Present and future of Photovoltaic Solar Electricity

Carlos del Cañizo Nadal

Instituto de Energía Solar

Universidad Politécnica de Madrid

UC Davids-Madrid Network showcase

Madrid, December the 9th, 2013

POLITÉCNICA
Instituto de Energía Solar

Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

Alternatives to cristalline silicon technology

Conclusions

Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

Alternatives to cristalline silicon technology

Conclusions

The Instituto de Energía Solar (IES-UPM)

Founder: **Antonio Luque**

Director : **Carlos del Cañizo;** **Vicedirector:** **Antonio Martí;** **Secretary:** **Ignacio Antón**

Personnel: **73 full-time staff (22 professors, 10 post-doc researchers, 25 PhD students, 16 administrative and maintenance staff) plus external PhD students & master students**

Mission: **Contribute to the development of Photovoltaic technology through R&D**

Five recognised research groups.

Research organised in 5 programs:

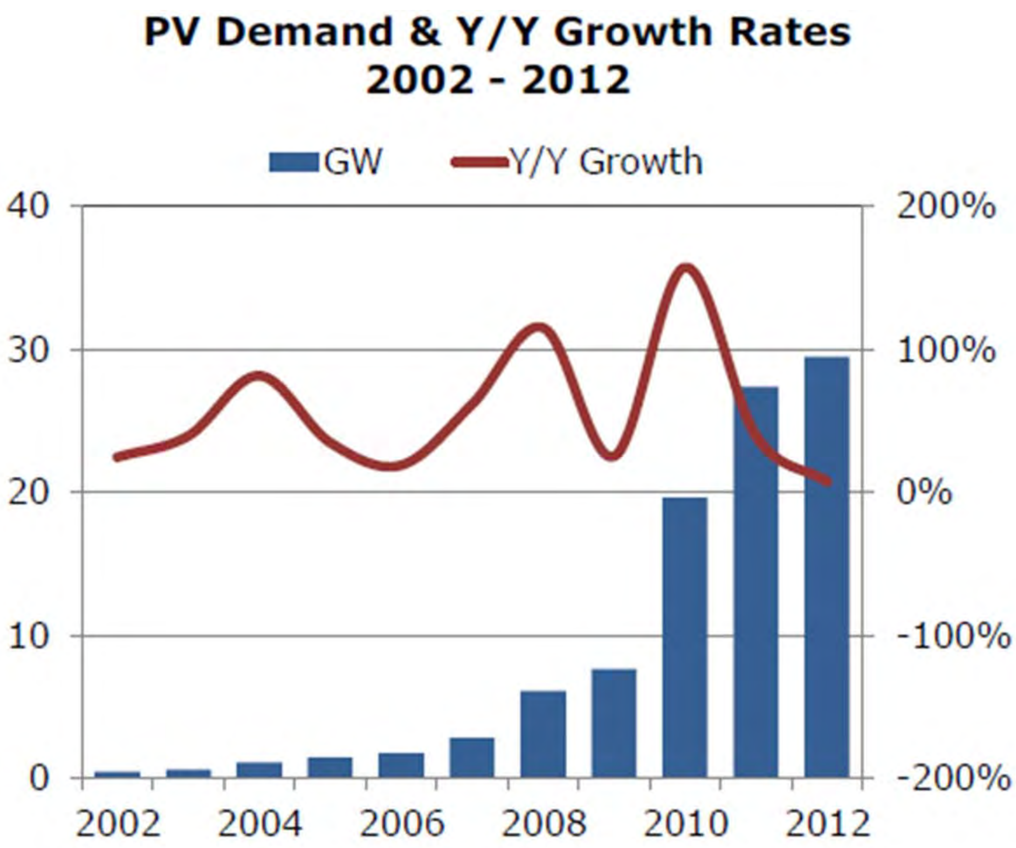
- **Silicon Technology**
- **Photovoltaic Systems**
- **Instr. and Systems Integration**
- **III-V Semiconductors**
- **Fundamental Studies & Quantum Calculations**

POLITÉCNICA
Instituto de Energía Solar

The photovoltaic market

In 2012, accumulated installed capacity reached 100 GW!

Today, ~ 6% of electricity demand in Italy and Germany, covered by PV. In Spain, ~ 3%



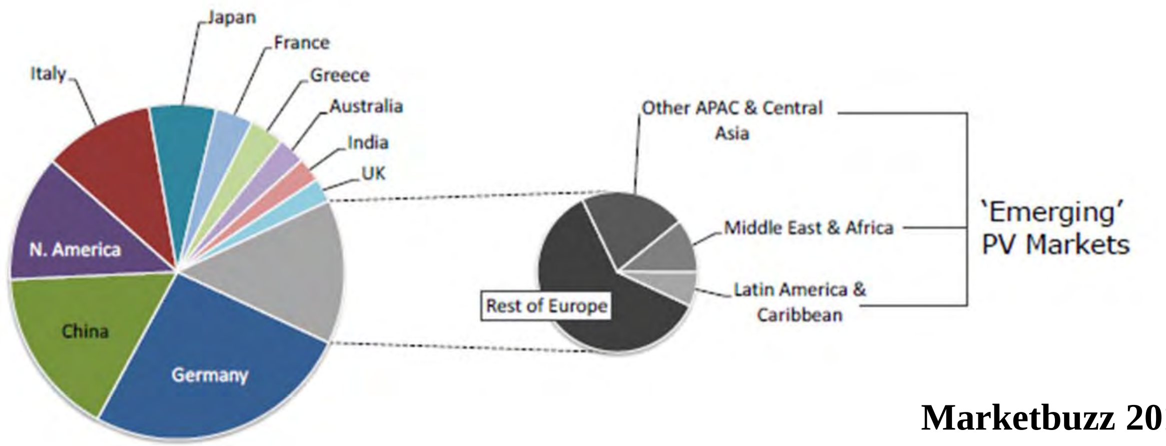
Marketbuzz 2013

After many years of strong growth, market stabilized in 2012

- **Weaker support in European markets**
- **Overcapacity remains (demand in the 30-40 GWs, capacity in the 40-60 GWs)**

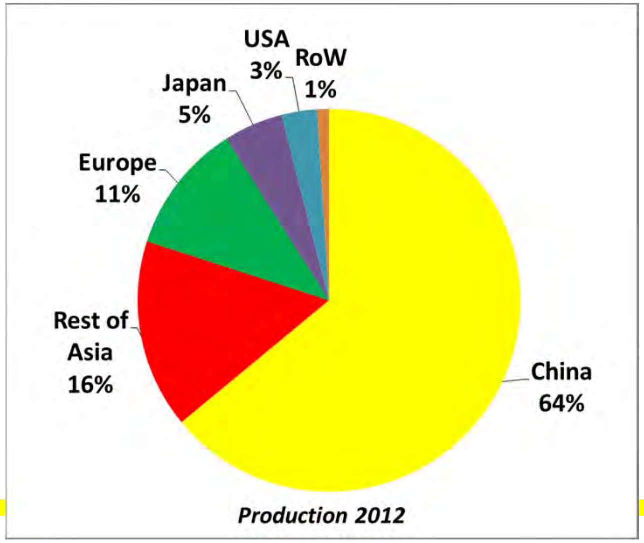
The photovoltaic market (2)

The market is becoming «less» European…



Marketbuzz 2013

… and Asia is consolidating its position as producer…



The photovoltaic shakeout

Many companies being pushed out of the market

Q.CELLS

DC WAFERS

Pevafersa energías renovables

SCHOTT solar

REC

SILICIO SOLAR

SOLTECTURE

LDK LIGHT OUR FUTURE 阳光照亮未来

A commercial dispute ongoing

Photograph: jdnx via Flickr

US imposes 31% anti-dumping tariff on Chinese PV imports

The US Department of Commerce (DOC) would impose anti-dumping tariffs of just over 31% on crystalline silicon PV cells and modules from major Chinese producers, after determining that exporters sold product in the US at "less than fair value".

PROCEDURES RELATING TO THE IMPLEMENTATION OF THE COMMON COMMERCIAL POLICY

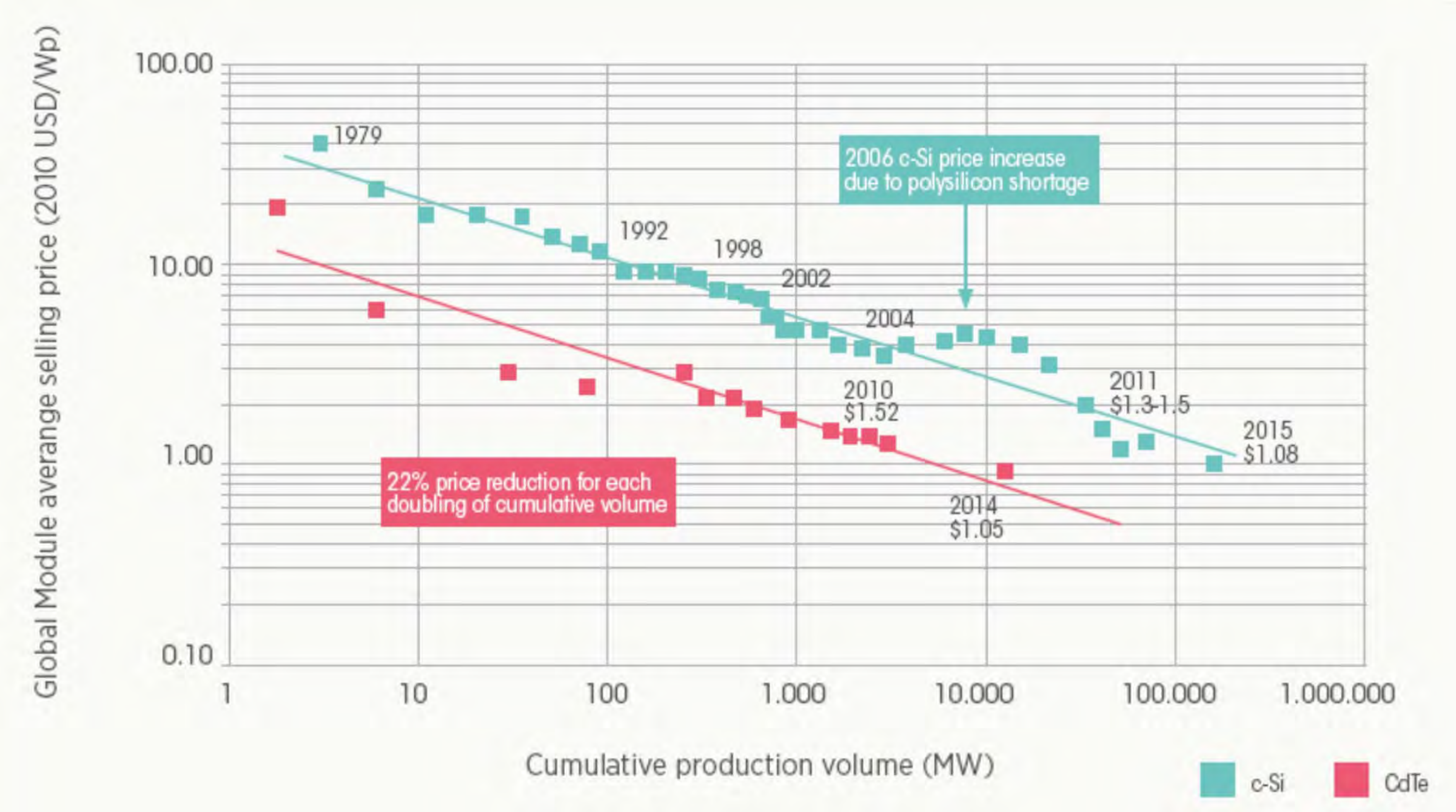
EUROPEAN COMMISSION

Notice of initiation of an anti-dumping proceeding concerning imports of crystalline silicon photovoltaic modules and key components (i.e. cells and wafers) originating in the People's Republic of China

(2012/C 269/04)

Evolution of technology price

PV module learning curve **IRENA 2012**



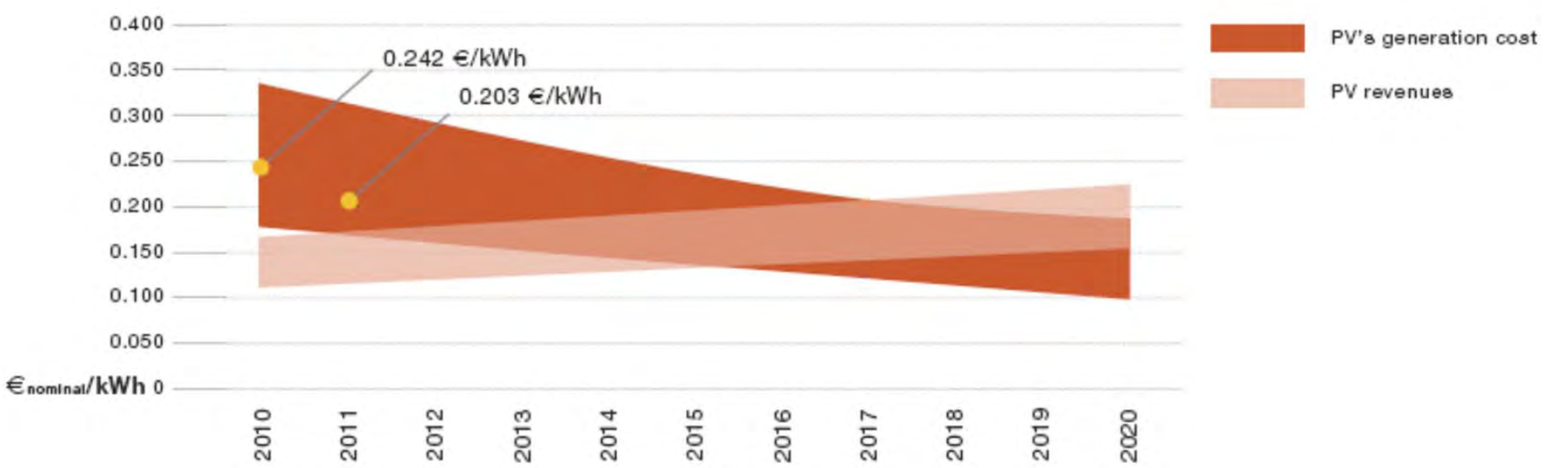
Steady reduction of PV price, closing the gap to competitiveness

