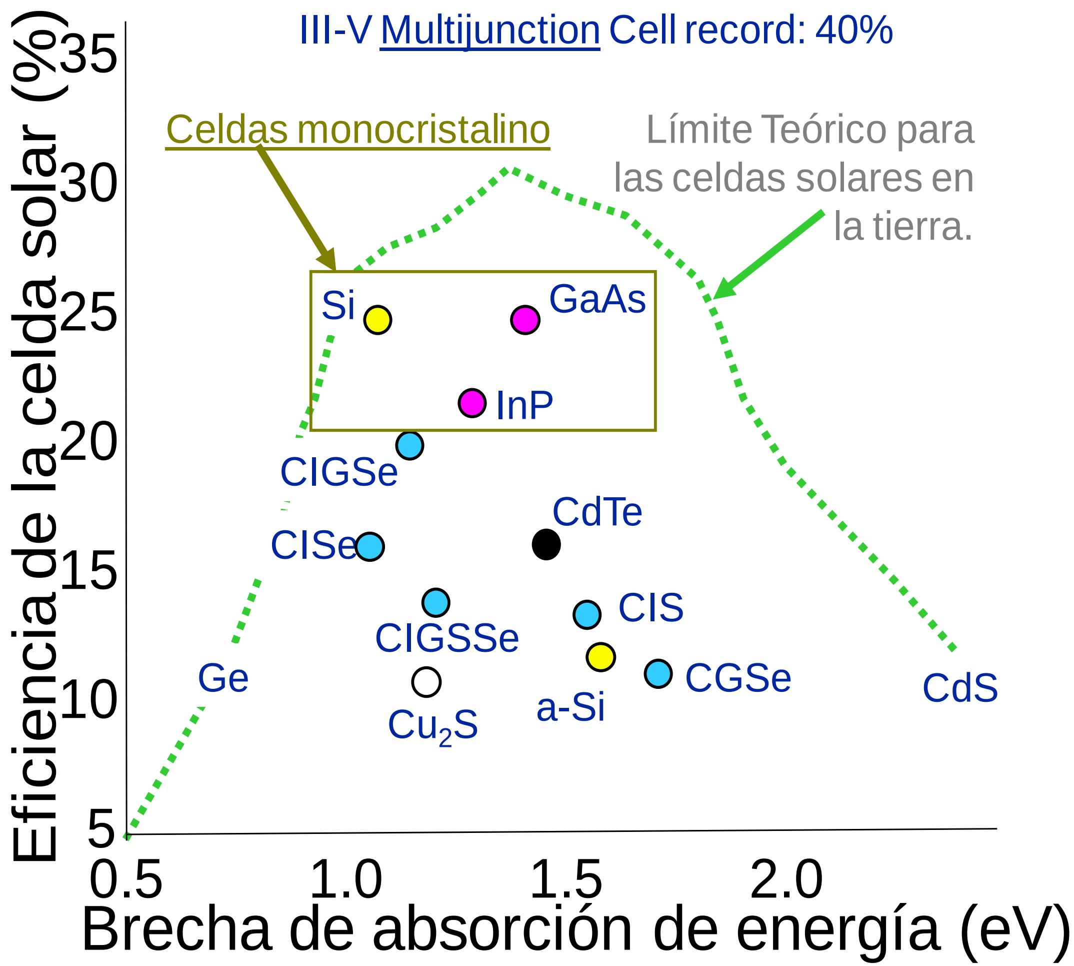
Los par electrón-huecos son separado por campo eléctrico existe en el interfaz, y permitiendo un flujo de electrones en el circuito externo

Eficiencia teórico vs. actual

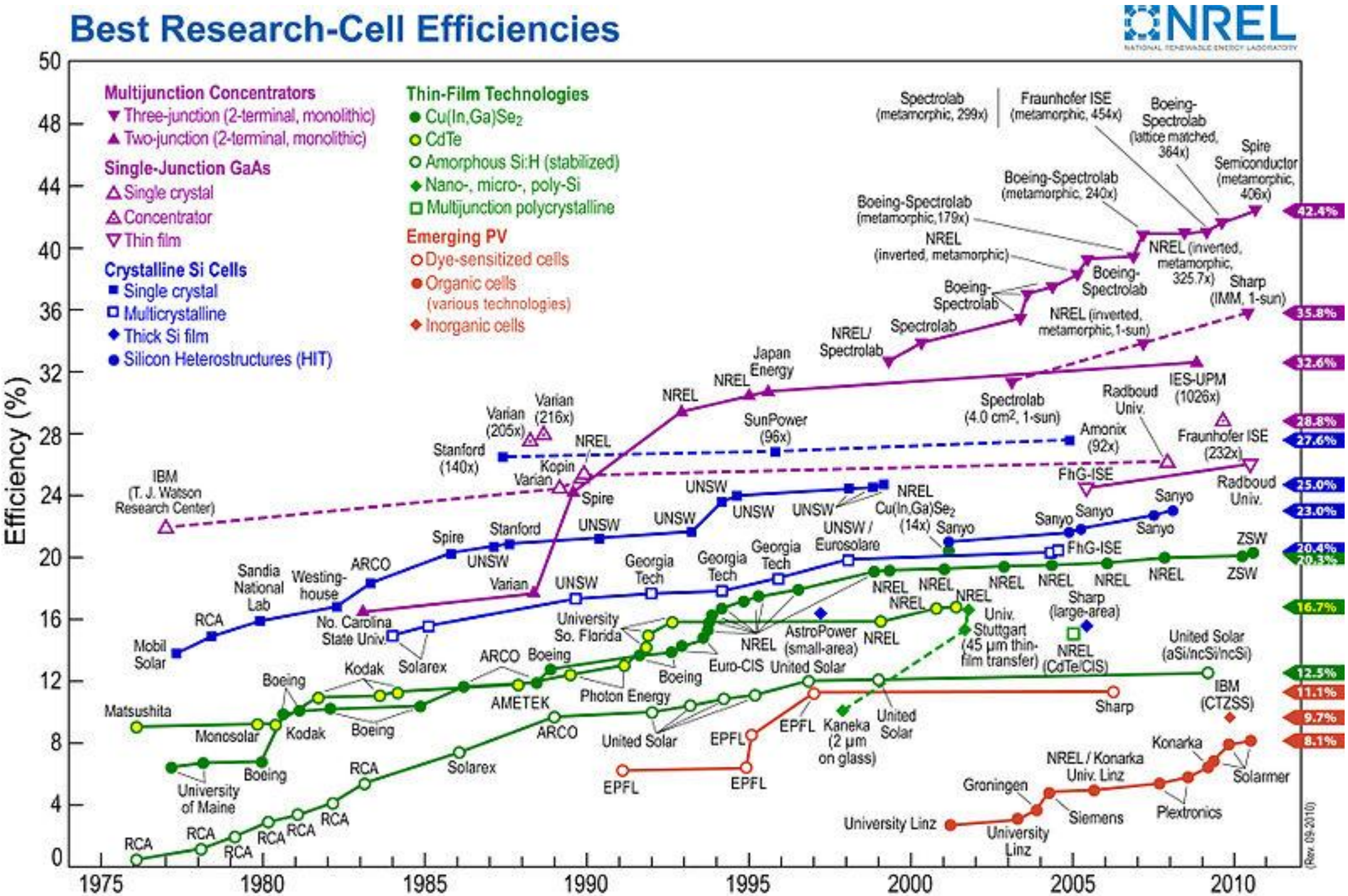
Celdas solares de unión simple

- Si-Silicio
- Compuestos del III-V
- Calcogenuros -CuIn

El Si y el GaAs están cerca de su límite teórico.



Courtesy- Angus Rockett, uiuc



Best Research-Cell Efficiencies
NREL
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Silicon Heterostructures (HIT)
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
Inorganic cells
Efficiency (%)
42.4%
35.8%
32.6%
28.8%
27.6%
25.0%
23.0%
20.4%
20.3%
16.7%
12.5%
11.1%
9.7%
8.1%
1975
1980
1985
1990
1995
2000
2005
2010
(Rev. 09-2010)

CdTe perspectives

Three Thin-Film PV Technologies & its Strengths

	Demonstrated Efficiency	Production Advantage	Materials Abundance/ Low Toxicity
a-Si			Strength
CdTe		Strength	
CIGS	Strength		

Each technology has different advantages.
Its not clear which (if any) advantage will yield a long-term product advantage.

Courtesy: Miguel Contreras, NREL

Some benefits of CdTe

-High α; 1μ CdTe absorbs >92% of the photons with hν> E_g

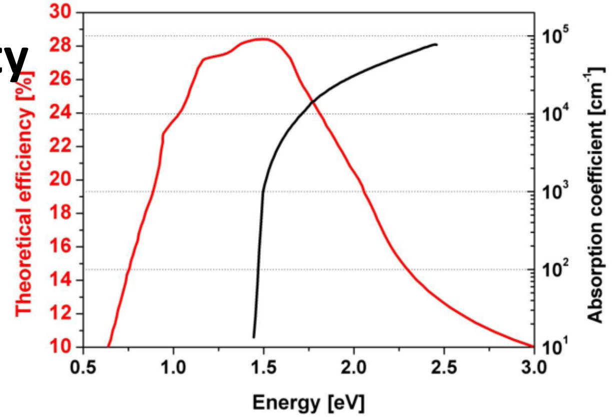
-Less than 2% of the equivalent semiconductor Si is required

-1.45eV close to the ideal band gap for high effciency

-A stable binary compound which can be deposited by more than 5 large volume manufacturing methods

-Simple manufacturing procedures-high reproducibility

-A low-temperature coefficient making it tolerable to higher module temp.



