Crystalline Silicon Solar Cells
- A Glance from Europe

Joachim John

Outline

• Introduction to IMEC

• Motivation Photovoltaic Solar Energy

• European Solar Energy Strategic Research Agenda

• IMEC Solar Energy

• Summary and Outlook
Introduction to IMEC

Statistics:
- Independent Belgian R&D institute
- Total Revenue (2006): 227 M€
- Personnel (2006): 1500
  - 330 visiting scientists and industrial residents
  - 220 PhD Students
- 35% non-Belgian, 51 nationalities
- Average age ≈ 35 years
- 1652 scientific papers, 139 invited, 97 patents filed

Infrastructure:
- 24,400m² offices and laboratories
- 5,200m² cleanroom I (200mm)
  - 1,750m² class 1
- 3,200m² cleanroom II (300mm)
  - Basic process: 90nm CMOS
- Pilot Lines
  - 300mm and 200mm silicon pilot line
  - solar cell pilot line
  - multi-chip-module pilot line
- Laboratories
  - Bio, Organic, RF, DSP
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Annual Revenue (M€)
- Total-revenue (NL)
- Total revenue (Flanders)

No. of scientific publications

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Motivation Photovoltaic's

Humanity’s Top Ten Problems for next 50 years

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

Energy Generation

- **Resources (what/how much)**
  - Conventional (coal, oil, gas, nuclear)
  - Renewable (solar, wind, water, geo, bio)

- **Cost (commercial)**
  - €/W (investment, amortization, materials, personal)

- **Environment (real costs)**
  - Coal, oil and gas: Social cost of coal (SCC)
  - Nuclear: (external costs)
    - storage of Plutonium waste (unsolved),
    - worst case scenario insurance (not existing),
    - decontamination of the nuclear power plant (not calculated)
Prices of coal, oil and gas increased from 2000-2005 factor 2-3, uranium factor 4.5

Source: Ministry for Environment, Germany (2007)

Impact on South Africa’s Biomes

Source: J. TURPIE et al, 2002

$\Delta T = 2.5^\circ C$
Consequential Costs

Caused by:
- Climate change
- Air pollution
- Water pollution
- Ground pollution

Increase of natural disasters 1950-2000

Consequential Costs

Increase and trend of economical damage of natural disasters 1950-2000

Source: Münchner Rück Insurance (2001)
Consequential Costs

In SA: 316Mt CO₂, 8.2 Tonnen CO₂ per person = Italy or France

Social cost of coal (SCC)

0.15 €/tCO₂ up to 3 €/tCO₂ *, (UK Department for Environment, Food and Rural Affairs - Defra)

Actual price of coal = 7ct/kWh,

* Downing et al. (2005)

Stock of Energy Source

Equivalent Stock of Energy Source

Annual Energy from the Sun

Uranium Natural Gas Oil Coal Annual Energy Demand

47 years* 62 years 64 years 200 years

Reasonably assured Resources (RAR)

* Red Book (NEA/OECD)
Change of the worldwide energy generation

Veränderung des weltweiten Energiemixes bis 2100

Source: scientific advice council of the federal government (Germany)

Renewable energy as a job motor

- 30,000 new jobs between 2000 and 2006 in Germany
- More jobs as in conventional energy industry together
Economy growth with less greenhouse gas emission

Decoupling Growth, Energy Consumption and Emissions

PV-market

Source: Federal Ministry of Economics and Technology, Germany 2006

Yearly Growth

Module Production

[Mwp/y]

1000

1500

2000

2500

500

0


Source: Maycock PV News

2006: 2.55 GW

World PV Growth (1989-2006)

Growth Rate

Module Production

Yearly Growth rate

20% 16% 19% 5% 4% 16% 12% 14% 42% 23% 36% 36% 33% 42% 68% 45%

40.2 46.5 55.4 57.9 60.1 69.6 66.6 125.8 154.3 201.3 287.7 390.2 525.2 742 1250 1818.

