Present and future of Photovoltaic Solar Electricity

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Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

Alternatives to crystalline silicon technology

Conclusions
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The photovoltaic (PV) industry

Continuous growth

Crystalline technology still dominant, but the share of other technologies is growing

Photon International 3/2011
Market still driven by public support, mainly in Europe, in particular in Germany
Solar cell production around the world

Production 2002

USA 21%
Japan 44%
Rest of Europe 16%
Malaysia 6%
Rest 6%
China 2%
Germany 9%

Production has moved recently to asiatic countries, specially China

Production 2011

China 57%
Japan 7%
Germany 7%
Rest Asia 4%
Rest Europe 2%
Taiwan 11%
Malaysia 6%
South Korea 3%
USA 3%
Rest 2%

Solar cell production: top ten

- Suntech (Ch)
- First Solar (USA)
- JA Solar (Ch)
- Yingli (Ch)
- Trina (Ch)
- Motech (Tw)
- Canadian (Ch)
- Hareon (Ch)
- SunPower (USA)
- Gintech (Tw)
Photons pump electrons from valence to conduction band
• Appropriate contacts insure conduction band electrons are delivered to load and recovered by the valence band
Design of solar cells

Cell is design to maximise the power delivered:

- Increasing generation of $e^- / h^+$ pairs (i.e., absorption of light)
- Reducing recombination (in bulk and surface)
- Minimising resistive effects
Increasing light absorption

✓ Texturing

✓ Anti-reflection coatings

✓ Texturing + anti-reflection coating $\Rightarrow R \leq 1\%$
Recombination losses

Crystalline defects and metal impurities produce recombination through traps:

- Use of high quality materials
- Fabrication in “clean rooms”
- Techniques to getter contaminant impurities
- Techniques to reduce recombination action of defects (hydrogenation)

Surface, a radical discontinuity in the crystal:

- “Passivation” of dangling bonds by deposition of dielectrics
- Diffusion of a dopant with the same type of the base (Back Surface Field)
Resistive losses

- Bulk and emitter resistances, subject to compromises (recombination, voltage...)
- Choice of appropriate metals (good contact, good conductivity)
- Contact resistance is reduced for highly doped silicon
- Design of metal grid subject to compromises (shadow, minimum finger width...)
Solar cell structures

Industrial

- “Solar grade” substrates
- Reduced number of process steps
- Screenprinted metallisation

EFFICIENCY $\approx 16$-$18\%$

Laboratory

- High quality substrate (Float Zone)
- Processed at “cleanroom”
- Photolithography and metallisation by evaporation in vacuum

EFFICIENCY $\approx 25\%$

Efficiency = \dfrac{\text{Electrical Power delivered}}{\text{Luminous Power received}}
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The Si value chain: from silica to systems

quartz → Reduction to metallurgical Si → Ultrapurification to polysilicon → Crystallisation → Wafering

carbon → Solar cell processing → Module assembly → System implementation
Metallurgical silicon production

• Reduction of quartz with carbon in an arc furnace \( \text{SiO}_2 + 2C \rightarrow \text{Si} + 2\text{CO} \)
• Product: metallurgical 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)

3HCl+Si (gm)→HCl₃Si+H₂
4HCl₃Si+H₂→Si (ge)+3SiCl₄+3H₂

• Raw materials: metallurgical silicon and HCl
• Product: Electronic grade silicon (99.9999999% pure)
• High energy consumption (100 kWh/kg)
Fluidized bed reactor

Distillation column

Polisilicon
The revolution in the Si feedstock market

- 2006-2007: Silicon shortage
  - Slow reaction of polysilicon producers to expand capacity
  - New entrants trying to acquire the technology
  - Intensive R&D on polysilicon purification for solar
The revolution in the Si feedstock market (2)

• 2009: Quick change of scenario towards oversupply
  - New capacity installed in a context of market slow-down
  - Pressure on new entrants, that need to demonstrate good material quality and low costs

• In the medium and long run:
  - PolySi production structure changing to a “distributed” one: ~5000 t of Si for a 1000 MWp PV plant
  - Technology changes when targeting “Solar Silicon”

Solar Silicon

Simplifying chlorosilane process
- Silane as volatile compound
- Alternatives to Siemens deposition system

Applying metallurgical steps
- Directional solidification
- Slagging
- Evaporation in vacuum
- …
Crystallisation

Very slow cooling of Si melt

Monocrystal growth

Multicrystal growth

Monocrystalline ingot

Multicrystalline ingot in blocks

Si (eg)

Crucible

Heat

Si melt

Xtal Si

Si melt (≥1500°C)
Wafering

Kerf losses of around 50%

0.2 mm
Solar cell processing (I)

Wafers 156 cm² p-type (B $10^{16}$ cm⁻³)

Cleaning and etching

Texturing

Cleaning

Phosphorus diffusion

Cleaning
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

Junction isolation

Plasma etch

Measure and classify

R ≅ 30%

CAR ≅ 10%

n ≅ 2; nd ≅ $\lambda$/4

Conductive paste

Cell

Politecnica
Solar cell processing for multicrystalline Si

Alternatives to alkaline texturing: acidic texturing, RIE,...