Estado actual

- Eficiencia record
  16.5%   (NREL)

- Tecnología
  comercializado

$1/Watt
Feb. 2009

First Solar.

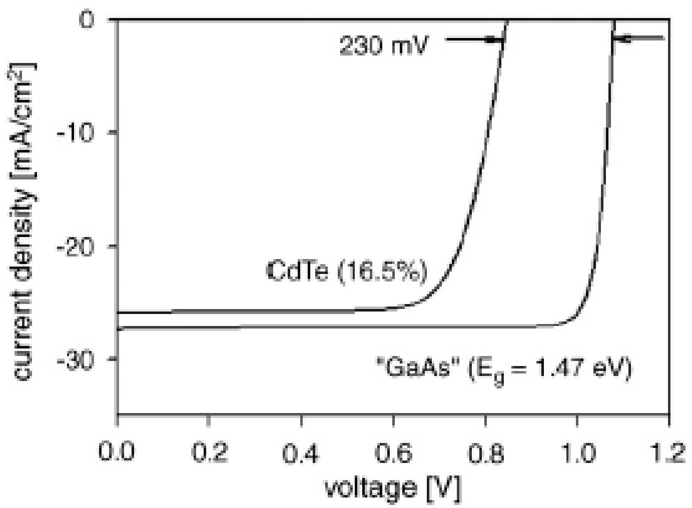
How well CdTe will do ?

-an ambitious and challenging prediction

If the CdTe voltage deficit is reduced with the same current and fill-factor, CdTe cells would achieve more than 20% efficiency.

Reason for the low voltage of CdTe cells is a combination of low carrier density (∼10^{14} cm^{-3}) and low absorber lifetime (generally below 1 ns).

With 10^{17} cm^{-3} carrier density, efficiency can be 22%



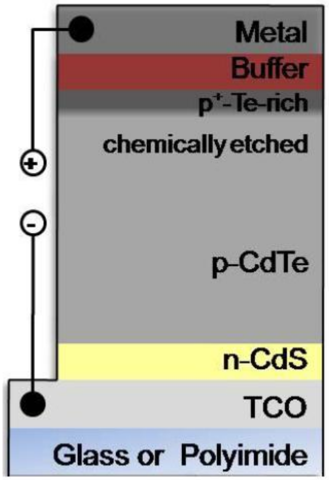
Comparison of record CdTe cell with GaAs adjusted for band gap.

James Sites et al. (Colorado State Uni.)

Thin Solid Films 515 (2007) 6099–6102

Challenges

- Reduce self-compensation effect of CdTe to increase acceptor concentration
- Reduce CdTe layer thickness to increase raw material yield
- Formation of low resistive and stable back contact
- Reducing CdS thickness to increase blue response



Some CdTe PV Companies

First Solar, OH	**1.4 GW in 2010**
Abound Solar, CO	**200 mW by 2011**

Antec Solar, Germany

Solar Fields, OH/Calyxo (Germany)

Primestar Solar, CO

WK (Willard & Kelsey) Solar Group, OH

CANRON, NY (and Canada)

Solexant, CA

Arendi, Italy

Advanced Solar Power, China

Xunlight26. OH

Wakonda, MA

Courtesy- Miguel Contreras, NREL

R & D activities at CIE-UNAM

Programa de CdTe en CIE

Metas:-

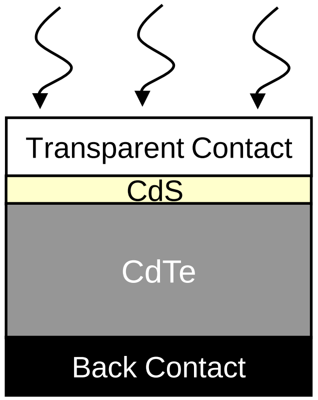
-**Desarrollar celdas de alta eficiencia**

-**Desarrollar tecnologías de sistemas**

-**Desarrollar nuevas materiales**

-**Innovación y transferencia de tecnología**

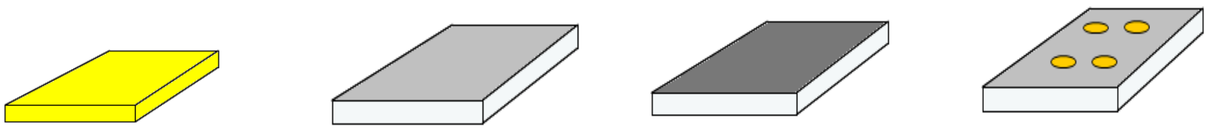
-**Mayor Academia-industria relación y Promover una industria PV nacional**



Programa de CdTe en CIE-

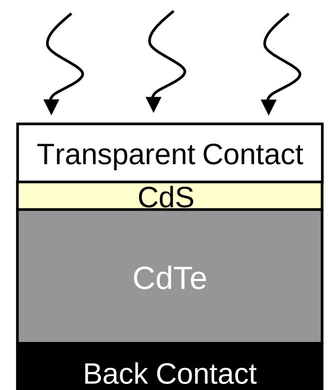
Device fabrication steps

All-CSS process: CdS, CdTe, $CdCl_2$



Vidrio conductor → CdS 100-150 nm → CSS-CdTe 4-6 μm → activation → back contact → contact diffusion

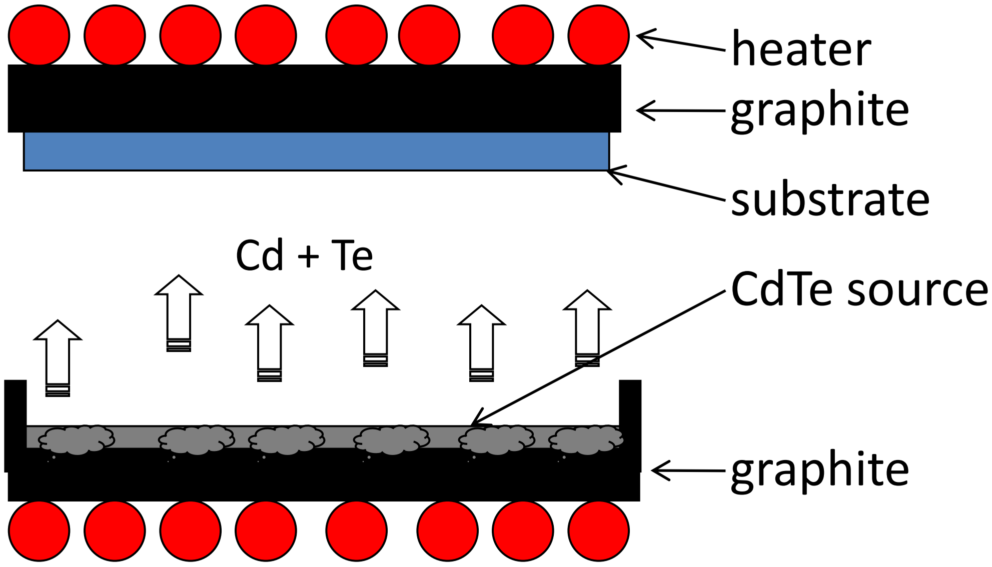
CdS, 2 min. **CdTe, 4 min.** **Cl_2, 10 min.** **Back contact** **Diffusion, 10 min.**



CSS process

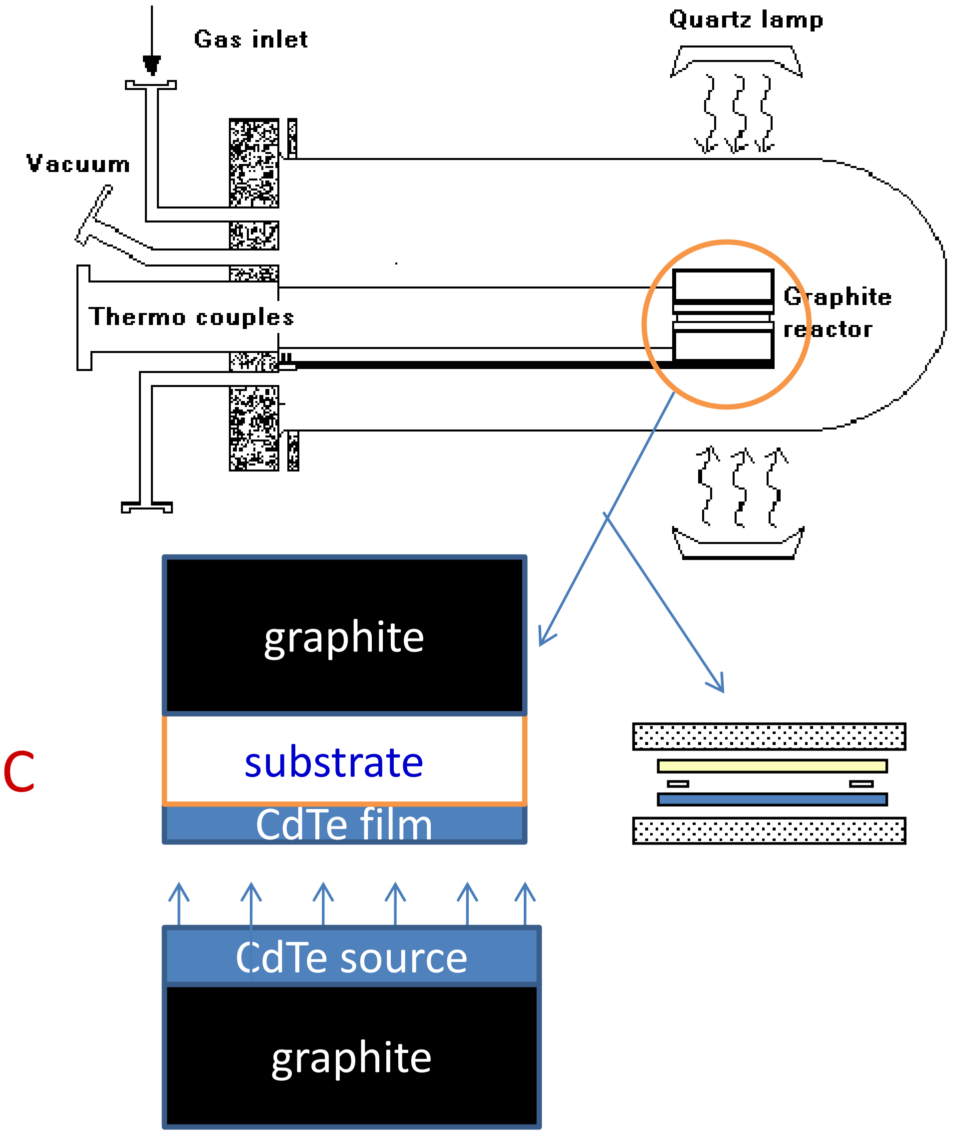
Sublimation- transforms directly from solid to vapor phase