POLITÉCNICA
Instituto de Energía Solar

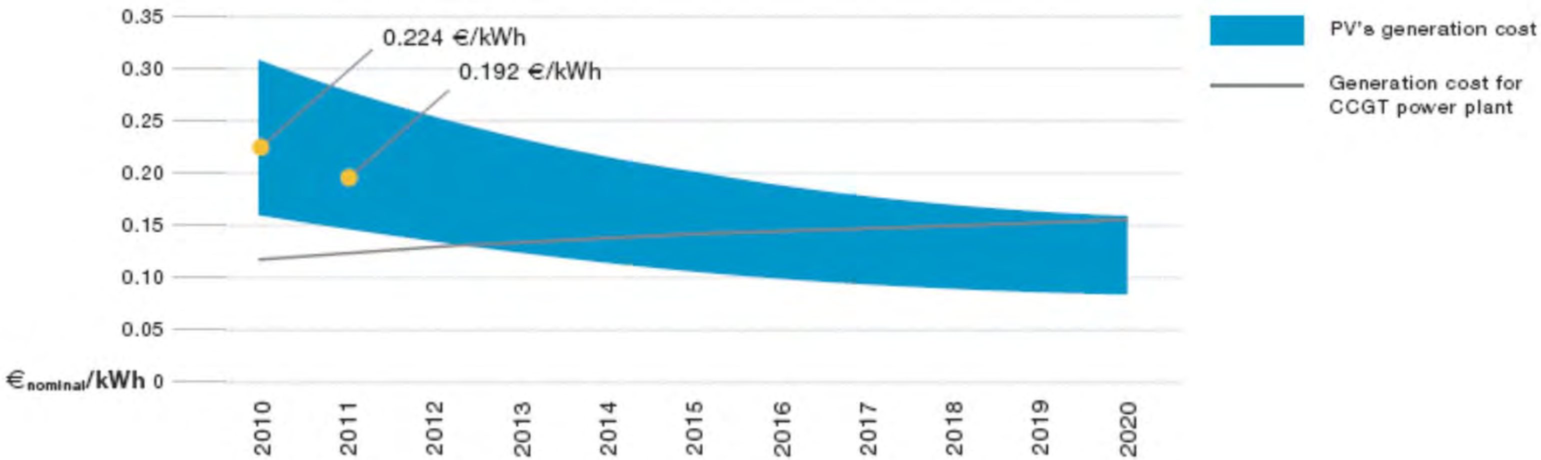
Evolution of technology price (2)

EPIA 2011

PV commercial system (100 kW)



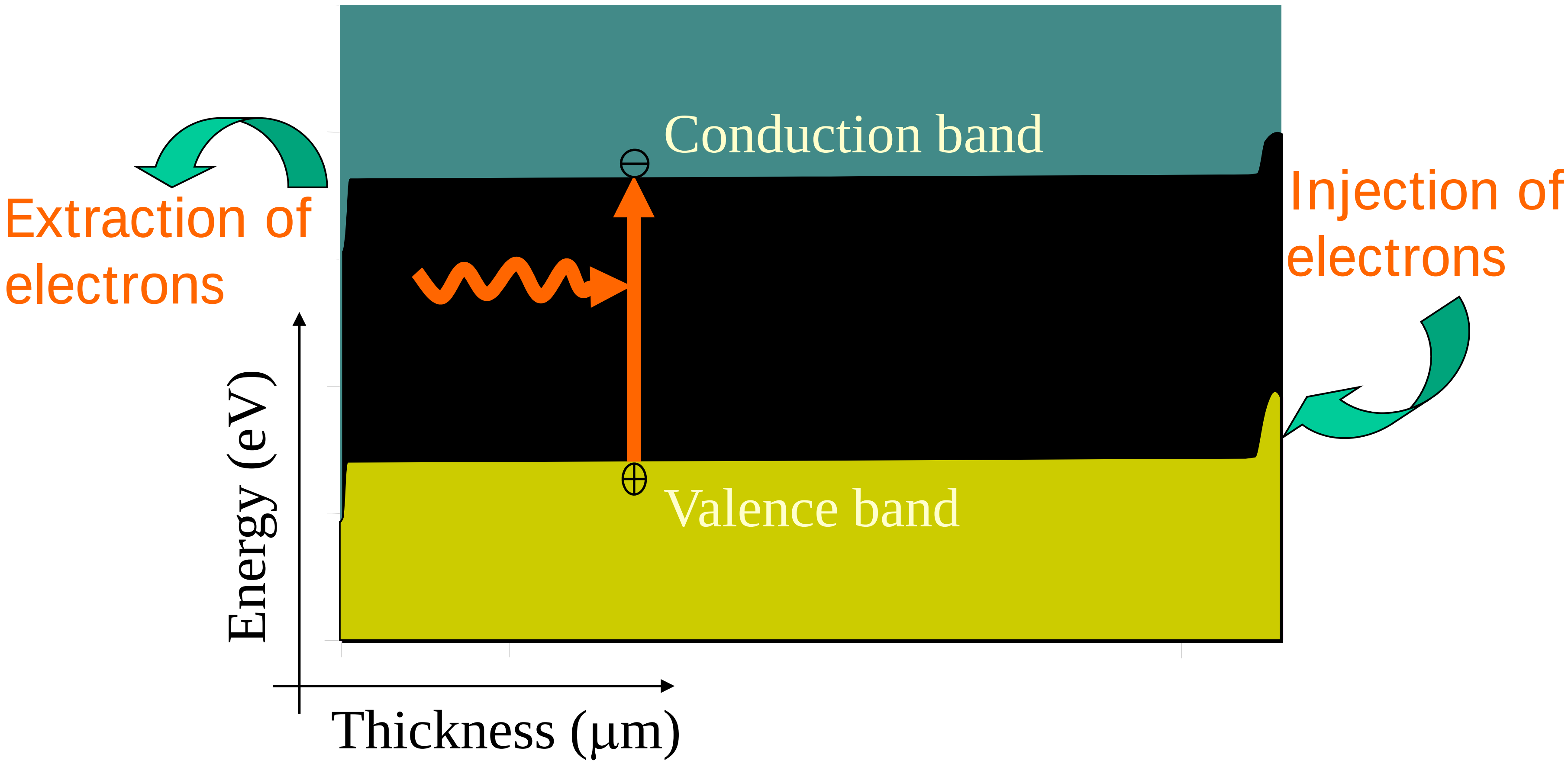
Large ground-mounted PV system (range of MW)



Most major EU markets can reach competitiveness before 2020 under a mature market assumption

POLITÉCNICA
Instituto de Energía Solar

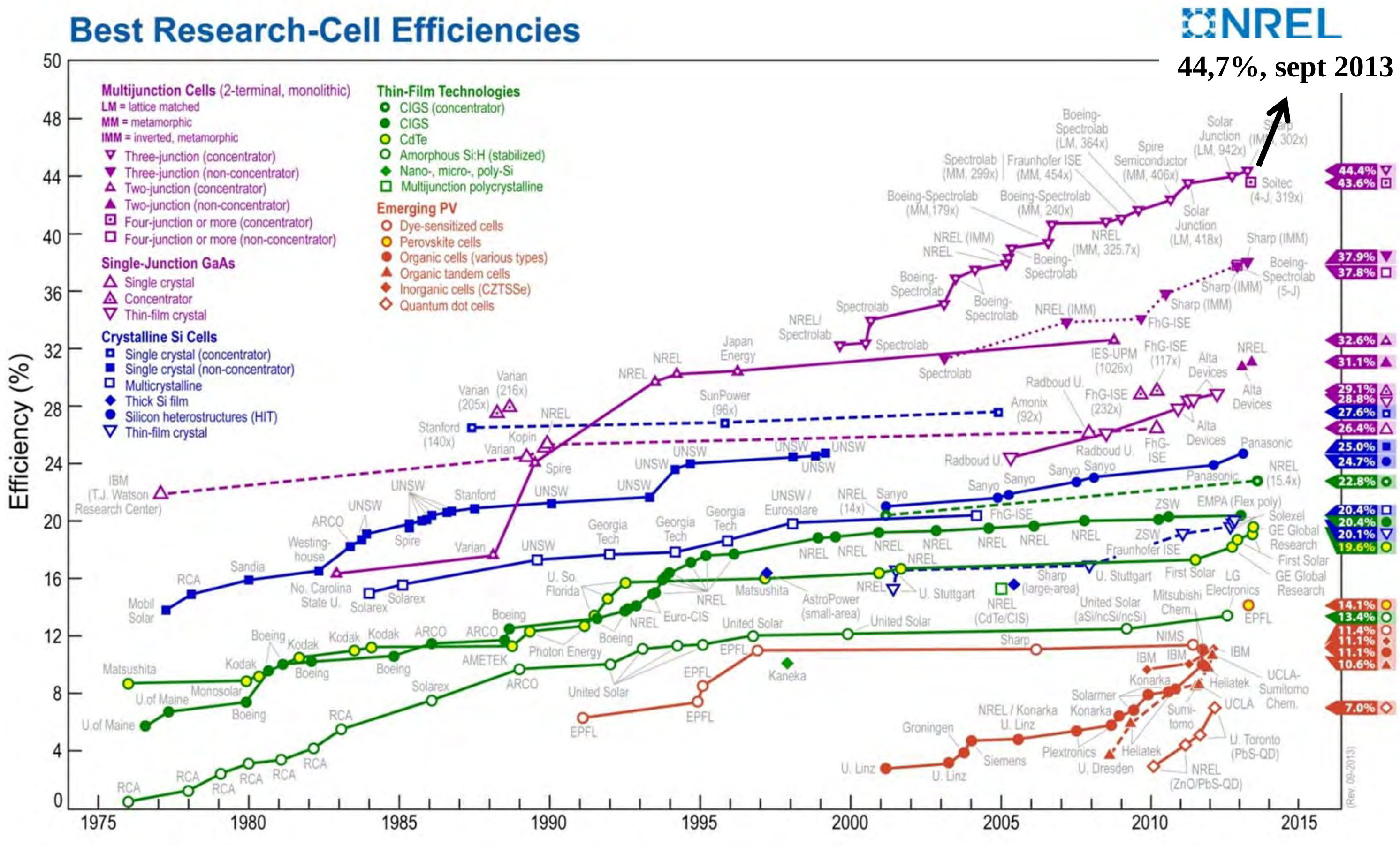
The grounds of the photovoltaic effect



- **Photons pump electrons from valence to conduction band**
- **Appropriate contacts insure conduction band electrons are delivered to load and recovered by the valence band**

POLITÉCNICA
Instituto de Energía Solar

Technological moves forward…



44,7%, sept 2013

Already in 2013!

- ✓ **mono-Si module: 22,4% (Sunpower)**
- ✓ **multi-Si module: 18,5% (Q-cells)**
- ✓ **CdTe module: 16,1% (First Solar)**
- ✓ **CPV module : 33,5% (Amonix)**

Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

Alternatives to cristalline silicon technology

Conclusions

The Si value chain: from silica to systems

quartz →
carbon →

Reduction to metallurgical Si

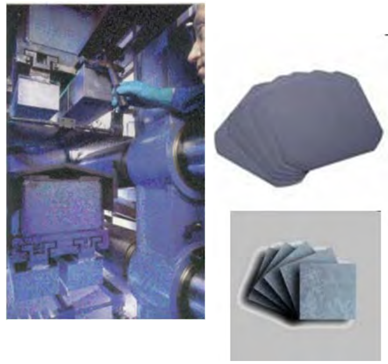
→

Ultrapurification to polysilicon

→

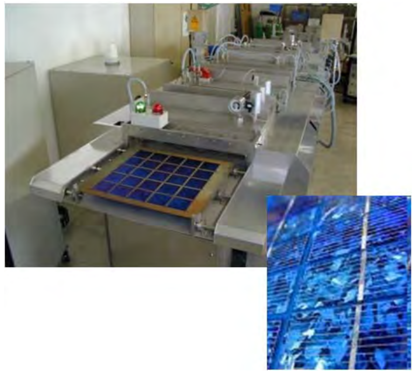
Crystallisation

→



Wafering

→



Solar cell processing

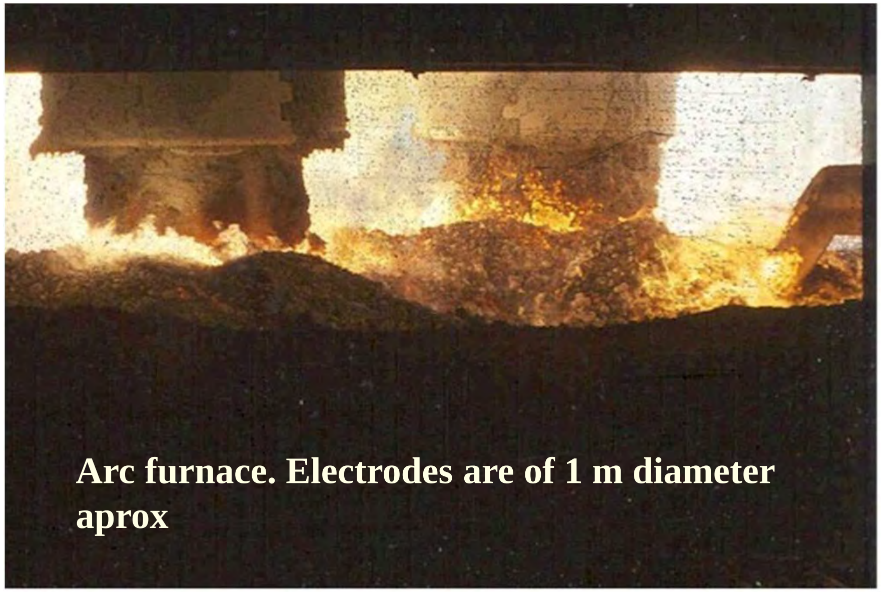
→

Module assembly

→

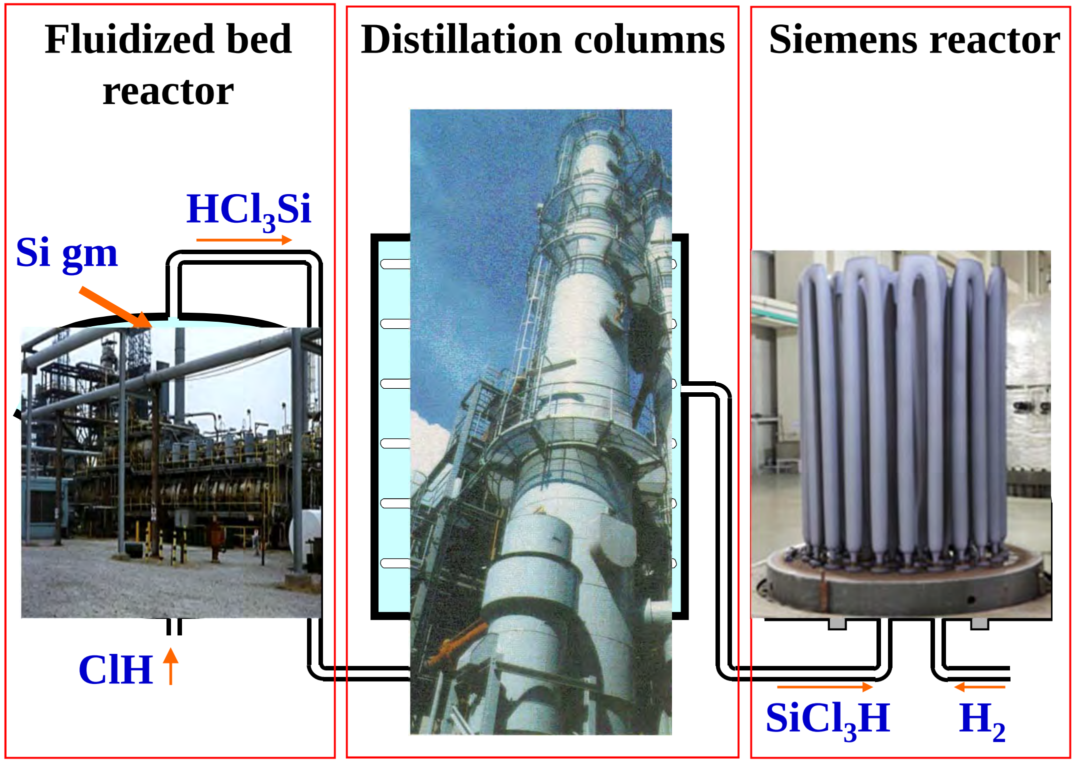
System implementation

Metallurgical silicon production



- Reduction of quartz with carbon in an arc furnace $SiO_2 + 2C \rightarrow Si + 2CO$
- Product: metallurgica silicon, 99% pure
- Electronics and Photovoltaics only use a small fraction (~10-15%) of the total production, which is devoted mainly to metallurgical industry