Integration of tailored gettering processes

Hydrogenation by Plasma-Enhanced Chemical Vapor Deposition during the SiNx AR coating
Automatic screenprinter

In-line furnace for firing

Diffusion furnaces

A solar cell factory
Module assembly (I)

Cell interconnection

Cu/Sn ribbon

Array of cells

Cell matrix

Automatic connection of cells
Module assembly (II)

Lamination:
Pressure at 100°C + Curing at 150°C:

*Cells are soaked in the flowing EVA, which becomes transparent and solidifies*
Off-grid installations

- PV Generator
- Power conditioning
- Battery
- DC Loads
- AC Loads
- Auxiliary generator
- Solar Home System
- Water pumping
- Isolated residential
Grid connected installations

PV Generator → Power conditioning → Grid

Instituto Energía Solar
Solar farms

PV Toledo, 1 MWp

Navarra, 9 MWp

Cuenca, 60 MWp

500 kWp Euclides©, Tenerife
BoS equipments

Batteries

DC/AC converters

Regulator
PV market breakdown (2007)
EPIA/Greenpeace, 2008

- Off-grid residential: 5%
- Off-grid industrial: 4%
- Consumer products: 1%
- Grid-connected: 90%
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Energy Pay Back Time (EPBT)

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

\[ EPBT = \frac{I_{\text{invested energy}}}{E_{\text{produced in a year}}} \]


Siemens module sc-Si SP75 (Knapp & Jester 2000)
Energy Pay Back Time (II)

Source: de Wild-Scholten, 26th European PVSEC, 2011
Evolution of technology price

Average PV module price in Europe

PV module learning curve

Steady reduction of PV price, closing the gap to competitiveness
Most major EU markets can reach competitiveness before 2020 under a mature market assumption
Advanced crystalline silicon technologies

HIT: Heterojunction with Intrinsic Thin layer (Sanyo)

- n-type wafers
- a-Si layers deposited at 200°C.
- Efficiencies at industrial level > 20%
- 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 > 22%
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Low cost approaches: Thin films

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

Direct fabrication of the module: layers are deposited and interconnected on the substrate (the glass, for instance)
Thin films: a-Si:H

- Energy gap: $E_G \approx 1.3-1.8$ eV
- Efficiency: $\eta \approx 7\%$
- Cost, maturity

<table>
<thead>
<tr>
<th>Commercial module</th>
<th>$\eta \approx 7%$</th>
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</thead>
<tbody>
<tr>
<td>Laboratory cell</td>
<td>$\eta \approx 12.1%$</td>
</tr>
<tr>
<td>Advantage</td>
<td>Cost, maturity</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Low stabilised efficiency</td>
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</tbody>
</table>
**Thin films: CIS y CdTe**

![Thin films diagram](image)

<table>
<thead>
<tr>
<th></th>
<th>CIS</th>
<th>CdTe</th>
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</thead>
<tbody>
<tr>
<td>$E_G \approx 1.1\text{eV}$</td>
<td></td>
<td>$E_G \approx 1.5\text{eV}$</td>
</tr>
<tr>
<td>Commercial module</td>
<td>$\eta \approx 12%$</td>
<td>$\eta \approx 10%$</td>
</tr>
<tr>
<td>Laboratory cell</td>
<td>$\eta \approx 20%$</td>
<td>$\eta \approx 17%$</td>
</tr>
<tr>
<td>Advantage</td>
<td>Higher efficiency</td>
<td>Lower cost</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Complex, scarcity of In</td>
<td>Scarcity and toxicity of Cd</td>
</tr>
</tbody>
</table>
High efficiency approach: PV concentration
High eff. approach: high concentration with GaAs cells

1,000 suns = 1 MW/m²
High efficiency approach: Third generation solar cells

• Tandem cell

Theoretical limit: $\eta=86.3\%$

Three junctions
$\eta=42\%$
High efficiency approach: Third generation solar cells (II)

- Intermediate Band Solar Cell

Theoretical limit: 63.3%
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• 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 will reach the competitive level in few years’ time
Summary of PV technologies

- tf-Si = thin-film silicon
- CIGSS = copper-indium/gallium-m-selenium/sulfur
- c-Si = wafer-type crystalline silicon
- X-tech = concentrator technology
- OSC = “organic” solar cells
- new concepts
- >2030: advanced versions of existing technologies & new conversion principles