-Escalable
-Alta tasa de deposito; 1-2 μm/s
-Less defect densities (near-thermal equilibrium process)
-Mayor eficiencia
-Low vacuum requirements
-Less maintenance
-All-CSS: CdS, CdTe, $CdCl_2$
-Easy integration in a production line



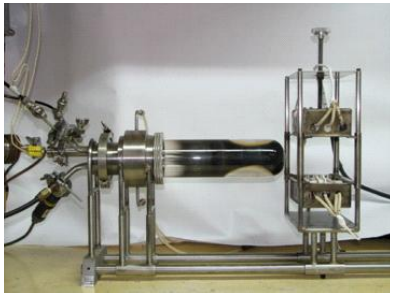
Laboratory scale CSS system

- Ambient: Ar (He)/O_2
- Pressure: 1-20 mbar
- Temp. of source: 600- 700 °C
- Temp. of substrate: 500 - 650 °C



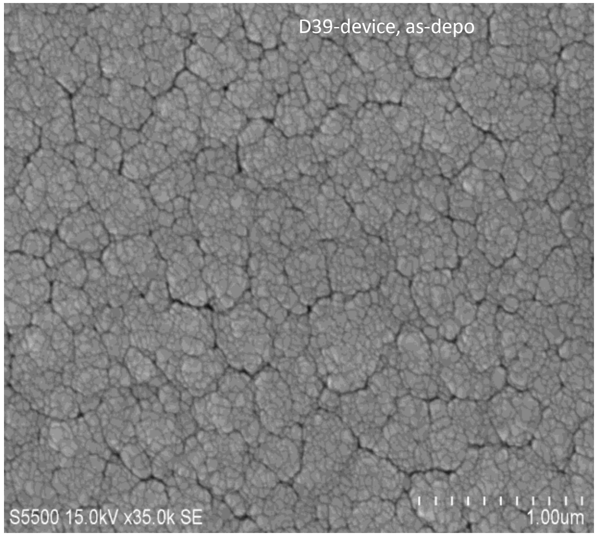
Thin Film processing capabilities

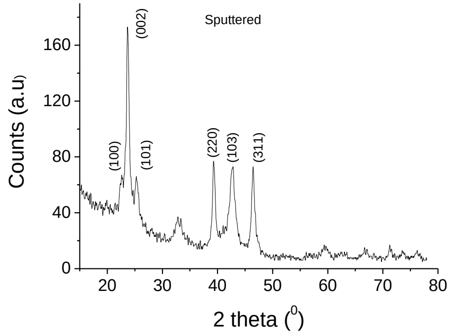
- **CSS**; CdTe & CdS
- **Sputtering**; CdTe & CdS
- **Co-evaporation**; Semiconductor alloys



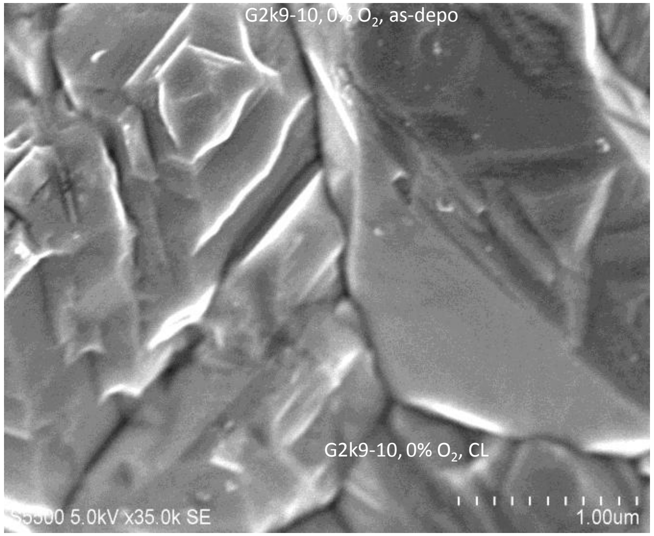
Sputtered vs. CSS CdTe films: recrystallization

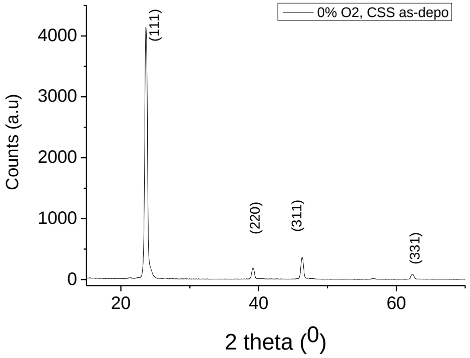
Sputtered





CSS deposited





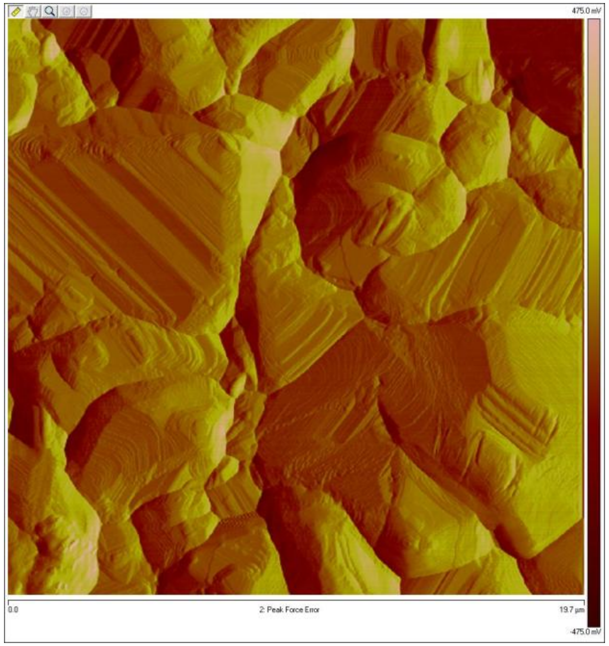
Film deposition @ ≈ 0.03 μm/min

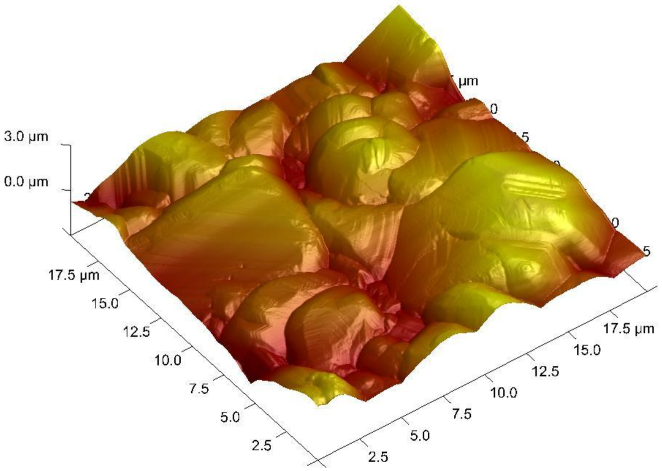
Process temp. 250 °C

Film deposition @≈ 1 μm/min

Process temp. 600 °C

AFM topography of CSS CdTe film





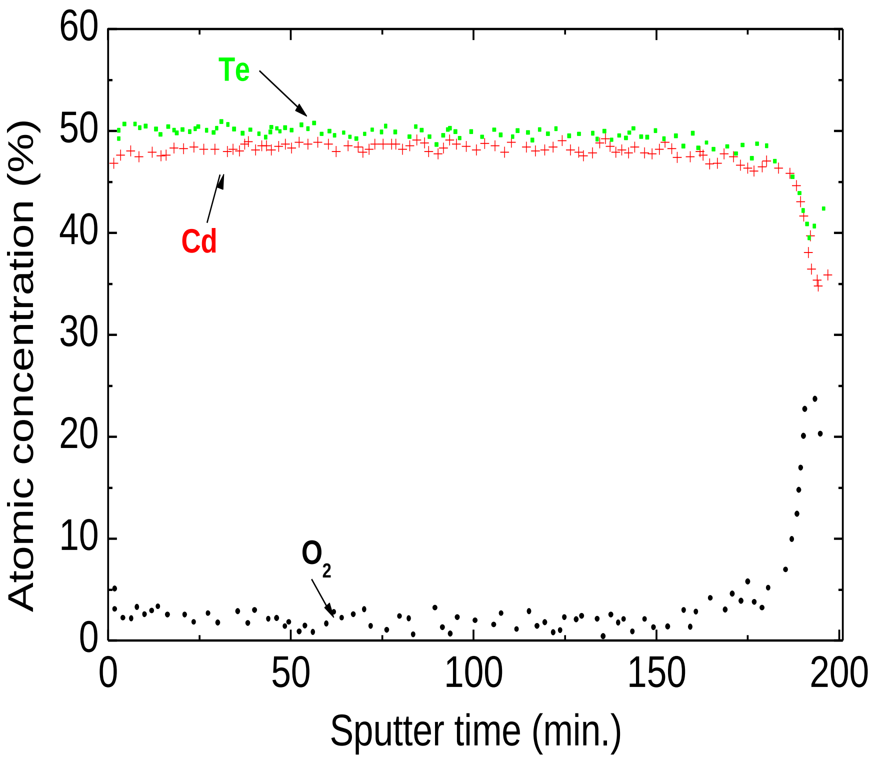
-Void-free (?) grain boundaries

-Large clusters of grains

AUGER depth profile

CSS- CdTe, on Mo substrate

He/O_2 = 80/50



- Rich in Te, typical of p-type
- Constant stoichiometry throughout the thickness
- Oxygen incorporated during CSS process