Electronic grade silicon production (polisilicon)



Ultrapure trichlorosilane

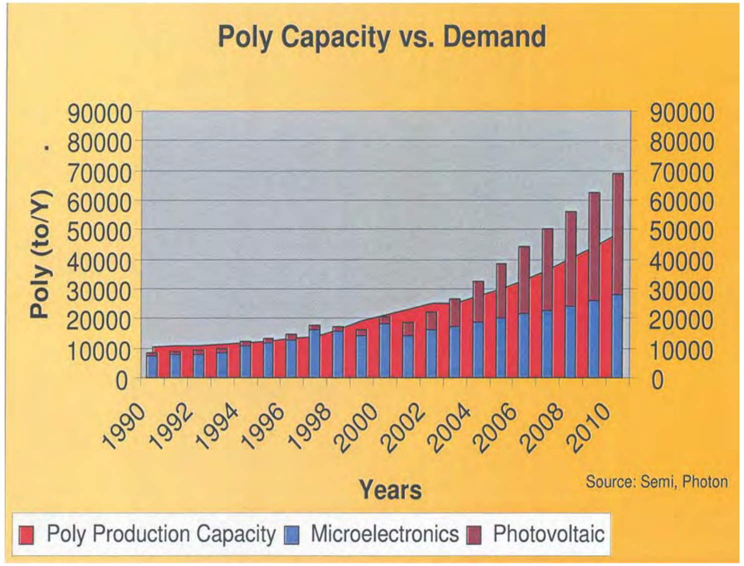
$3HCl+Si\ (gm) \rightarrow HCl_3Si+H_2$ $4HCl_3Si+H_2 \rightarrow Si\ (ge)+3SiCl_4+3H_2$

- Raw materials: metallurgical silicon and HCl
- Product: Electronic grade silicon (99.9999999% pure)
- High energy consumption (50-100 kWh/kg)

POLITÉCNICA
Instituto de Energía Solar

The revolution in the Si feedstock market

P. Fath, A. Mozer, 3rd Solar Si Conf, 2006



- **<2006: Market driven by Microelectronics**
- **2006-2007: Silicon shortage**
  - **- Prices rocketed**
  - **- New entrants trying to enter**
- **2009-2012: Change of scenario towards oversupply**
  - **- Market now driven by Photovoltaics**
  - **- Pressure due to very low prices**

Solar Silicon

Simplifying chlorosilane process

-Silane as volatile compound
-Alternatives to Siemens deposition system

Applying metallurgical steps

-Directional solidification
-Slagging
-Evaporation in vacuum
-…

POLITÉCNICA
Instituto de Energía Solar

Centesil: research on solar silicon

CENTESIL
Centro de tecnología del silicio solar

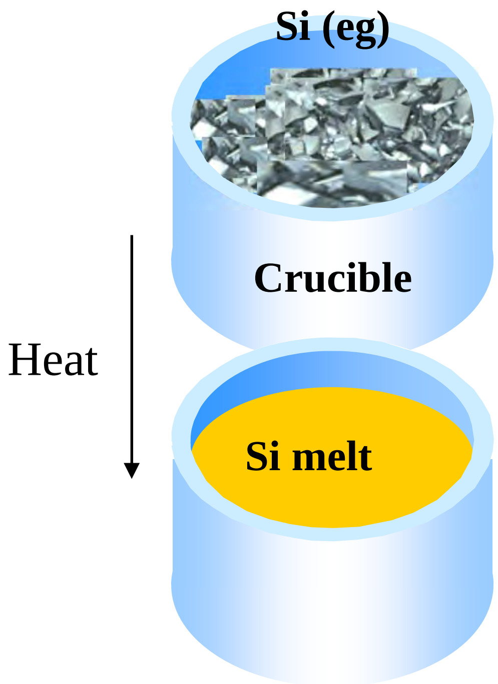
Corporation formed in 2006 by two Universities and three companies

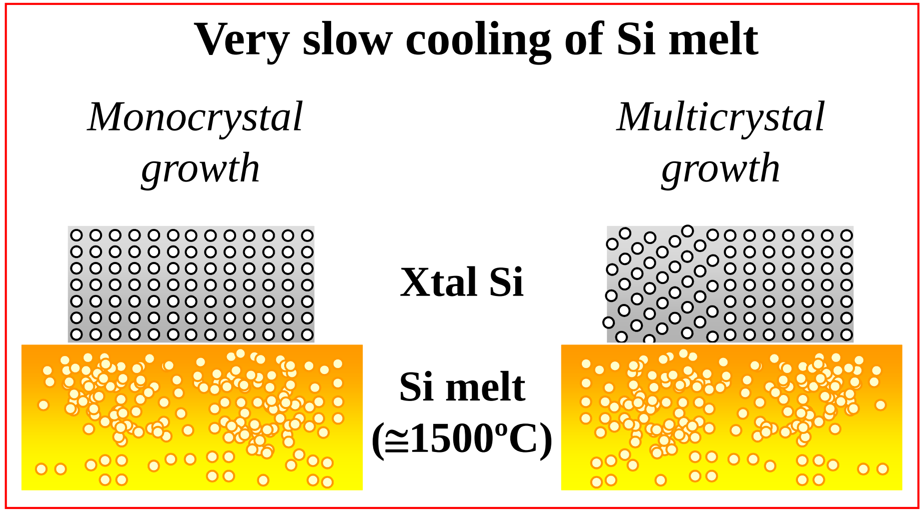
- ✓ **Flexible tool for R&D on polysilicon**
- ✓ **50-100 t/a poly pilot plant that follows the chlorosilane route**
- ✓ **Value chain from feedstock to solar cell**

Advances in the installation stage

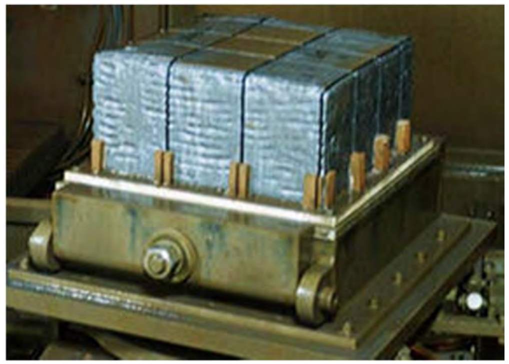
POLITÉCNICA
Instituto de Energía Solar

Crystallisation

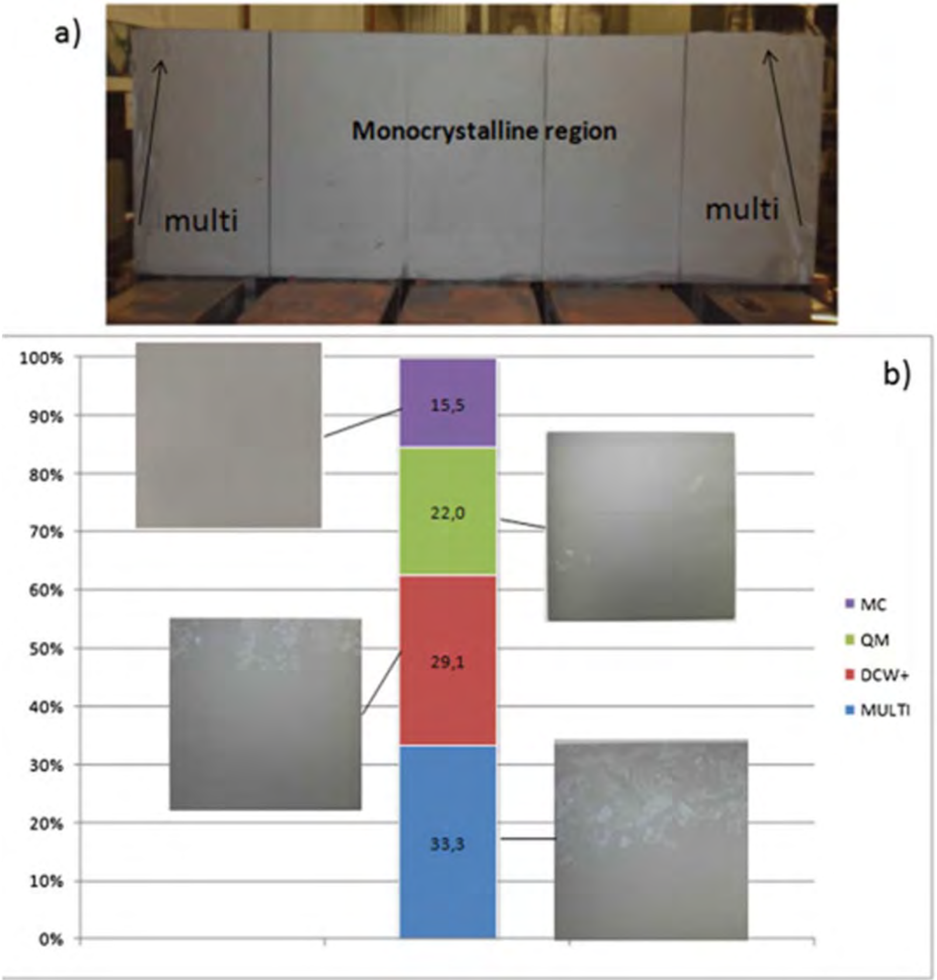





Monocrystalline ingot

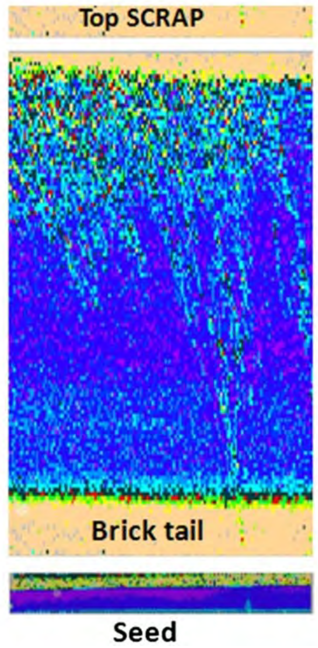

Multicrystalline ingot in blocks

A third way for crystallisation: Mono-cast approach

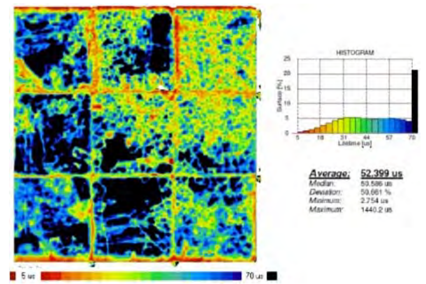


- 😐 **Wafers of different "classes" in the same ingot**
- ☺ **Efficiency enhancement potential +1%-1.5% absolute**
- ☹ **Large dispersion on cell efficiencies, depending on the wafer position in the ingot**

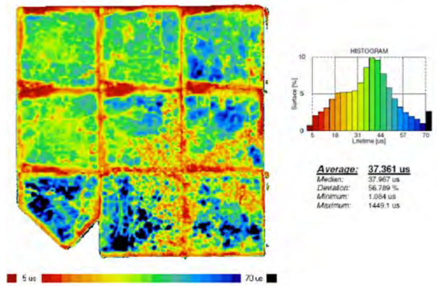
Understanding Mono-cast performance at IES



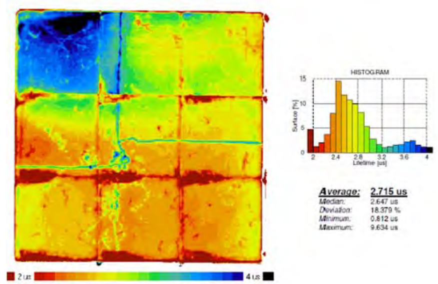
Attention, colour of each graphic correspond to different scales



•Areas of lifetime over 50 μs!!