20% 20%

2006: 2.55 GW
### Present PV-technologies: terrestrial application

<table>
<thead>
<tr>
<th>Cell Technology</th>
<th>Type of junction</th>
<th>Lab efficiency [%]</th>
<th>Industrial efficiency [%]</th>
<th>Market share [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk crystalline Si solar cells</td>
<td>p-n homojunction</td>
<td>24.7</td>
<td>13 – 17</td>
<td>92</td>
</tr>
<tr>
<td>a-Si:H</td>
<td>p-n homojunction</td>
<td>13</td>
<td>6-7 single junction</td>
<td>5</td>
</tr>
<tr>
<td>(a-Si:H; a-SiGe:H; mc-Si)</td>
<td>p-n homojunction multijunction</td>
<td></td>
<td>9-10 multijunction</td>
<td></td>
</tr>
<tr>
<td>CuIn(Ga)Se$_2$(S$_2$)$_2$=CIS</td>
<td>p-n heterojunction with CdS</td>
<td>18.8</td>
<td>9 - 13</td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>p-n heterojunction with CdS</td>
<td>17</td>
<td>9 - 12</td>
<td></td>
</tr>
</tbody>
</table>

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A Strategic Research Agenda for PV Solar Energy Technology

Source: Photovoltaic Technology Platform, 2007

European Research Agenda

Source: European Technology Platform 2007
**European Research Agenda**

**Solar energy generation costs**

- **1980**: 2.00 Euro/kWh
- **2007**: 0.30 Euro/kWh
- **2015**: 0.06 Euro/kWh
- **2030**: 0.03 Euro/kWh
- **Long term**: 

Source: European Technology Platform 2007

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**Energy pay-back time**

- **1980**: 10 years
- **2007**: 2 years
- **2015**: 1 year
- **2030**: 0.5 years
- **Long term**: 0.25 years

Source: European Technology Platform 2007
European Research Agenda

Concentrator efficiency

- 10% in 1980
- 25% in 2007
- 30% in 2015
- 40% in 2030
- 60% long term

Source: European Technology Platform 2007

European Research Agenda

Flat-plate module efficiency

- 8% in 1980
- 15% in 2007
- 20% in 2015
- 25% in 2030
- 40% long term

Source: European Technology Platform 2007
Learning curve

1. Module price decrease by 20% for every doubling of the cumulative Production
2. Keeping the dynamics, 1$/Module price will be reached at 10GW cumulative production in 2008

Grid Parity in Europe 2010

![Map of Europe with grid parity irradiation and PV generation cost data]

- irradiation (kWh/m²-yr)
- PV generation cost ($/kWh)

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Generation Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.50</td>
</tr>
<tr>
<td>1000</td>
<td>0.30</td>
</tr>
<tr>
<td>1400</td>
<td>0.21</td>
</tr>
<tr>
<td>1800</td>
<td>0.17</td>
</tr>
</tbody>
</table>

 Courtesy of A. Jaeger-Waldau
 JRC, ISPRA
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SOLAR+ Roadmap: 1 sun

Silicon Solar Cell Program

- Thin crystalline Si (200 → 80 µm)
- Higher efficiency (15→20%) Si-ribbons
- Thin-film crystalline Si (<20 µm)

Organic Photovoltaics

- Consumer applications
- Ambient intelligence
- Higher efficiency
- Stability
- Large-scale application?

Direct cost (C/Wₚ) on module level

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.75</td>
<td>&lt; 0.5</td>
</tr>
</tbody>
</table>
Evolutionary scenario for crystalline Si PV

- Sustained decrease in active layer thickness
- Five technologies
- Only one major transition for introduction of each technology

Present value chain: Cell processing

- Wafer Cutting/Separation
- Saw damage removal + texturing
- POCl Diffusion
- Parasitic Junction Removal
- PECVD SiNx:H ARC layer
- Screen Printed Metallisation
- Co-firing

Average efficiency in production:
Multi ~ 15 %, Mono ~ 16 %
### IMEC solar cell scientific highlights 2007

- Concentrator cells
  - N+1
- i-PERC
- IBC
  - N+2
- Thin film
  - N+3

Presented at the

**22nd European Photovoltaic Solar Energy Conference and Exhibition, Milano, Italy 2007**

3000 participants and 520 Exhibitors

### Single junction GaAs solar cell on Ge substrate

**New world record efficiency achieved: 24.7%**

New world record efficiency achieved: 24.7%

- Device ID: S004
- Device Temperature: 25.0 ± 1.0 °C
- Device Area: 1.6cm²
- Spectral: AM1.5 G (IEC 989)
- Irradiation: 1000 W/m²