CdTe/CdS devices

parameters that can affect your device

-Glass cleaning

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-Process temperature

-Ramping

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-Process gas

-Pressure

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-CdS layer

-CdTe formation conditions- role of O_2

-Junction activation

-Amount of Cl

-Duration

-Back contacts

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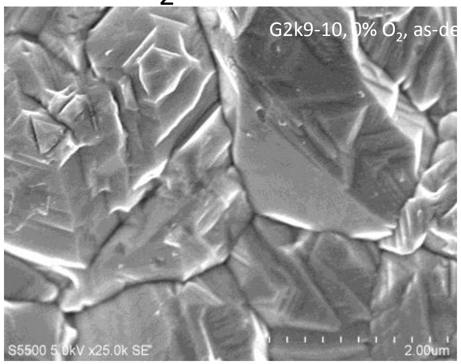
- AR coating

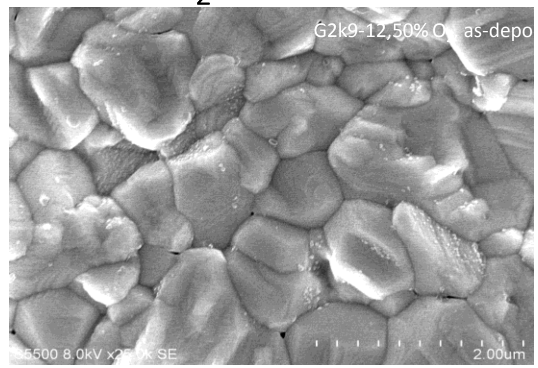
(i) Influence of O_2 in CSS chamber

As-deposited films

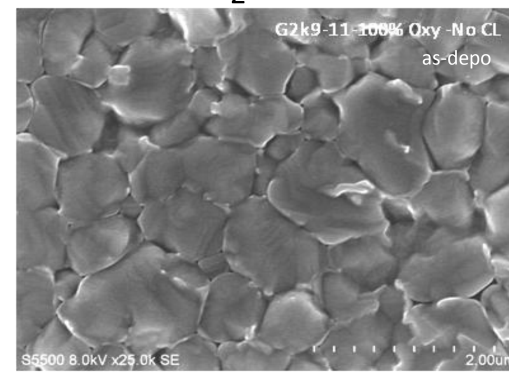
O_2 = 0%



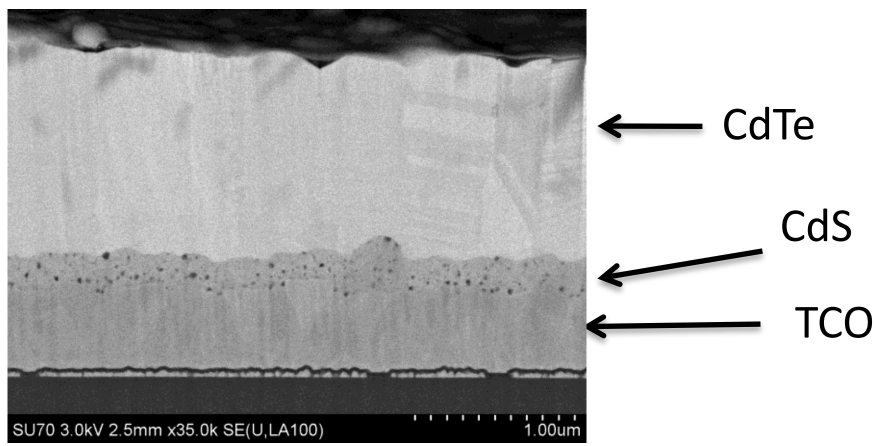
O_2 = 50%



O_2 = 100%



Grain size ➡ ≈2 μm | ≈ 0.85 μm | ≈ 0.88 μm

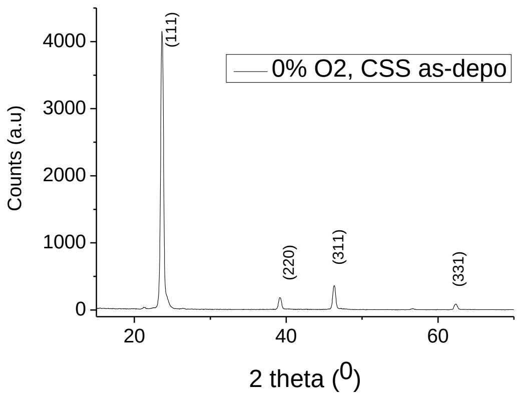


The CdTe nucleation sites increases with O_2, resulting in lower growth rate, small grains, and more compact film.

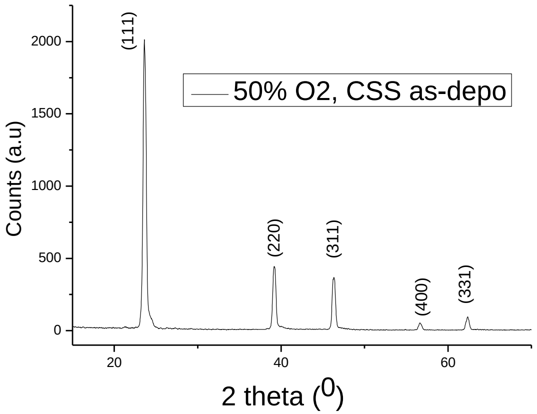
Influence of O_2 in CSS chamber

As-deposited films

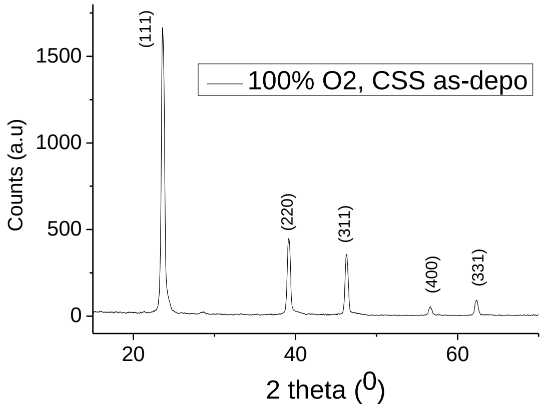
O_2 = 0%



O_2 = 50%



O_2 = 100%



In O_2 environment, films grow with less preference for a direction

Junction:- O_2 in CSS chamber & "S", "Te" diffusion

Some known facts:

- Grain boundary diffusion can be retarded by oxygen annealing
- Interdiffusion depends on O_2 level in the CdS film, in low O_2 films "S" diffusion is significant, leading to thinning of CdS film.
- When CdS is annealed in O_2, both "S" and "Te" diffusion is controlled
- Consumption of CdS lead to TCO/CdTe junction
- CBD CdS film has less thinning compared to CSS and sputtered films: CBD film has more O_2, received from the bath
- CBD CdS devices has superior performance than non-CBD CdS film devices

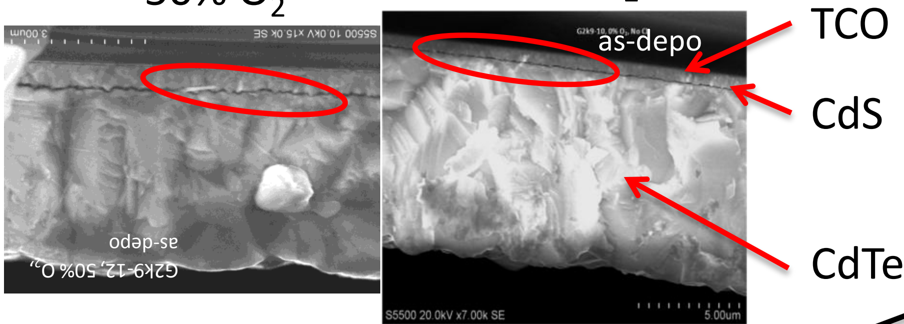
[1] D. S. Albin, et al.; Prog. Photo:Research & Appl. 10 (2002) 309
[2] D. S. Albin, et al.; AIP Conf Proc. 394 (1996) 665