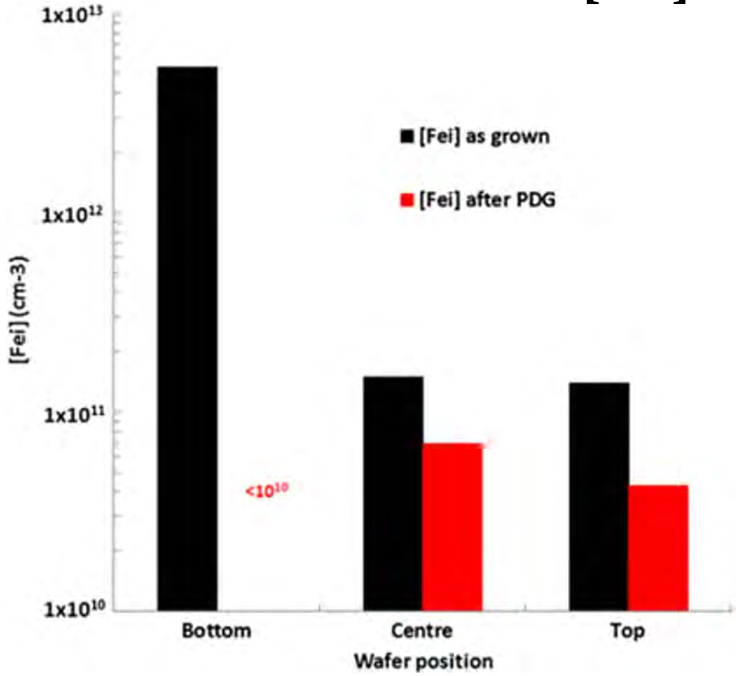


•Good results, over 30 μs!!



•Lifetimes around 4 μs

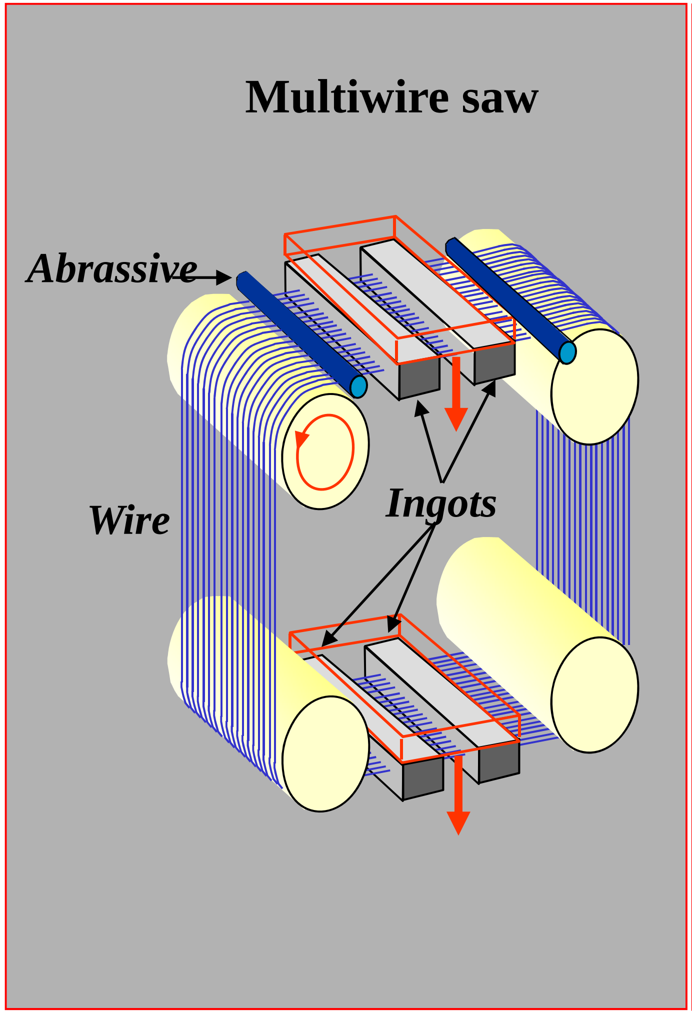
✓Effect of P diffusion on [Fei]

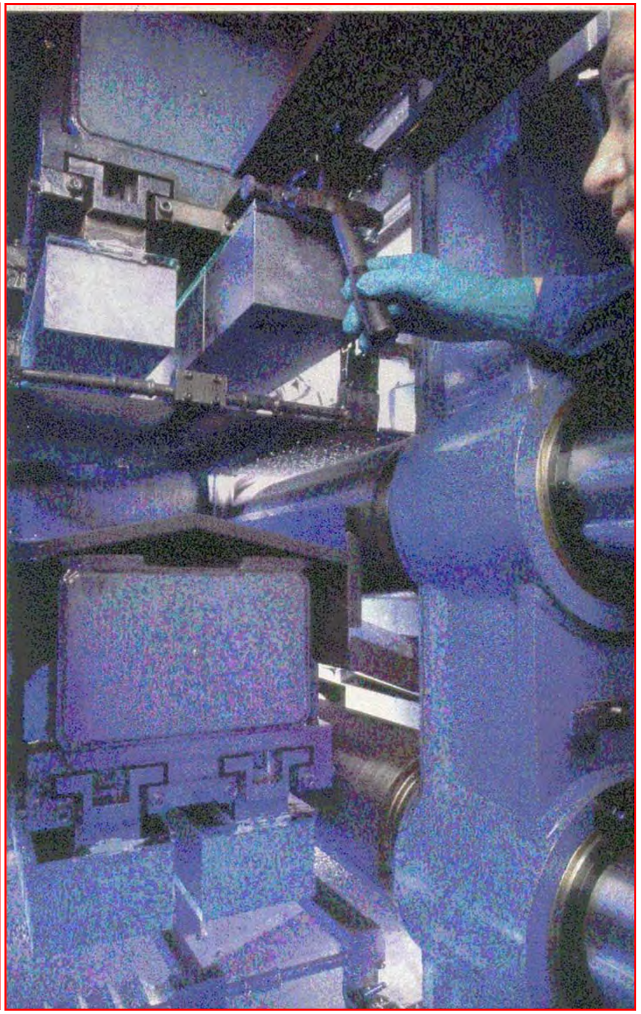


•Crystalline defects at the interface seed-ingot propagate from bottom to top, difficulting impurity removal and causing material heterogeneity

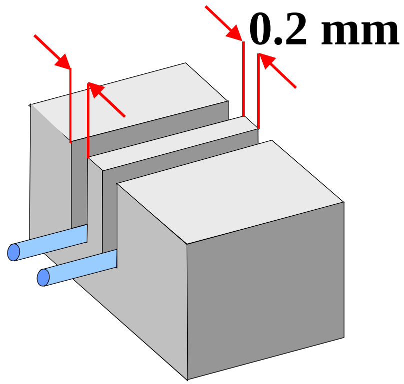
POLITÉCNICA
Instituto de Energía Solar

Wafering



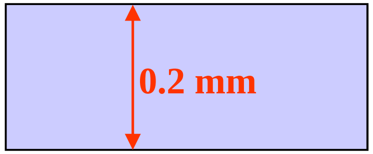


Kerf losses of around 50%



Solar cell processing (I)

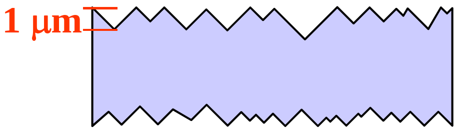
Wafers 156 cm^2 p-type (B 10^{16} cm^{-3})



Cleaning and etching

KOH

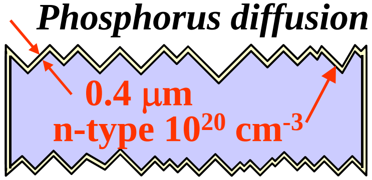
Texturing



KOH bath
85 ºC

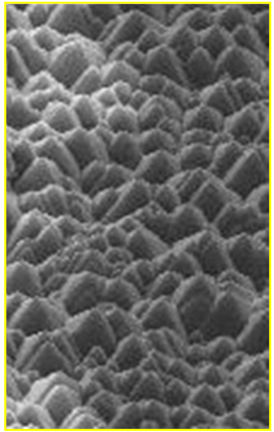
Cleaning

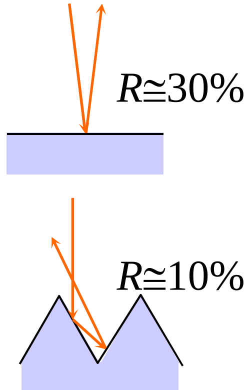
Phosphorus diffusion

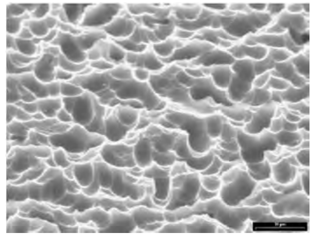


900 ºC, 1/2 h

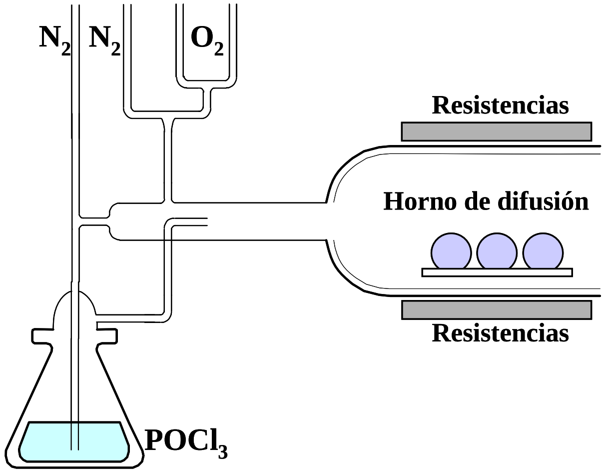
Cleaning







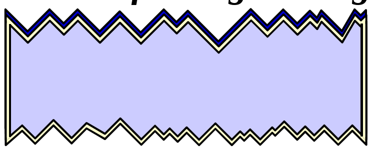
Acidic texturing for multi



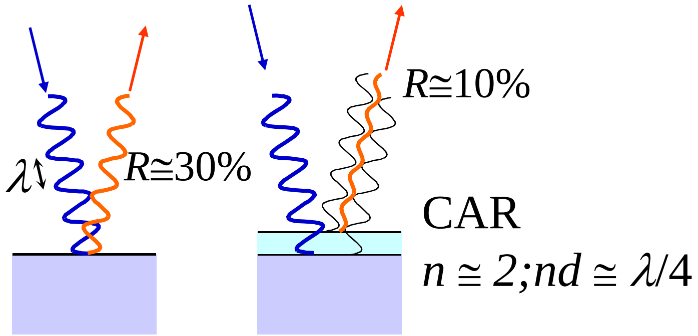
POLITÉCNICA
Instituto de Energía Solar

Solar cell processing (II)

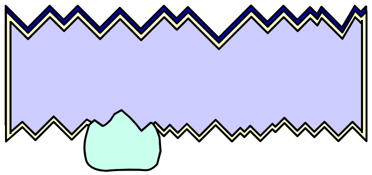
Anti-reflecting coating



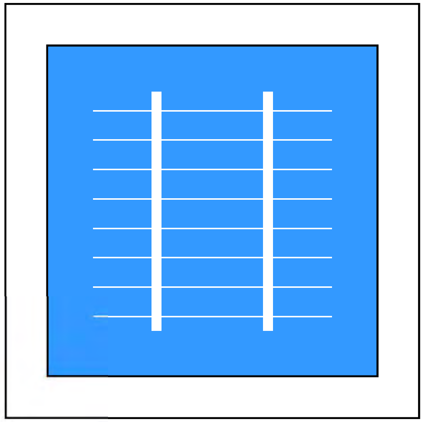
CVD
SiN_x:H



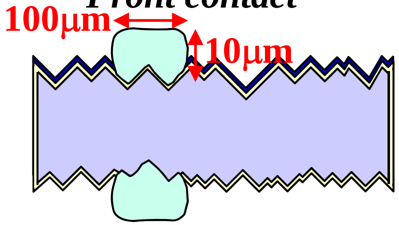
Rear contact

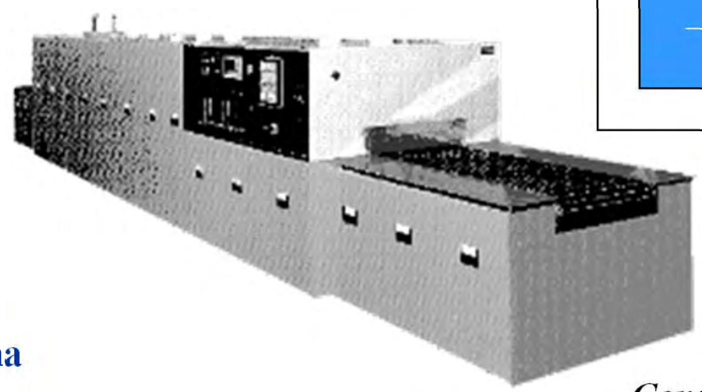


Screenprinting of a conductive paste Fired in a IR furnace (800°C,10 min)

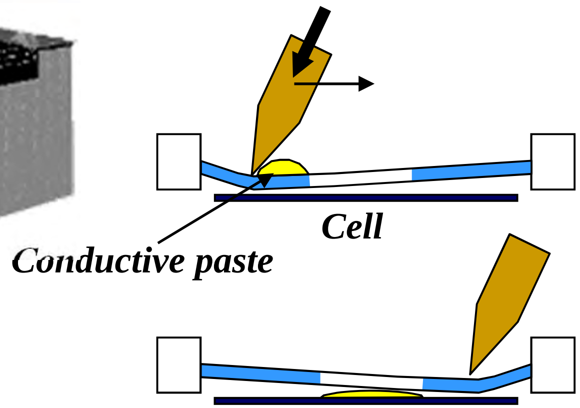


Front contact

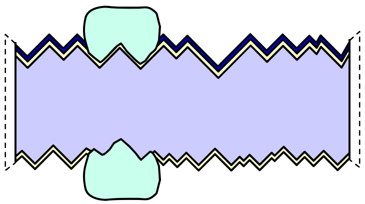




In-line furnace for firing



Junction isolation

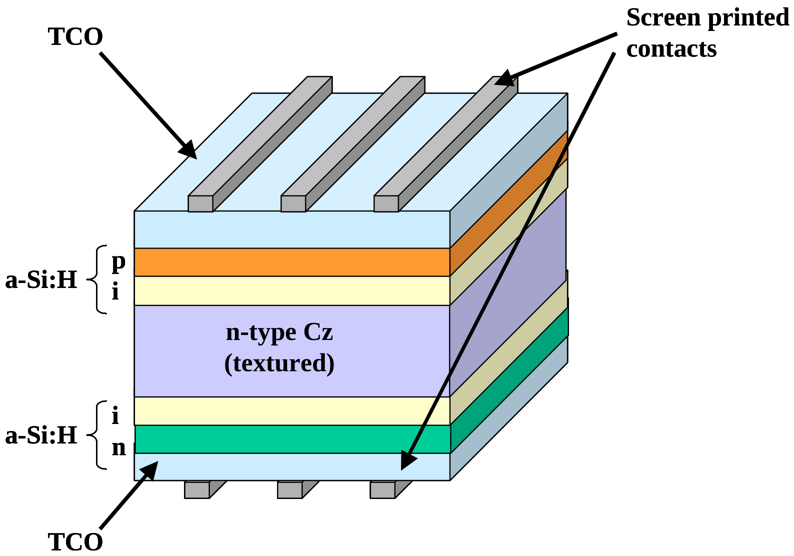


Plasma etch

Measure and classify

Advanced crystalline silicon technologies

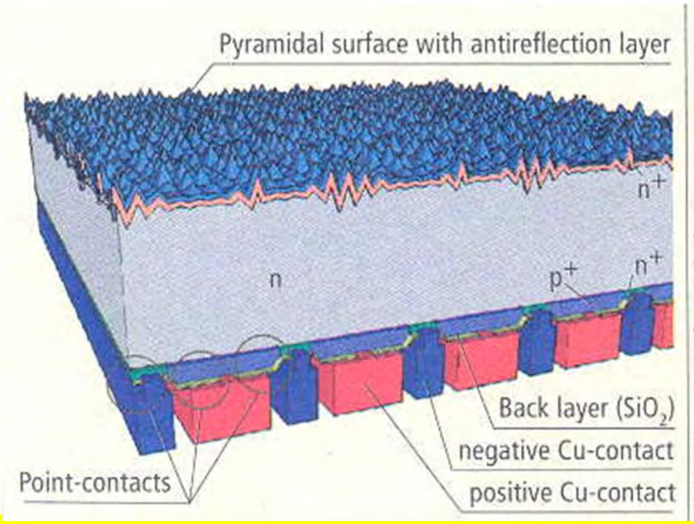
HIT:Heterojunction with Intrinsic Thin layer (Sanyo/Panasonic)