![Graph of current-voltage characteristics](image)

- $V_{oc} = 8.086 V$
- $I_{sc} = 7.396 mA$
- $P_e = 2.84 W$
- Efficiency = 34.67%

Achieved in ESA-IMAGER project, on germanium substrate with improved micro-defect distribution

Courtesy of Giovanni Flamand
i-PERC cells on very thin substrates

<table>
<thead>
<tr>
<th>Passivation stack</th>
<th>Local Al BSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 μm mc-Si</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (cm²)</th>
<th>J(sc) (mA/cm²)</th>
<th>V(sc) (mV)</th>
<th>FF (%)</th>
<th>Effic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i-PERC(best)</td>
<td>156</td>
<td>34.8</td>
<td>623</td>
<td>77.1</td>
</tr>
<tr>
<td>i-PERC (av)</td>
<td>156</td>
<td>34.5</td>
<td>623</td>
<td>77.0</td>
</tr>
<tr>
<td>Full Al BSF (av)</td>
<td>156</td>
<td>32.8</td>
<td>614</td>
<td>74.6</td>
</tr>
</tbody>
</table>

Stress-induced lift-off process

- Stress-induced lift-off process (1st layer transfer)
- Si substrate to be re-used
- Chemical stress-removal and bonding to alternative substrate (2nd layer transfer)

First solar cell

- J(sc) = 26.7 mA.cm⁻²
- V(sc) = 550 mV
- FF = 67.8 %
- R_series = 980 Ω.cm²
- R_shunt = 4300 Ω.cm²
- Efficiency = 10.0 %

Rear-side cell processing (IBC)
Simulation of stress-induced lift-off

Epi-free lift-off approach

- lift-off and transfer to glass using anodic bonding
- a-Si:H/c-Si heterojunction structure implemented on bonded layers
- Proof-of-concept cell!
### Crystalline Si solar cells: Benchmarking

<table>
<thead>
<tr>
<th>Technology</th>
<th>Uniqueness / recent achievements</th>
<th>Main competitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-PERC</td>
<td>Unique process (patented by IMEC) Closest to industrial implementation of all potential local-BSF approaches Highest efficiency results on thin large-area substrates (16.7%, 130 μm multi)</td>
<td>ISE (LFC), but their process still relies on high-quality thermal oxide at rear side</td>
</tr>
<tr>
<td>IBC</td>
<td>Link with manufacturer of ultra-thin ribbons (SolarForce) Rearside HIT-emitter</td>
<td>UKON, ISE, ECN</td>
</tr>
<tr>
<td>Epitaxial cells</td>
<td>Unique process based on porous Si reflector (patented by IMEC) and high-T CVD Highest efficiency results obtained on large area substrates – epitaxial emitter (14.9%)</td>
<td>ISE Uni.Neuchatel – Juelich microcrystalline Si (low deposition rates)</td>
</tr>
<tr>
<td>SionGlass</td>
<td>Best worldwide results obtained with AIC-process (patented for use on ceramics) –8% Highest efficiency potential for thin crystalline Si films on non-Si carrier</td>
<td>UNSW, HMI</td>
</tr>
</tbody>
</table>

### Summary

- **Face the challenge:**
  - Energy supply for 10 Billion people by using a carbon free and environment friendly energy generation

- **The answer can only come from renewable energy**

- **Industry has understood that renewable energy is a chance and not a threat**

- **Europe has defined a strategic research agenda**
  - Clear commitments to a carbon free economy based on renewable energy generation.

- **PV Aim:**
  - Reach grid parity as fast as possible by increasing the efficiency and reduce the cost of the solar cell.
Outlook

- **IMEC**
  - Backside passivation of thin bulk silicon solar cells
  - Thin film silicon solar cells
  - Innovative new concepts like quantum dots or nano structures

- **Europe**
  - PV Grid parity of whole Europe until 2030
  - System energy pay back time: 1 year (2015)
  - Turn key system price: 2.5 €/Wp (2015)
  - Solar energy generation cost: 0.15 €/kWh (2015)
  - Flat plate efficiency: 20% (2015)