O_2 in CSS chamber & CdS consumption

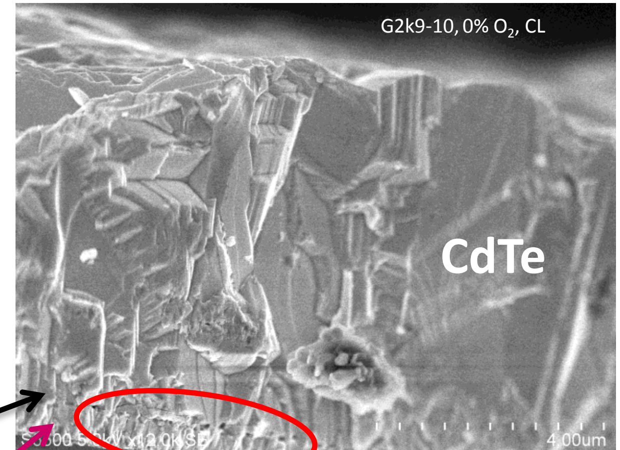
Tec 7/CdS/CdTe

O_2 in CSS chamber

50% O_2 | 0% O_2

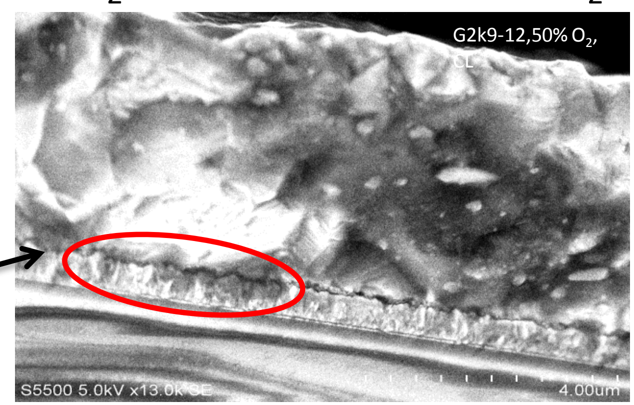


$CdCl_2$ @390 C, CdTe in 0% O_2



TCO

$CdCl_2$ @390 C, CdTe in 50% O_2



CdS consumed in 0% O_2 case, consumption is not uniform, lateral non-uniformities at the interface.
However CdS almost retained in 50% O_2 case.

CBD-CdS, no pre-treatments for the CdS film. O_2 level mentioned corresponds to CdTe deposition

Junction- O_2 annealing of CdS and interface diffusion

Short & long wavelength QE

Short λ:

-shallow CdS absorption edge for both, significant for as-deposited case

-less response at 580-650 nm for as-depo. case

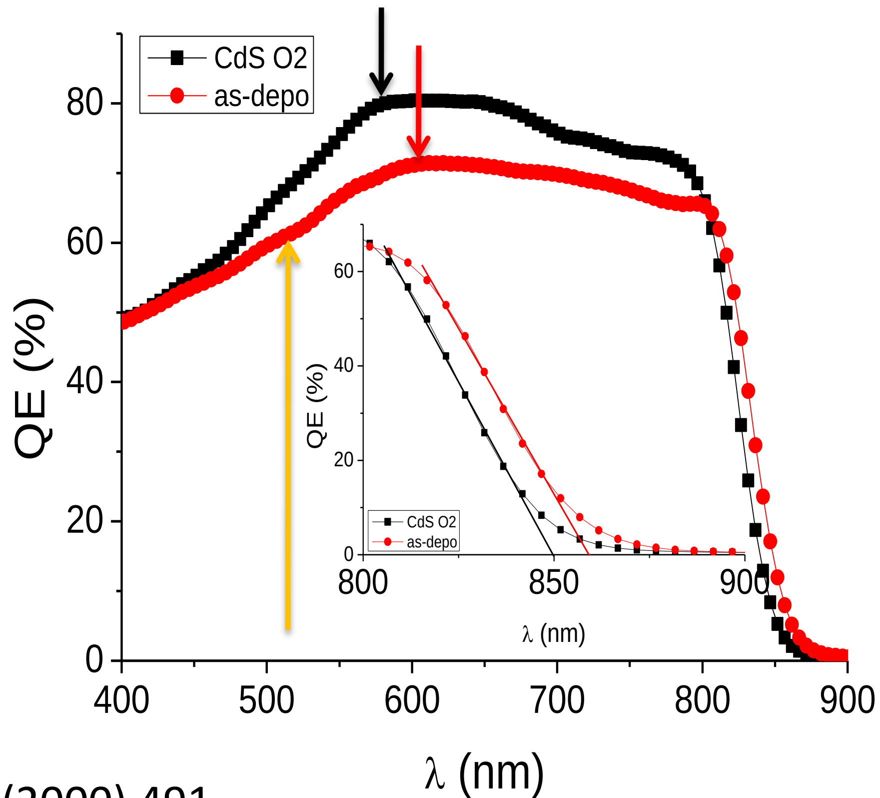
Evidence of Te diffusion, lowering E_g; $CdS_{1-x}Te_x$

Long λ:

-Shift in absorption edge for as-depo. case

Evidence of "S" diffusion to CdTe, lowering E_g; $CdTe_{1-y}S_y$

CdS film annealed in O_2 at 450 C for 45 min
CSS CdTe @ 600 C, He/O2 = 2/8



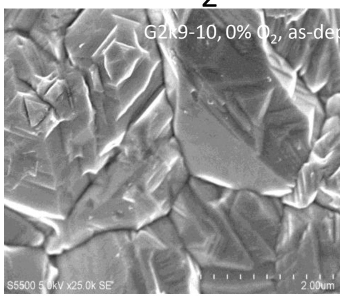
[1] X. Wu, Solar Energy 77 (2004) 803

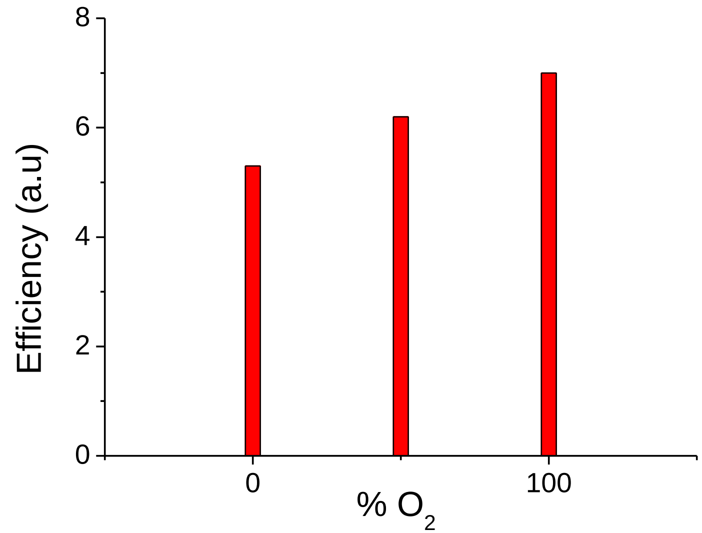
[2] B.E. McCandless, et al.; Proc. 28th IEEE PVSC (2000) 491

Efficiency vs. O_2 in CSS chamber

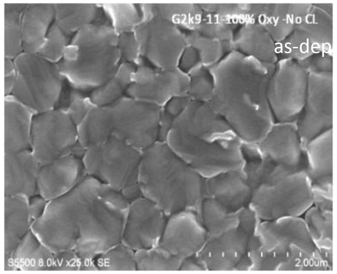
→ Tec 7/CBD-CdS/CSS-CdTe/(Cu-Au); CdS: 100-120 nm, CdTe: ≈ 5μm, (Cu-Au): ≈ (3-30)nm

0% O_2





100% O_2



<u>On an average 20 % increase in efficiency</u>

-Passivation of CdTe grain boundaries (trade off with grain size)

-Increased carrier concentration

-Reduced resistivity

-Minimum interdiffusion, CdS/CdTe heterojunction

More or less same difference observed in the case of CdS annealed in O_2 prior to CdTe deposition

(ii) Junction activation

Most crucial step in device fabrication:-vapor chloride treatment at temperatures in the range 400 ^oC

-Increased p-type doping due to formation of an acceptor complex (Cl^-+V_{cd})

* high voltage

-Low series resistance

* high current

-Modification of band gap states

* compensation

-Recrystallization leading to grain growth and modification of grain boundaries

* reduced shunting

-Spatial junction uniformity and alloying

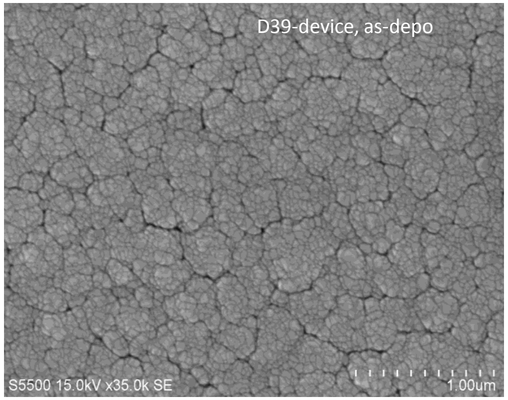
* High yield

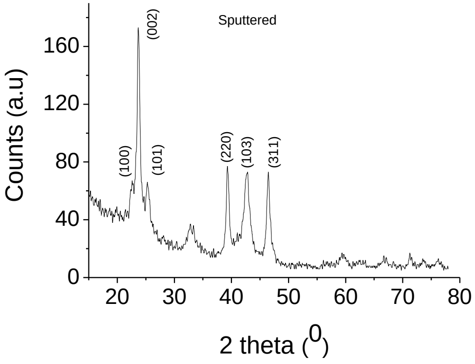
-Excess Cl can form compensating donors (Cl_{Te}), damaging the cell