- n-type wafers
- a-Si layers deposited at 200ºC.
- Efficiencies at industrial level > 23%
- Bifacial structure

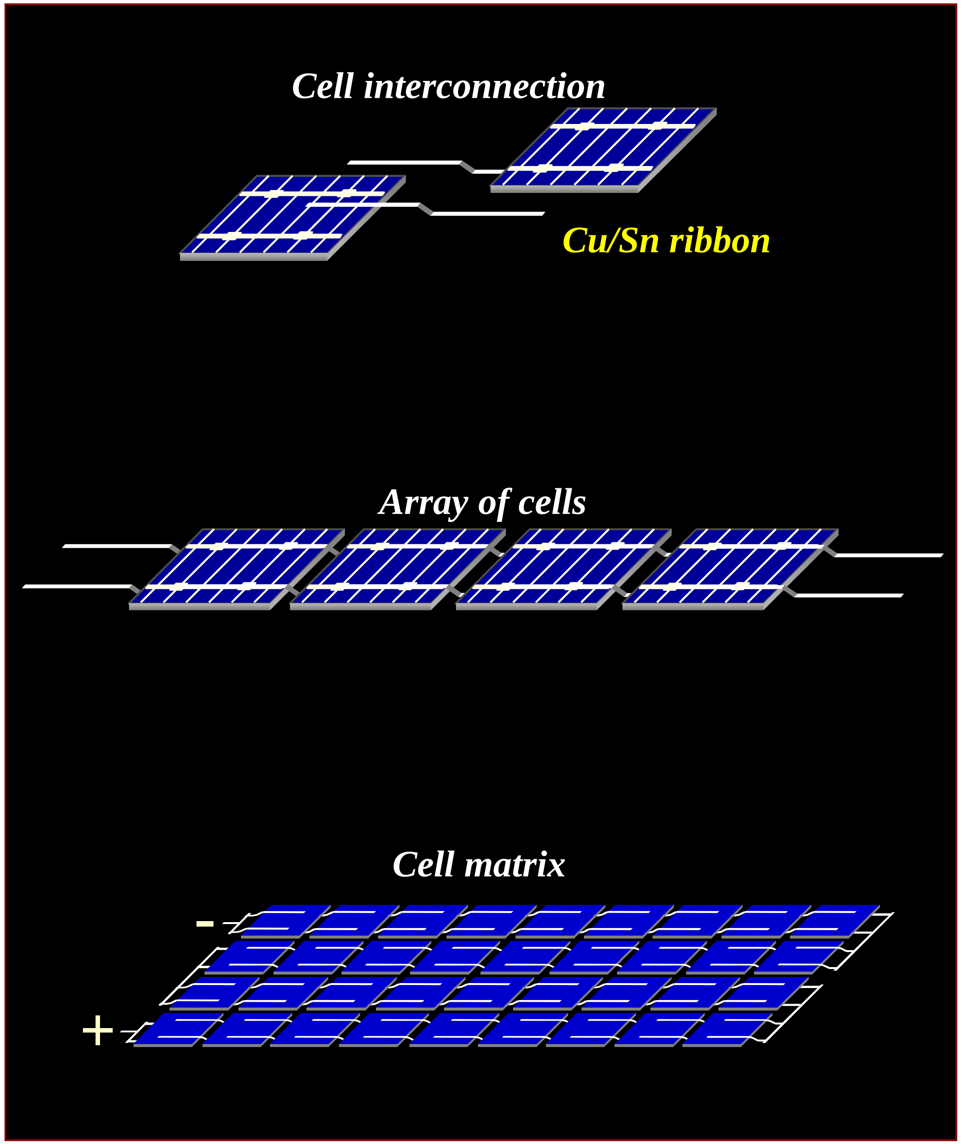
Point-Contact Cell (SunPower)

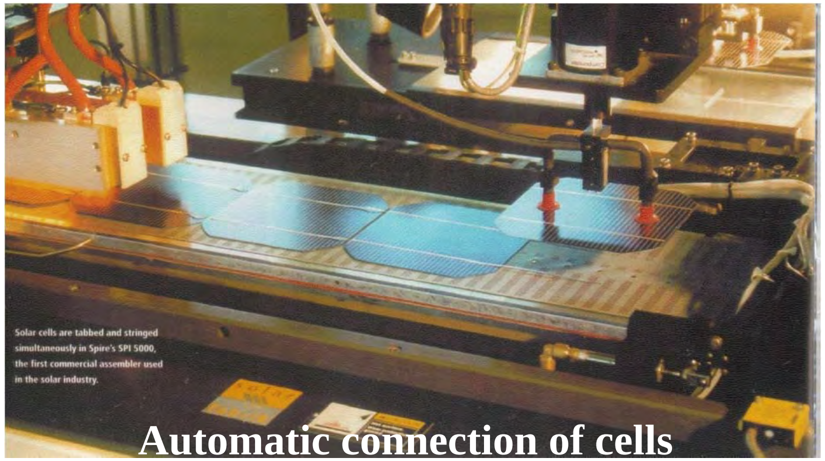
- Both p+ and n+ contacts at the rear, with two alternated "comb-like" structures
- Use of highest quality wafers
- Efficiencies at industrial level > 23%



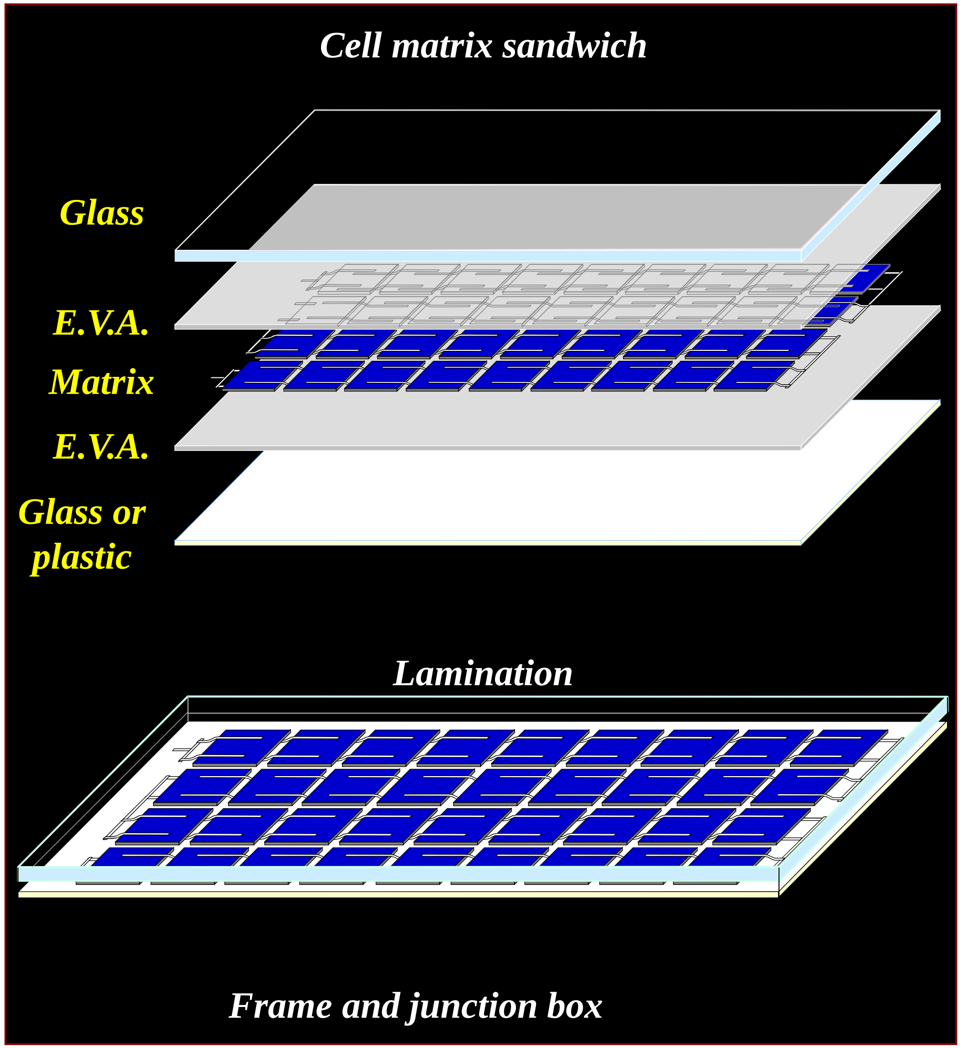
POLITÉCNICA
Instituto de Energía Solar

Module assembly (I)





Module assembly (II)



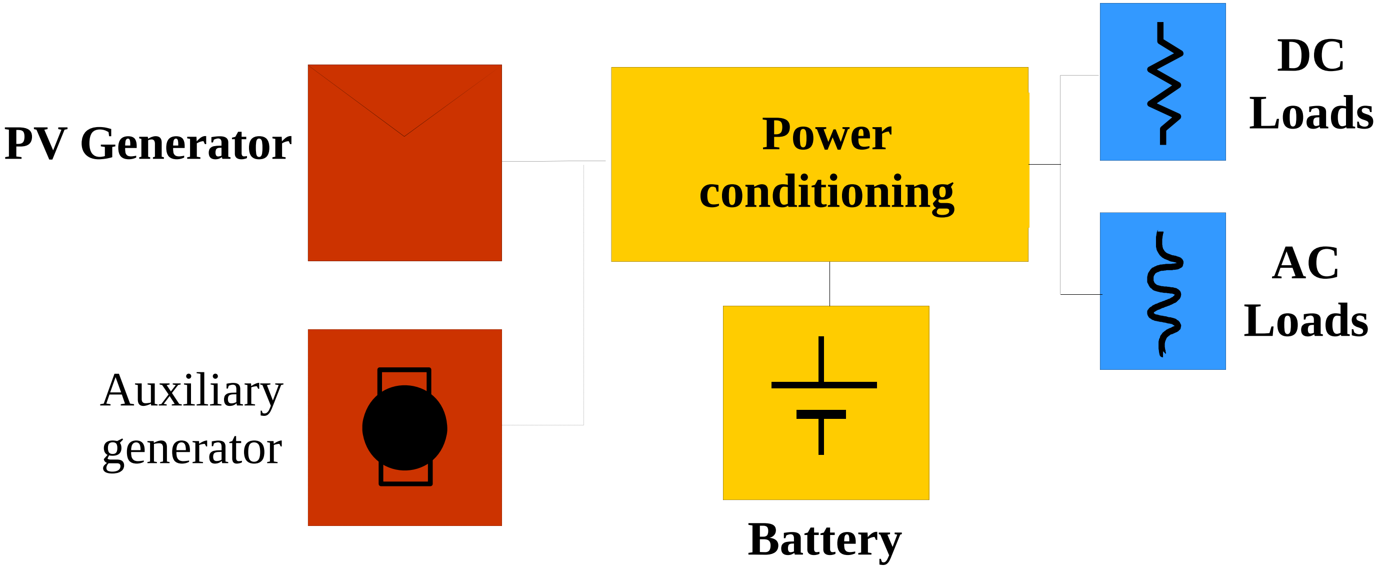
Lamination:

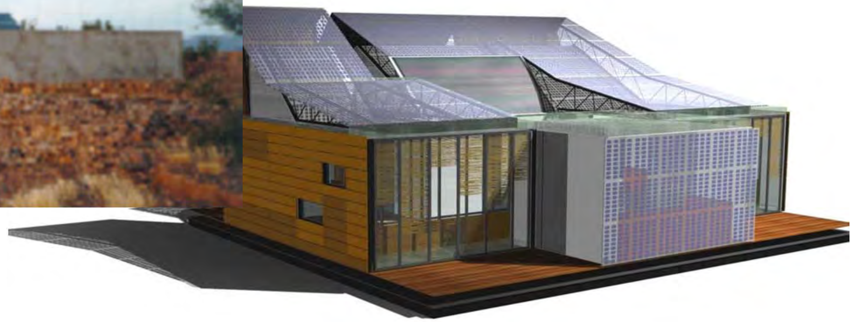
Pressure at 100ºC + Curing at 150ºC:

Cells are soaked in the flowing EVA, which becomes transparent and solidifies

Laminator

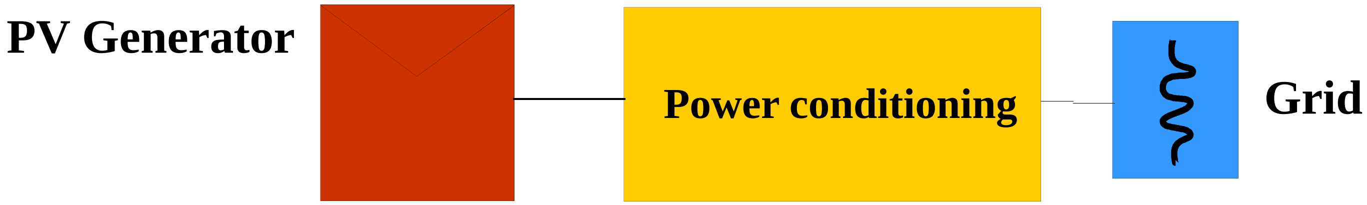
Off-grid instalations





Isolated residential

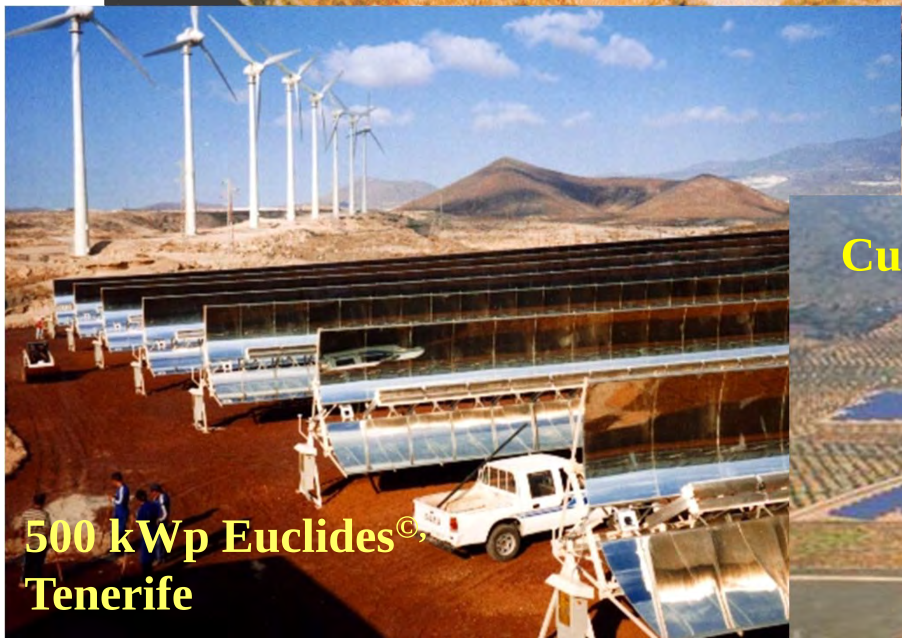
Grid connected instalations



Solar farms


PV Toledo, 1 MWp


Navarra, 9 MWp


500 kWp Euclides©,
Tenerife


Cuenca, 60 MWp

BoS equipments

Batteries

Regulator

DC/AC converters

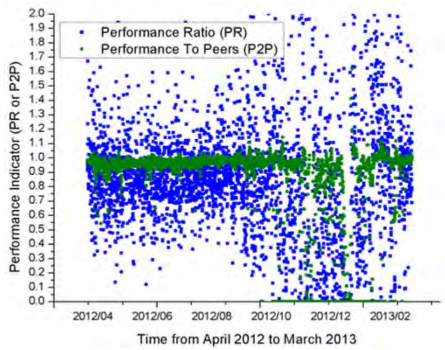
POLITÉCNICA
Instituto de Energía Solar

Research on Photovoltaic Systems at IES

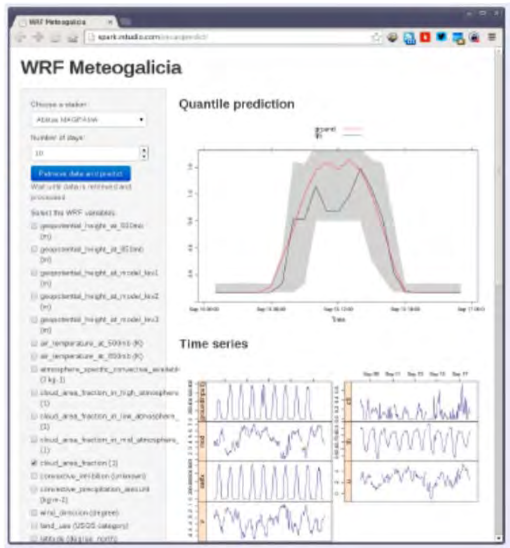
Need to develop implementation procedures, engineering methods and quality control procedures associated to PV applications

- ✓ **High power PV water pumping technology has been developed and a demonstrator has been installed**

- ✓ **European R&D project PVCROPS for high PV system penetration, ongoing**
- ✓ **BIPV: diagnosis of performance**



- ✓ **PV plants: prediction**



POLITÉCNICA
Instituto de Energía Solar

Introduction

Crystalline silicon technology, from quartz to system

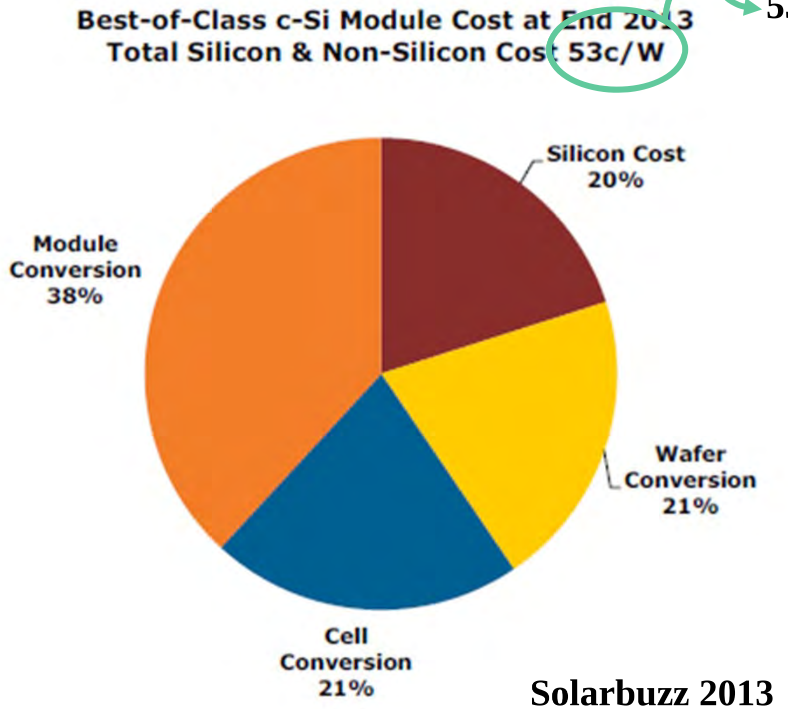
Economical and environmental issues

Alternatives to cristalline silicon technology

Conclusions

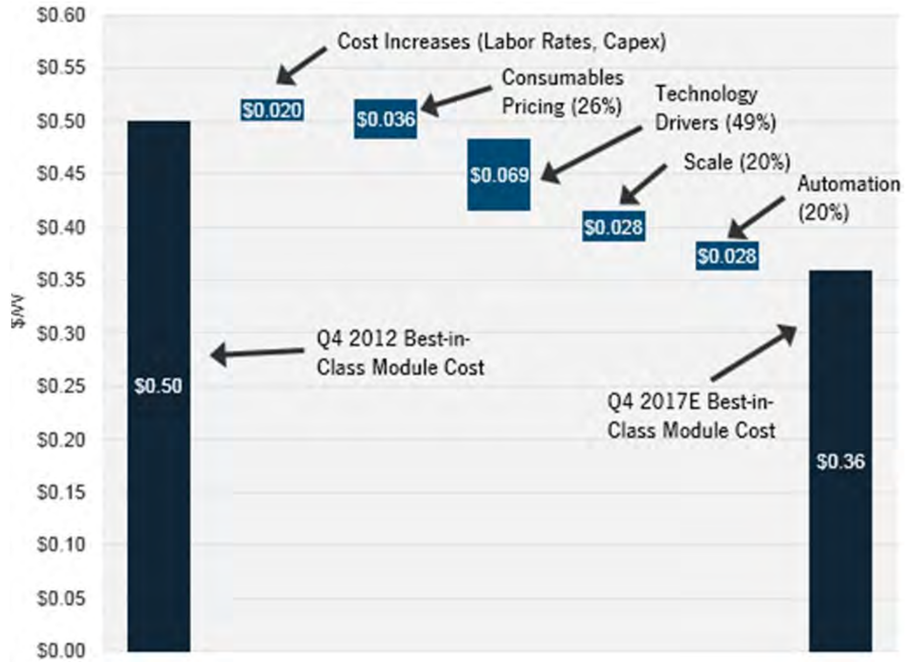
The crystalline Si module cost

53 c$/W ~ 40 c€/W

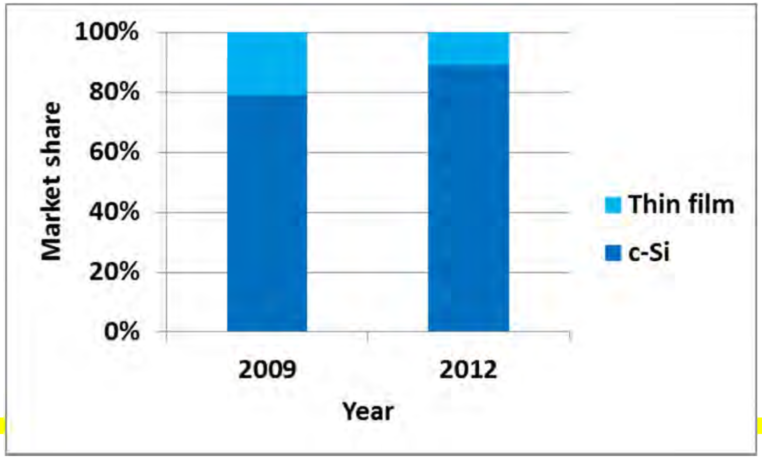


Solarbuzz 2013

GTM Research 2013



… what puts pressure on alternative technologies to c-Si

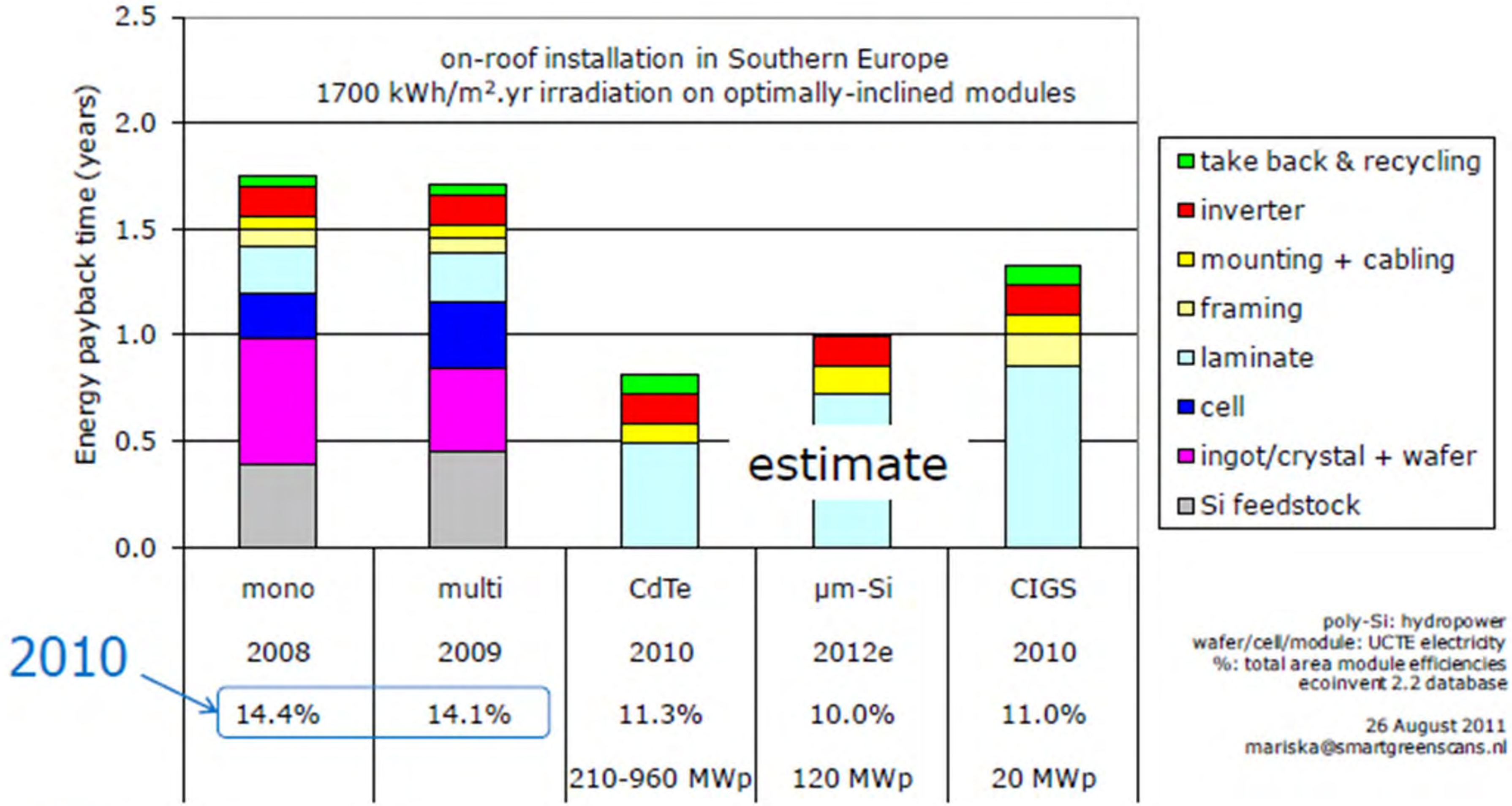


POLITÉCNICA
Instituto de Energía Solar

Energy Pay Back Time

Time needed by the PV system to give back the energy invested in its fabrication

$$EPBT = \frac{Invested\ energy}{Energy\ produced\ in\ a\ year}$$



de Wild-Scholten, 26th European PVSEC, 2011

Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

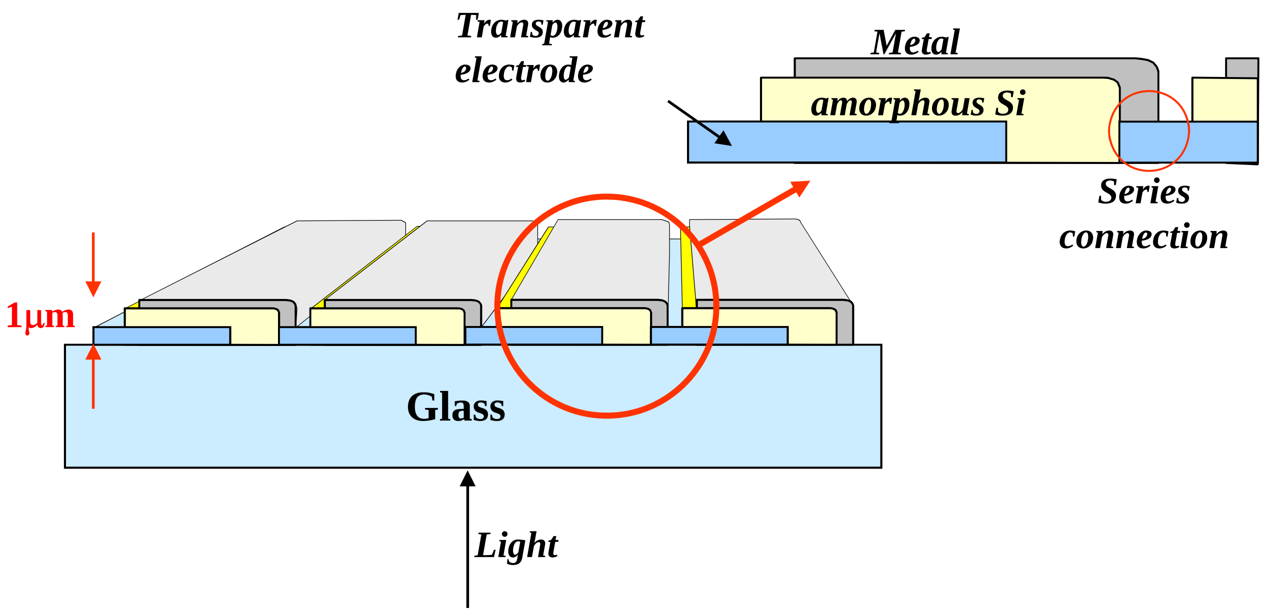
Alternatives to cristalline silicon technology