Sptterred-CdTe: effect of chloride treatments

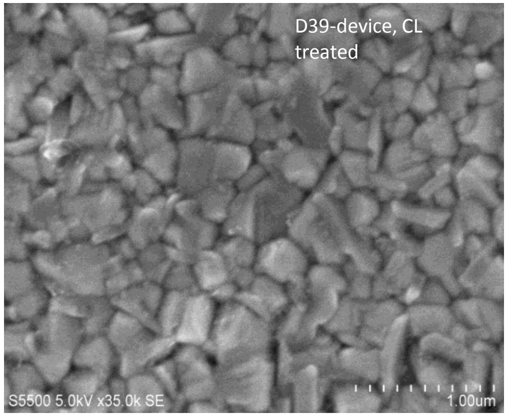
Grains- 50 nm

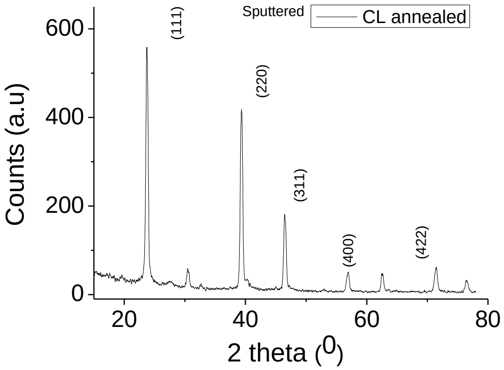
As-deposited





Chloride annealed





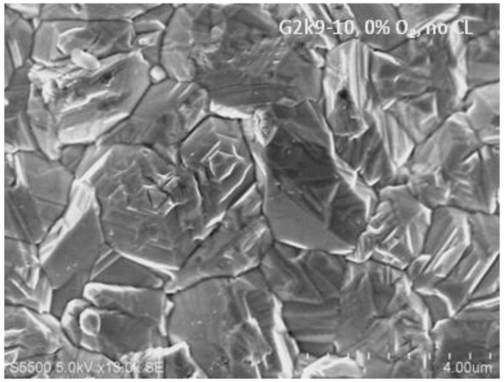
Grains- 200 nm

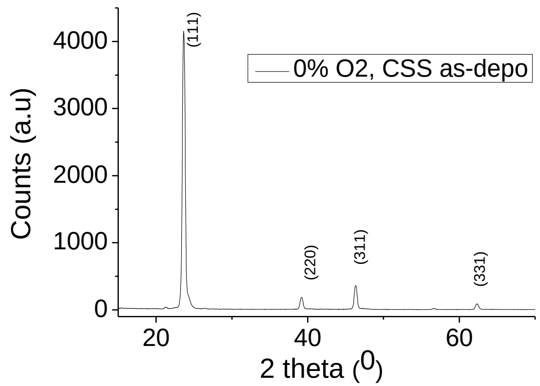
Process temp. 200-250 °C

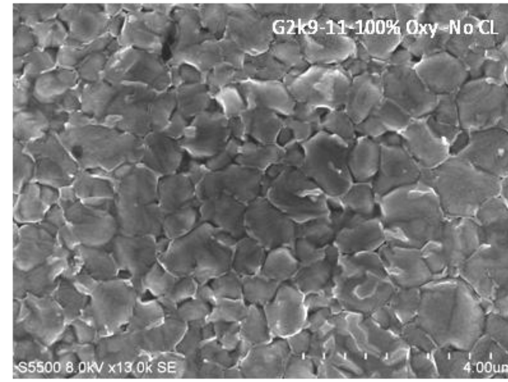
-Recrystallization evident
-Grain growth significant

CSS-CdTe: effect of chloride treatments

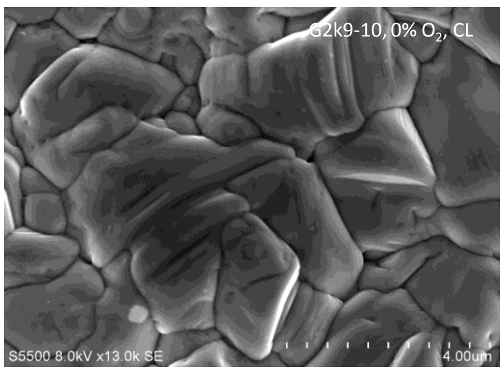
O_2 = 0% | O_2 = 100%

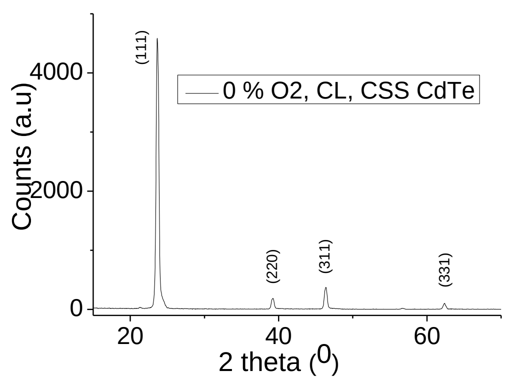


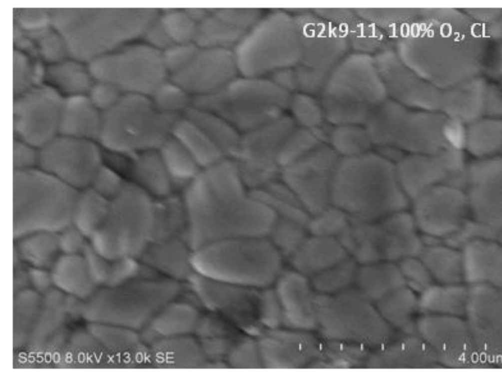




as-deposited







vapor chloride annealed

$N_A = 3.5\times10^{13}$ cm^3 | $N_A = 1.9\times10^{14}$ cm^3

Recrystallization happens in all cases; Grain size remains more or less same

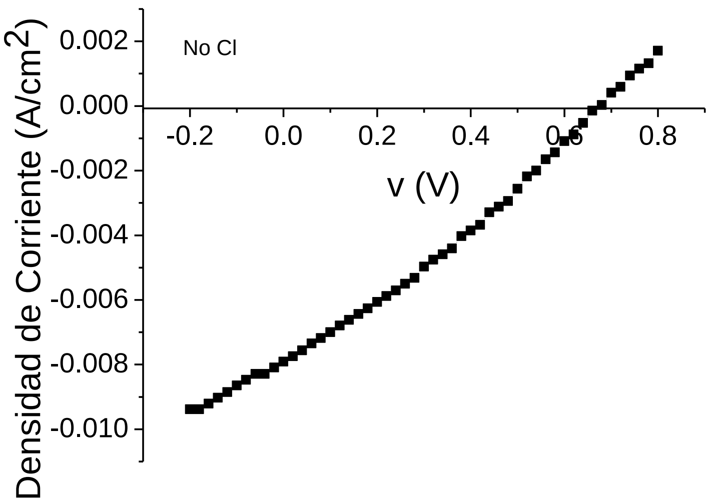
Chloride annealing do not reverse the O_2 effect:

For films deposited at higher temp, the surface energy is already minimum, hence no secondary recrystallization. Same can happen with the presence of native oxides *

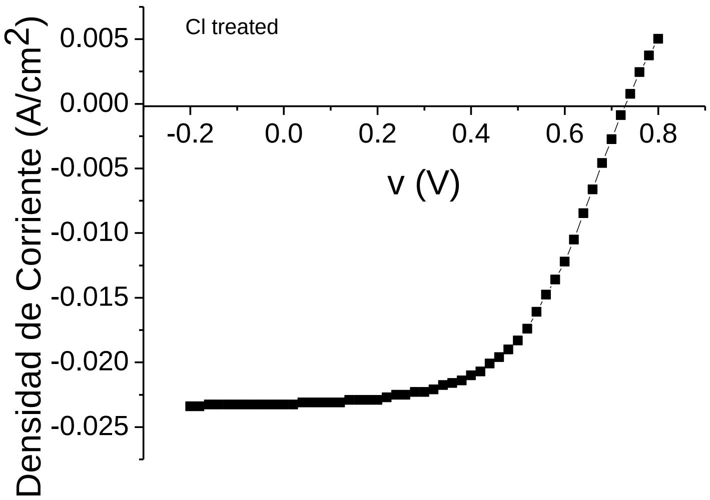
* B. E. McCandles & J.R. Sites; "Cadmium Telluride Solar Cells", Handbook of Photovoltaic Science & Engineering, John Wiley & Sons, 2003

Chloride treatments-
effect on device performance

Device without Cl treatment



Device with Cl treatment



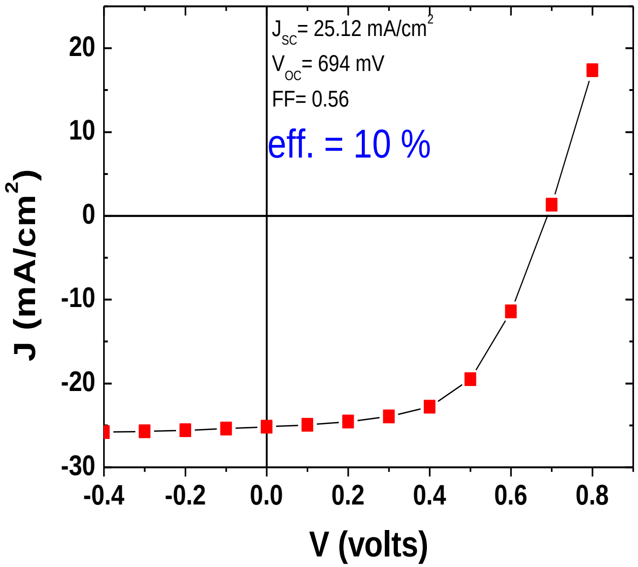
-Higher FF

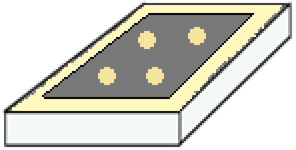
-Higher J_{sc}

Small area CdTe/CdS cell

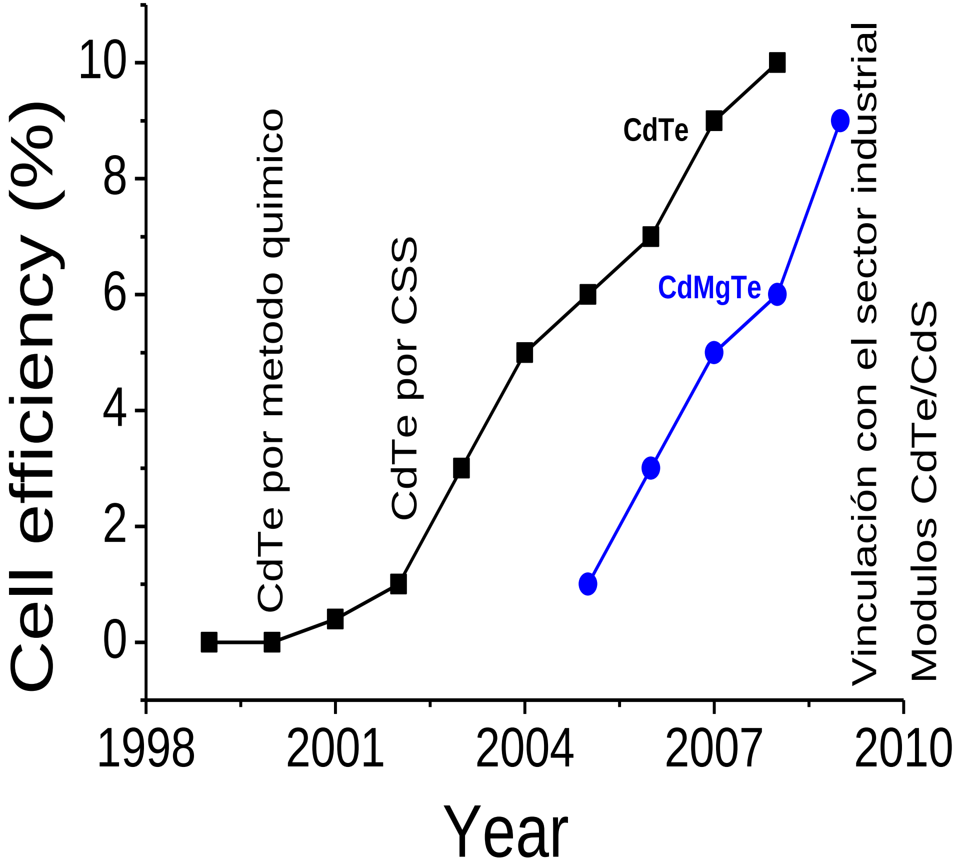
Tec 7/CBD-CdS/CSS-CdTe/(Cu-Au)

-No HRT
-No CdTe etching, contact applied directly
- No antireflection coating
-Tec 7 substrate, low transmittance





Our Antecedentes in CdTe Technology



CdTe toxicity issues

How much cadmium (Cd) is encapsulated in CdTe modules?

- CdTe layer contains 3 to 9 g/m^2
- CdS contains less than 1 g/m^2

Both elemental materials (Cd & Te) are produced as byproducts of mining processes (primarily zinc mining and copper refining) and present in quantities to support multi-GWs of annual production

http://www.nrel.gov/pv/cdte

- Anderson, B. A. (2000). "Materials availability for large-scale thin film photovoltaics." *Progress in Photovoltaics*, 8, pp. 61-76.
- Zweibel, K. (1999). "Issues in thin film PV manufacturing cost reduction." *Solar Energy Materials and Solar Cells*, 59, pp. 1-18.

Does CdTe pose health risk ?

- CdTe is more stable and less soluble than elemental Cd and therefore is likely to be much less toxic.

- The vapor pressure of CdTe at ambient conditions is zero. therefore, it is impossible for vapors or dust to be generated when using PV modules.

- Exposure of pieces of CdTe PV modules to flame temperatures from 760 to 1100°C illustrated that CdTe diffuses into glass, rather than being released into the atmosphere.

http://www.nrel.gov/pv/cdte
http://www.firstsolar.com/en/CdTe.php

Does CdTe pose health risk ?- Reports from Europe

"During standard operation of CdTe PV systems, there are no cadmium emissions - to air, to water, or to soil……. Accordingly, large-scale deployment of CdTe PV can be considered safe to human health and the environment." French Ministry of Ecology, Energy, Sustainable Development and the Sea. It concluded that, 2009

"....CdTe used in PV is in an environmental stable form that does not leak into the environment during normal use or foreseeable accidents....“; Joint Research Center and moderated by the German Environment Ministry

http://www.firstsolar.com/en/CdTe.php

Does CdTe pose health risk?

- The trace amounts of cadmium in a thin-film PV module do not approach toxic levels.

- A rechargeable nickel cadmium battery contains about 2,500 times more cadmium per kilowatt-hour than does a CdTe module.

- The cadmium found in PV modules is inert and sealed better than the cadmium found in NiCd batteries.

http://www.nrel.gov/pv/cdte

What are the sources of Cd exposure to humans?

Sources and Relative Contributions of Cd exposure to Humans (data from Europe)	
Phosphate fertilizers	41.3 %
Fossil fuel combustion	22.0 %
Iron and steel production	16.7 %
Natural sources	8.0 %
Non-ferrous metals	6.3 %
Cement production	2.5 %
Cadmium products	**2.5 %**
Incineration	1.0 %

Environmental Resources Limited (ERL), (February 1990). Evaluation of the Sources of Human and Environmental Contamination by Cadmium. Prepared for the Commission of the European Community, Directorate General for Environment, Consumer Protection and Nuclear Safety, London.

“Escalamiento de celdas solares de CdTe” – proyecto SENER

Aprobado:- octubre 2009

Firma de Convenio:- Febrero 2011

Periodo de proyecto:- 2011-2013

“Escalamiento de celdas solares de CdTe”

Objetivo del proyecto:

Optimización de varios procesamientos involucrados en el desarrollo de heteroestructuras **fotovoltaicas de CdTe/CdS** para alcanzar uniformidad de las películas y una eficiencia arriba de 8% **en área mayor que 100 cm^2.**

Resultados Esperados

(i) Prototipo de mini-módulos de CdTe/CdS rayada por láser y interconectada, con un eficiencia arriba de 8%.

(ii) Transferencia tecnología de procesamiento de módulos fotovoltaicas de CdTe/CdS a sector industrial.

(iii) Vinculación con sector industrial y un impulso para el creación de industria fotovoltaica nacional.