Conclusions

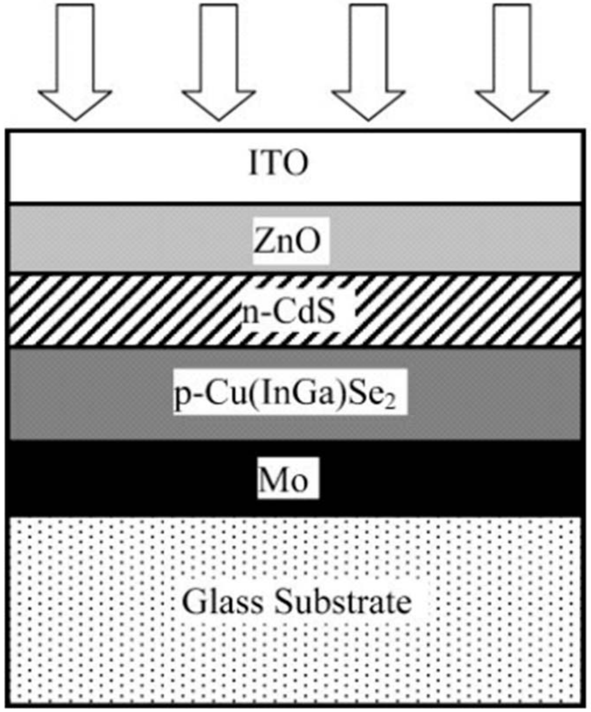
Low cost approaches: Thin films

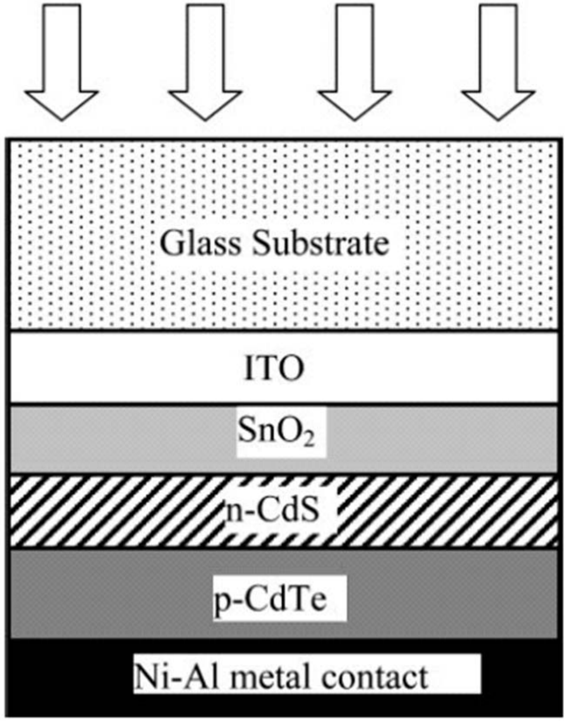
A big portion of light is absorbed in the first few microns (depending on the material): posibility to SAVE material

Direct fabrication of the module: layers are deposited and interconnected on the substrate (the glass, for instance)



Thin films: CIS y CdTe

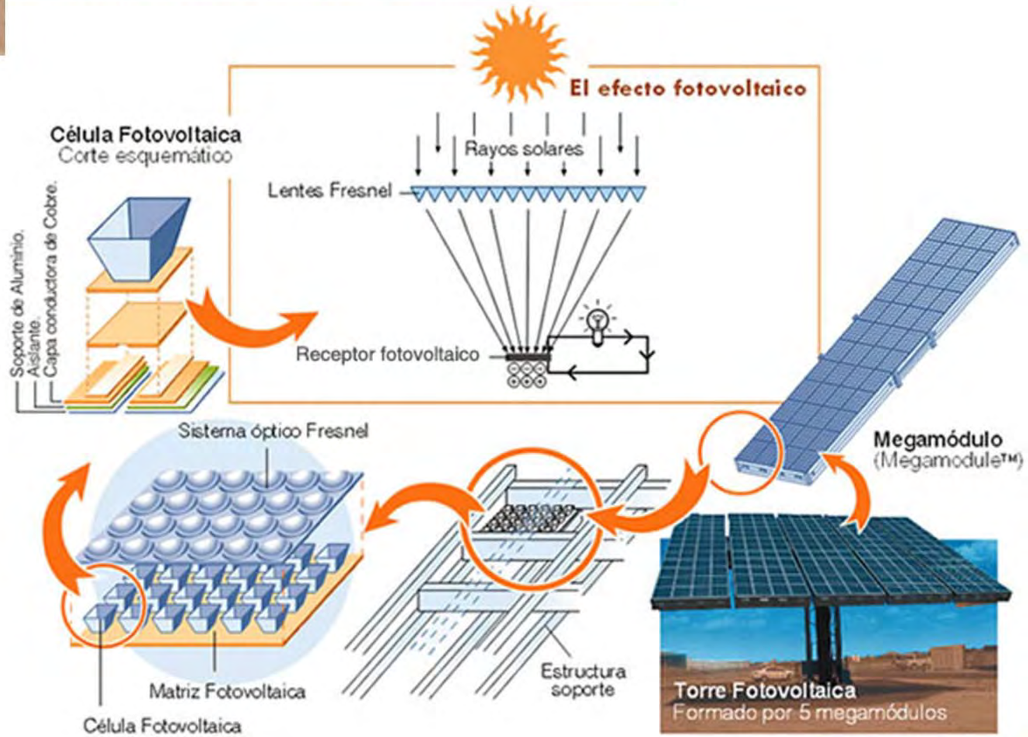




	CIS	CdTe
	$E_G \cong$ **1.1eV**	$E_G \cong$ **1.5eV**
Commercial module	$\eta \cong$ **15 %**	$\eta \cong$ **15 %**
Laboratory cell	$\eta \cong$ **20 %**	$\eta \cong$ **18 %**
Advantage	Higher efficiency	Lower cost
Disadvantage	Complex, scarcity of In	Scarcity and toxicity of Cd

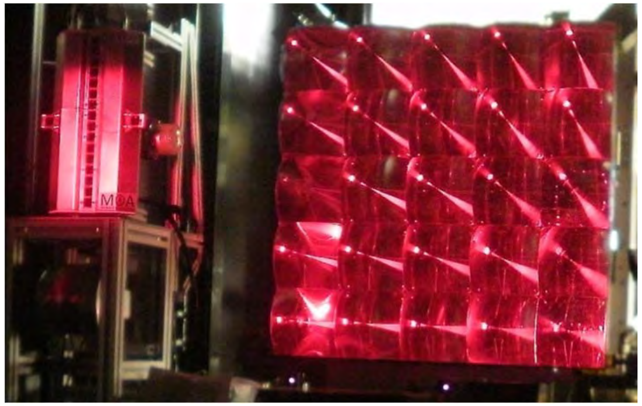
POLITÉCNICA
Instituto de Energía Solar

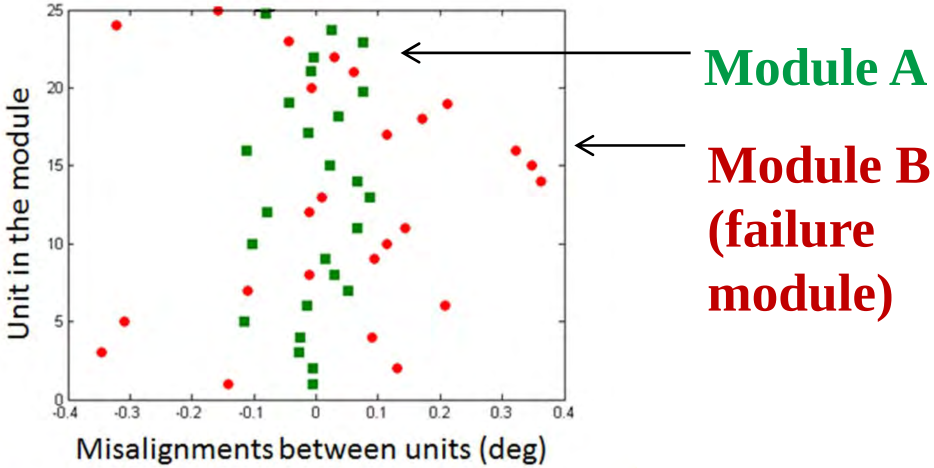
High efficiency approach: PV concentration (CPV)



Design of CPV components and instruments at IES

Module Optical Analyser for CPV submodule misalignment identification



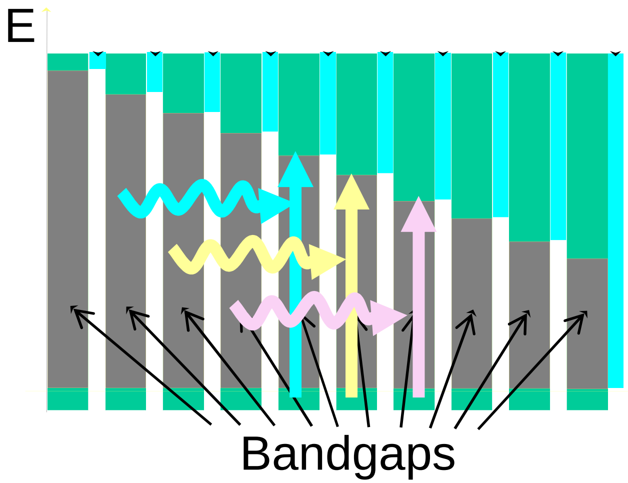


An R&D Center to validate CPV technologies: ISFOC

According to a plan of the IES-UPM, an Institute for CPV Systems was created in Spain in 2008, to validate CPV technologies developed worldwide: Solfocus (US), Concentrix (DE), Isofotón (ES), Arima (TW), Encore (US), CSLM (ES)…

High efficiency approach: tandem solar cell

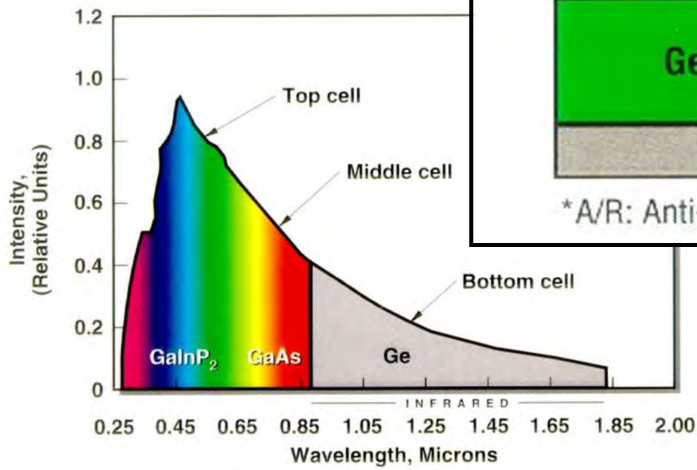
- **Tandem / MultiJunction solar cells**

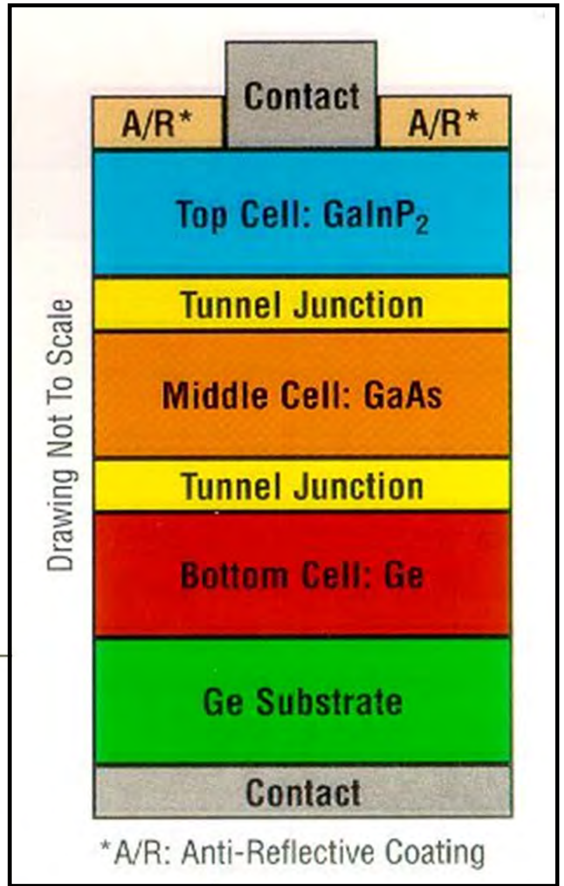


Theoretical limit: η=86,3%

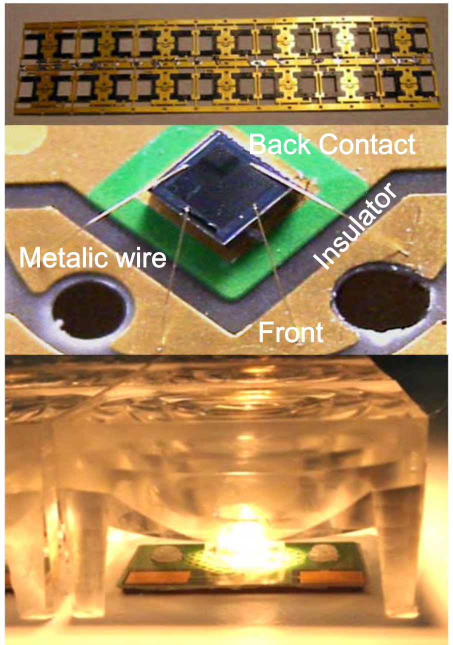
Record efficiency 4J cell =44,7%

- **3J solar cell**



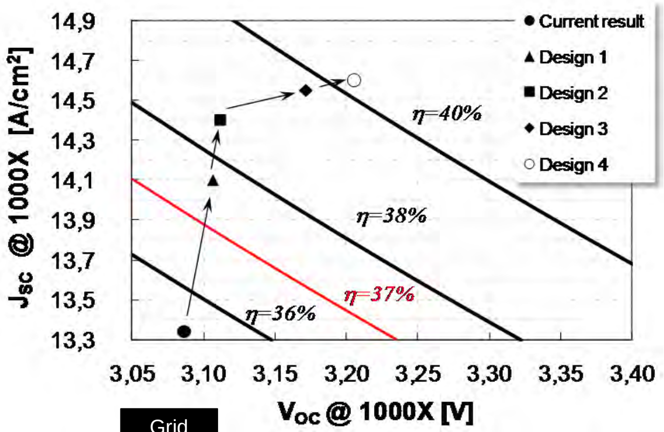


High efficiency approach: tandem solar cells at IES



✓**Current status at IES: 3J solar cell of 39,2%**

✓**Roadmap for efficiency improvement**



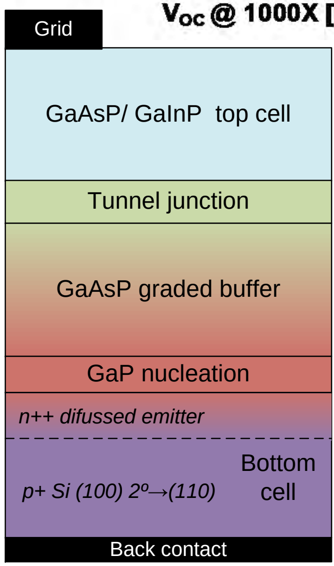
Design #1: Raise Middle Cell current to Top Cell level

Design #2: Non- absorbing Tunnel Junction

Design #3: High-E_g GaInP for Top Cell

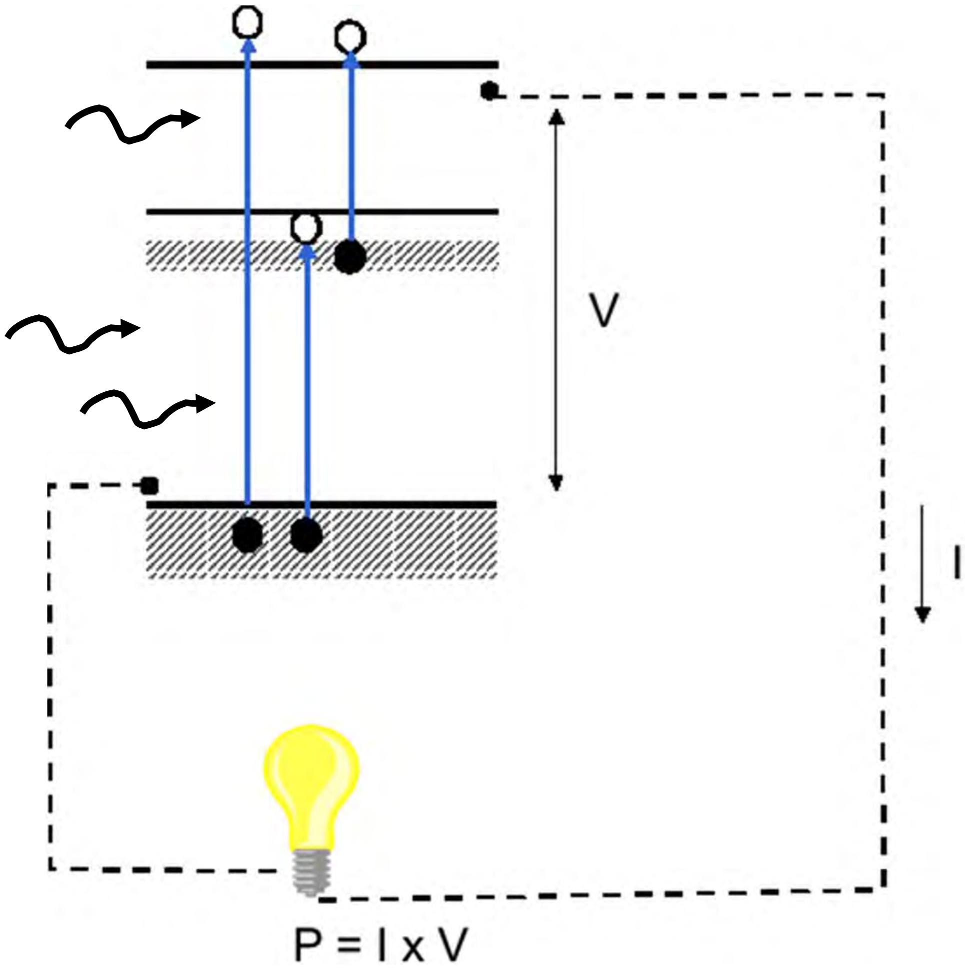
Design #4: Improve Top Cell Window/Emitter Quantum Efficiency

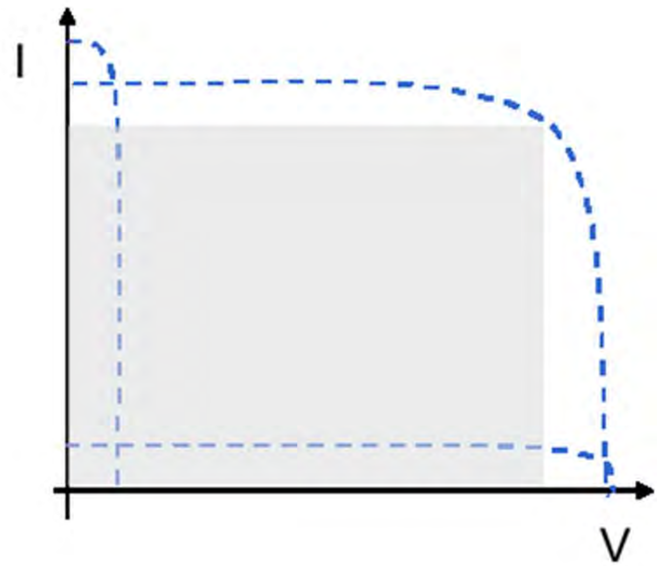
✓**Substitution of Ge bottom cell by Si**



High efficiency approach: Intermediate Band Solar Cell

- **Intermediate Band Solar Cells (IBSC)**



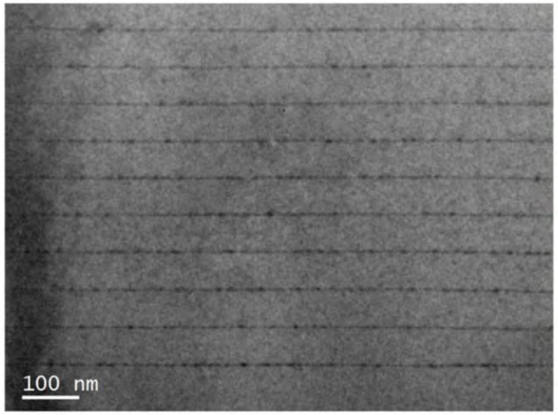


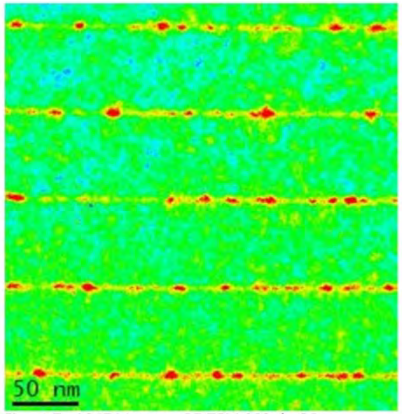
Theoretical limit: 63,3%

Intermediate band materials and solar cells: an IES proposal followed worldwide

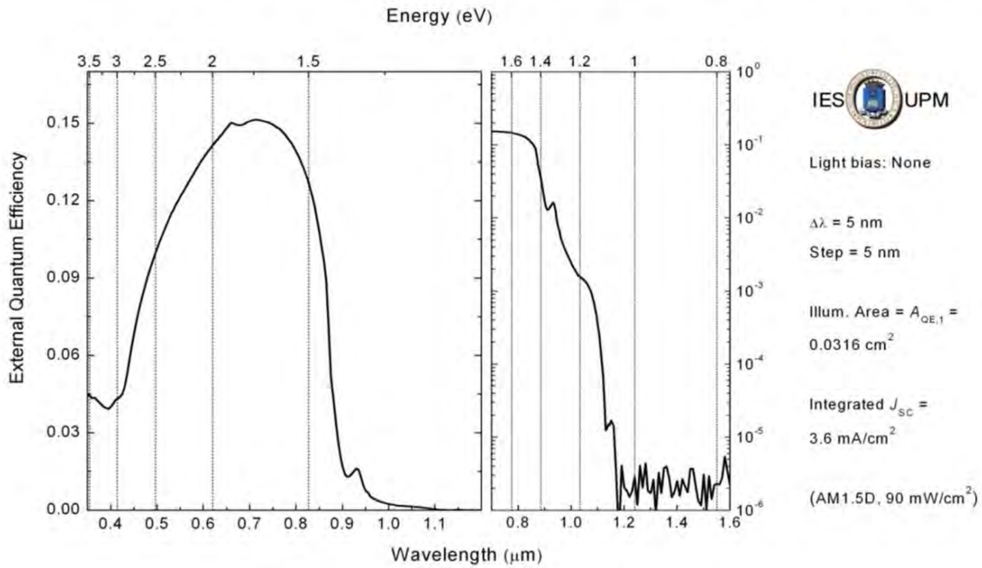
		Sub-bandgap transitions				Extra-photocurrent			Voltage Preservation
	Experimental test / Material	Absorption[a]	PR	PL	EL	Sub-bandgap SR or QE	Jsc increase	2-photon PC	$I_L - V_{OC}$ or J - V
QD	In(Ga)As/Ga(N,P,Sb)As	[57-60][e]	[65, 70, 71]	[57, 58, 60, 64, 65, 69]	[54, 55][b,e]	[17-26, 33-35]	[21-23, 25, 33, 35]	[46, 47][e]	[51, 52][b,e]
	GaSb/GaAs			[28, 29, 68]		[27-29]	[27, 29]		
	InAs/AlGaAs	[58]	[71]	[58, 64, 66]		[30, 31]			
	GaAs/AlGaAs	[61][e]		[61, 67]		[32]		[32][e]	
HMA	ZnTe:O	[36, 62]	[36]	[37]		[36-38]	[37]	[36-38]	
	Ga(P,Sb)As:N	[39]	[39-42, 72]	[39]	[42]	[39-42]		[40, 41]	
Bulk with DLI	GaN:Cr,Mn	[44, 63]				[44][d]			
	GaAs:Ti		[43]			[43]			[43][e]
	CuGaS2:Sn,Fe	[45, 49]				[45][c]			
	CuInS2:Sn	[49]		[49]			[49]		
		On IB material				On IBSC prototype			

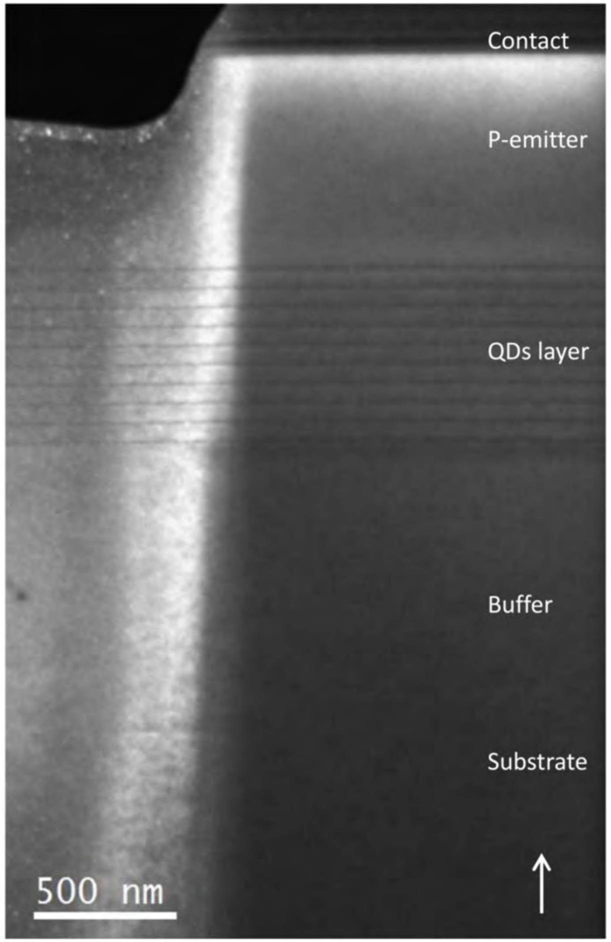
Quantum Dot IBSC processed at IES





(10 x InAs/GaAs QDs, p-i-n GaAs solar cell grown and processed at IES-UPM)





TEM pictures by U. Cádiz

POLITÉCNICA
Instituto de Energía Solar

Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

Alternatives to cristalline silicon technology

Conclusions

Conclusions

- **Silicon technology is dominating PV industry today**
- **Manufacturers choose the device structure reaching compromises between efficiency and fabrication cost**
- **With current technology, the energy invested in the fabrication of a PV system can be recovered in less than two years in South of Europe**
- **There are new concepts being explored which can significantly reduce the cost of the technology**
- **Photovoltaic solar energy is already competitive in some areas, and will reach broader competitiveness in the short run**

POLITÉCNICA

Instituto de Energía Solar

Developing PV

since 1979