(iv) Desarrollo de recursos humanos a nivel posgrado

(v) Integración de varios grupos nacionales en el tema de celdas solares

(vi) Creación de infraestructura

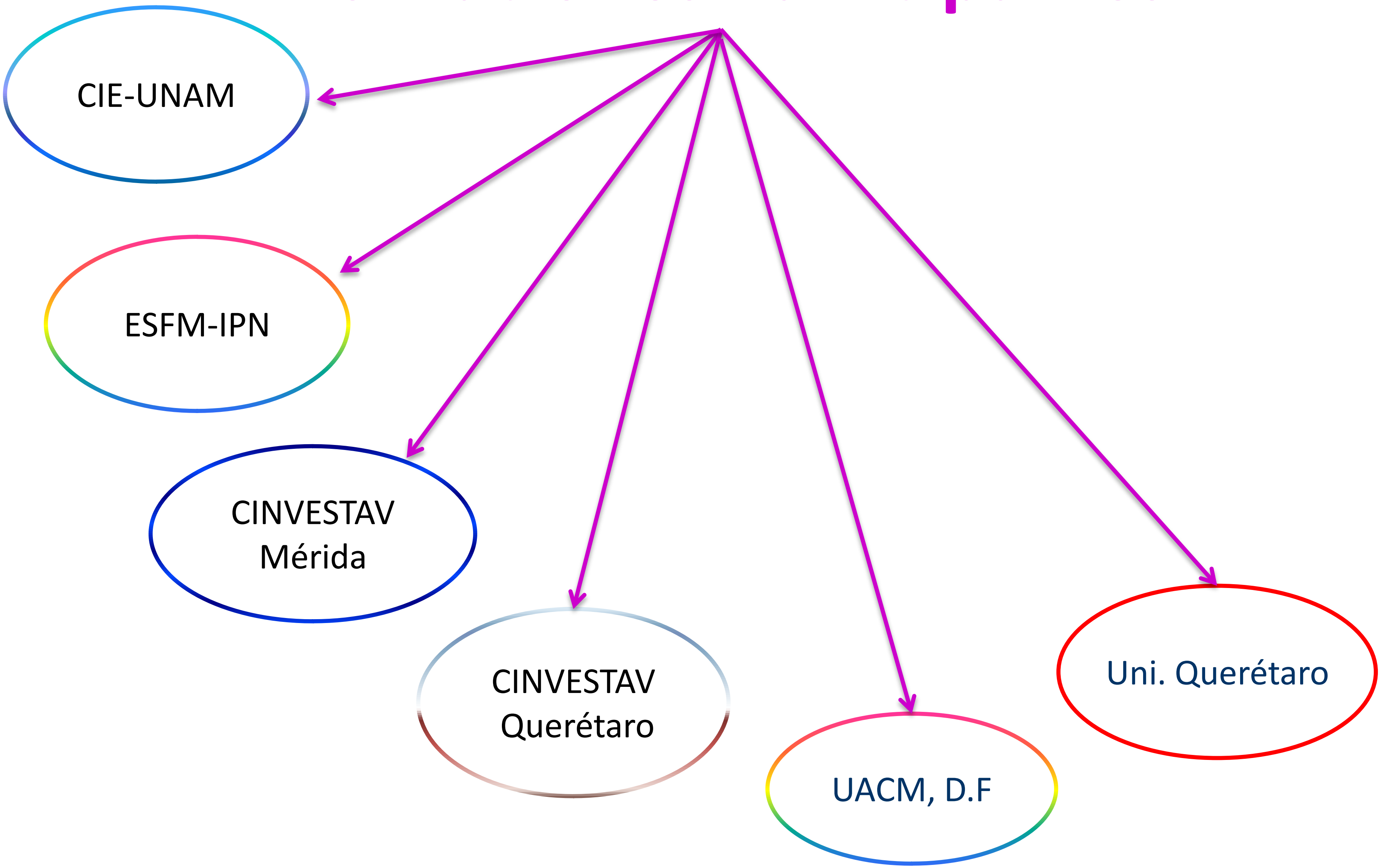
Transferencia de la tecnología- un reto

- En México, no hay una industria propio de fotovoltaico

-Existe algunos fabricas/maquiladoras

-Existe instituciones con conocimiento en prototipos
  - CIE-UNAM
  - ESFM-IPN
  - CINVESTAV

Instituciones Participantes

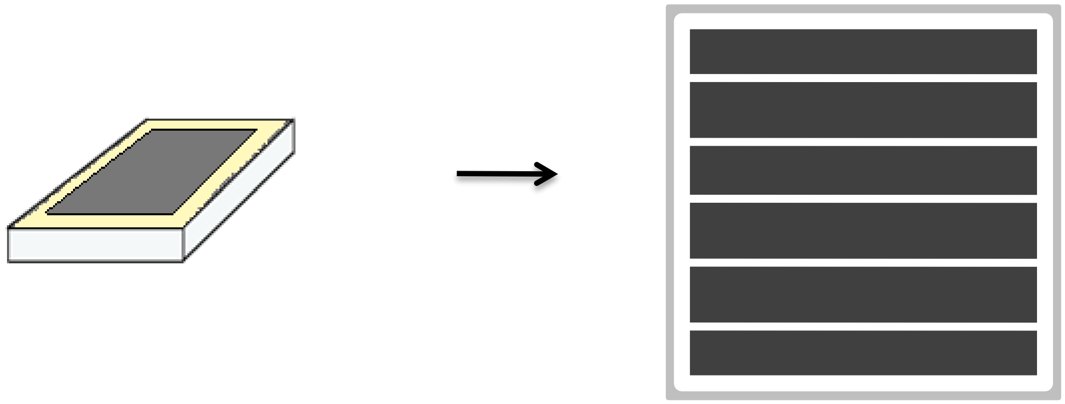


Transferencia tecnológica y vinculación con sector productivo

Metas en corto y mediano plazo

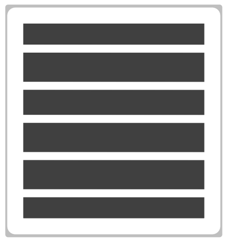
Módulo (100 cm^2)

Celda (4 cm^2)



Celdas rayada y interconectada

Aplicaciones de Mini-módulos



Módulo

Aplicaciones

mini cargador

semáforos

Lámparas de calle

sensor

casa solar

Planta piloto

-Batch processing,

- todo un proceso: CSS

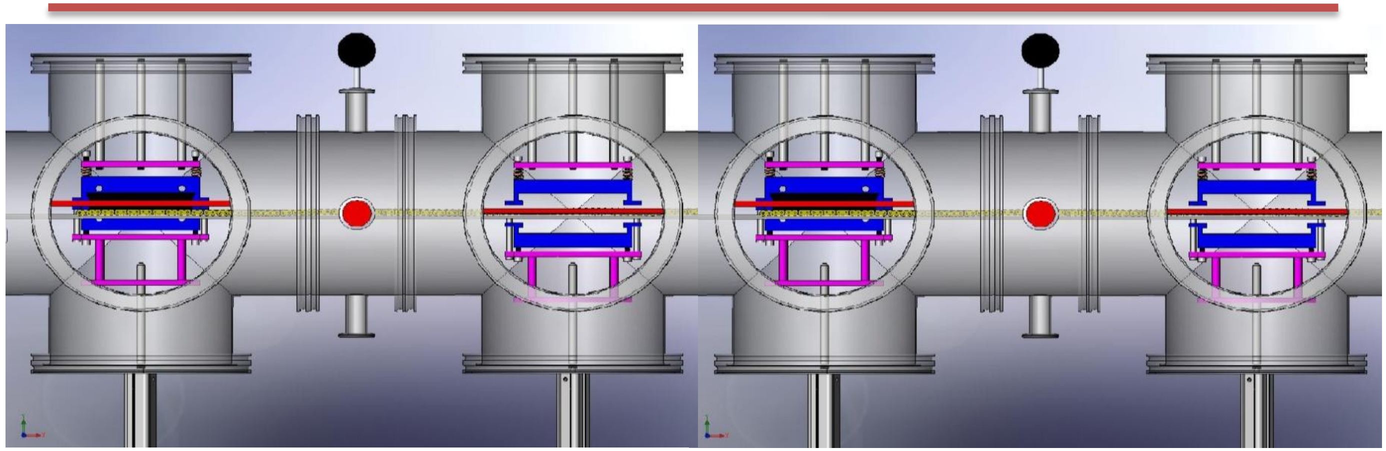
-Low vacuum, low cost systems

-All-dry process, material utilization, high efficiency

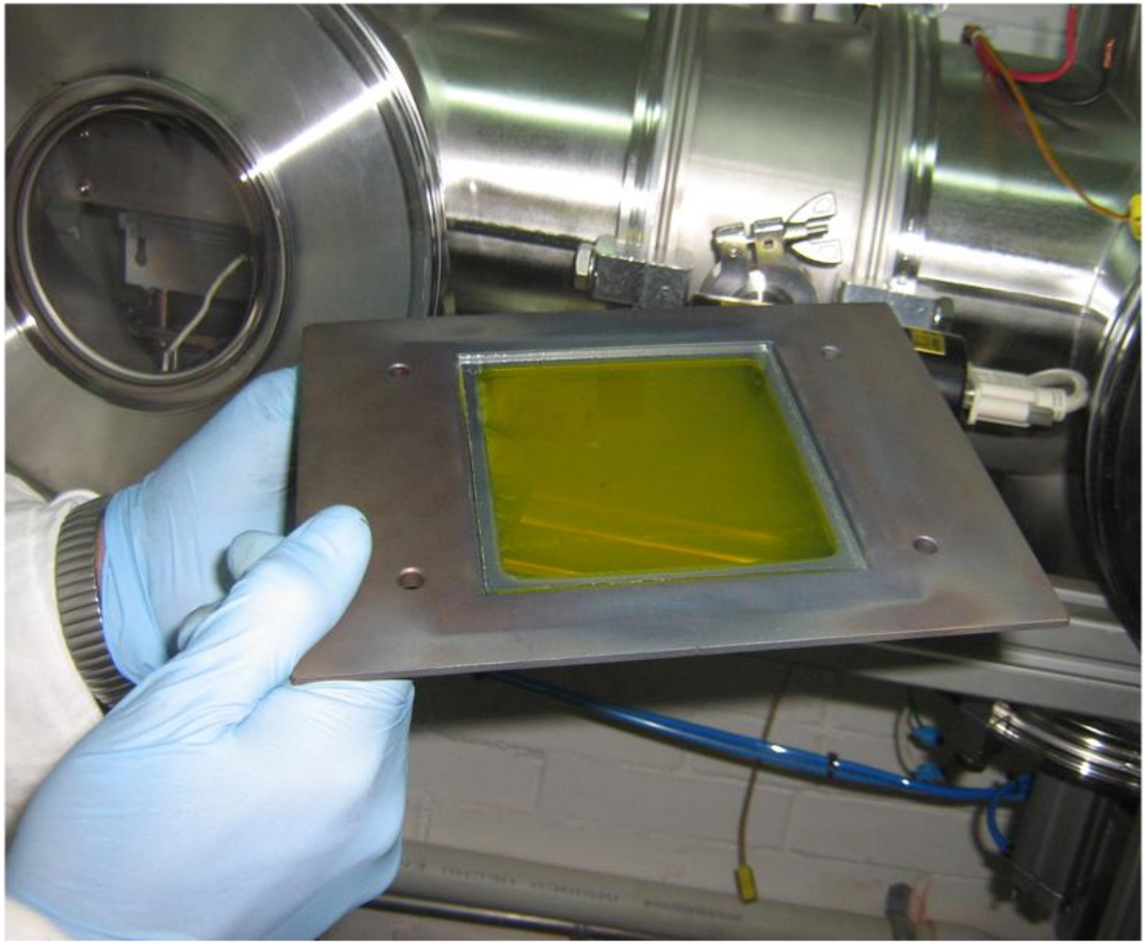
-Easy scale up

CdS | CdTe | activacion | Contacto posterior

Vidrio conductor →



Película de CdS en área 100 cm^2, depositado en la planta piloto (primera prueba)



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- Post doctoral fellows
- Technicians

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thank you