Thin-film silicon solar cells: the « micromorph » option

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Outline

• History of PV (« Looking back »)
• Present status of PV
• Amorphous silicon
• Microcrystalline silicon
• Micromorph Tandem cells
History of Photovoltaics: « Looking back »

**Alessandro Volta,**
- Italian Physicist, from Como (Lombardy),
- Invented the Electric Battery in 1800

**Alexandre Edmond Becquerel,**
- French Physicist
- Observed, for the first time, in 1839, the interaction between light and electricity, which is the basis of the photovoltaic effect
Julius Elster and Hans Geitel

- High School Teachers in Wolfenbüttel (Germany)
- Built the first *Photovoltaic Solar Cell* around 1891, based on alkaline metals (Na, K, …)

Exhibition and Commemoration:
September 2007 to Jan 2008
www.elster-geitel.de
Researchers at Bell Laboratories, N.J. (USA)
• Built in 1953 the first photovoltaic solar cells based on Silicon (with an efficiency of 5%)

In 1954, the *U.S. News & World Report* wrote:
…..one day such silicon strips……
“may provide more power than all the world’s coal, oil and uranium”
Since the « Arab Oil Embargo » (1973),

- Many Countries (USA, AUS, J, EU, CH, India,.. ) have set up R&D programmes and built demonstration sites to encourage the use of Photovoltaics

- Photovoltaic (PV) module production has been steadily increasing, by 25 to 30 % per year

- PV Module prices have been steadily decreasing, by 5-7% per year
Photovoltaics: present status

Since the year 2000,

• Europe « wakes up »:
  Feed-in tariffs for electricity produced by Photovoltaic Modules, based on « actual generation cost »:
  - Germany, 2000
  - Spain, Italy, France, Greece,… (2006/2007),
  - Switzerland (2008)!

• European PV Industry
  starts a phase of rapid growth
Photovoltaics: present status

Today, solar electricity
• costs around 0.50 €/kWh (in CH)
• but has to compete on the grid-connected electric power market, where the kWh is often sold for less than 10 € Cents/kWh

Solar electricity therefore needs continued political support
And strong R&D support to be able to establish itself
Photovoltaics: present status

- Over 90% of today’s PV modules are Wafer-based Crystalline Silicon modules
- This technology has profited from the wide experience of Microelectronics Industry
- Excellent performance results are achieved

Such wafers/modules:
- are at present limited to rather small dimensions
- consume a large amount of production energy
- have energy payback times of several years

This technology is facing a supply problem with the high-purity silicon used as raw material

It is therefore re-assuring that we have today various alternative technologies
A technological alternative

Thin-film silicon (first, amorphous silicon) is one of the alternatives:

- Wide production and field experience
- Synergy with LCD display Industry
- Raw materials non-toxic and abundant
- Low energy payback times
- Flexible modules are possible
- Suitable for Building Integration

Low-temperature (≈200°C) plasma fabrication process

Low optical absorption in material
→ Light trapping needed in cells

Facade at the Bavarian Ministry for Environmental Protection (1993)
Amorphous silicon (a-Si:H) PV modules

- Roughness of Layers, such as Transparent contact layers (SnO$_2$, ZnO) leads to scattering and trapping of light

- Amorphous silicon suffers from initial light-induced degradation

  - **Stabilized module efficiencies only**
  
  $\approx 6-6.5\%$ (MHI, Kaneka, Schott Solar,…)

- Tandem and multi-junction cells can basically help increase efficiency by 1-2 %

- Triple-junction **flexible** modules with amorphous silicon-germanium alloys are available from Uni-Solar (USA)
Very-High frequency plasma enhanced CVD

- In 1985 we started our laboratory for amorphous silicon solar cells at IMT Neuchâtel.
- We had not enough funds to purchase commercial deposition equipment with the standard 13.56 MHz plasma excitation frequency. We had to build the deposition reactors ourselves. We therefore chose **80 MHz** as plasma excitation frequency.
- This was the beginning of the **Very High Frequency (VHF)** Plasma Deposition Technique (**Freq > 25 MHz**)
- VHF allows one to increase deposition rates and obtain up to 3 x higher fabrication throughputs. This means considerable savings in investment costs
- VHF is at present used by many Industries involved in the production of amorphous silicon modules
With VHF Plasma Deposition it became « easy » to produce high-quality *hydrogenated microcrystalline silicon (µc-Si:H)*

In 1995 IMT made the first microcrystalline cells with over 5% efficiency

- they have (almost) no light-ind. degrad.
- they absorb near-Infrared light (gap 1.1 eV)

Since then, many other labs have also started to study microcrystalline silicon

This form of thin-film silicon is complementary to amorphous silicon (gap 1.75 eV)

**Microstructure of p-i-n µc-Si:H solar cell**

Microcryst. Si is very complex: crystallites + amorphous phase + « cracks »!
The « micromorph » tandem:

μc-Si + a-Si → an « ideal » combination

- IMT pioneered in 1994 the μc-Si:H/a-Si:H or « micromorph » tandem
- Today, stabilized cell efficiencies of 11 to 12 % can be obtained with these tandems

→ In such a micromorph tandem, the solar spectrum is ideally shared between top (a-Si:H) and bottom (μc-Si:H) cell
μc-Si + a-Si → an « ideal » combination?

Maximum efficiency plot for tandem cells
Conditions: all photons above \( E_g \) absorbed \( V_{oc} \) & FF a/c to semi-empirical limits

Energy gaps \( E_g \) of μc-Si:H and a-Si:H form an almost ideal combination

Upper efficiency limit for micro-morph tandem cell:
\[ \eta > 30 \% \]


but we are today (11.7% stabilized eff.) still very far from upper limit (>30%) → WHY?
The «micromorph» tandem: µc-Si + a-Si

→ limitations in current $J_{sc}$

µc-Si
At present far too low
$J_{sc} \approx 23$-$25$ mA/cm$^2$
instead of 44 mA/cm$^2$
Solution: light trapping

a-Si
Individual cell (almost) OK
within Tandem: Problem!
(light trapping more difficult here)
Solution: Intermediate Reflector
between top and bottom cell

Maximum short-circuit current density $J_{sc}$ as a function of the gap $E_g$, for AM1.5
The « micromorph » tandem: \( \mu c\)-Si + a-Si

→ limitations in voltage \( V_{oc} \)

\( \mu c\)-Si

(500-600 mV : almost OK)

a-Si

Far below limit value

{0.9 V instead of 1.4 V}

Reason: \( E_F \) cannot be pushed by doping near to \( E_C/E_V \), due to amorphous structure (Bandtails)

No known way out !

Semi-theoretical limit for \( V_{oc} \) as a function of gap \( E_g \), for AM 1.5 illumination, calculated a/c to the diode equation with \( J_o=1.5\times10^5 \) A/cm\(^2\) x exp\((E_g/kT)\) reverse saturation current
The « micromorph » \( \mu c-Si + a-Si \) tandem: lab cells $\leftrightarrow$ theoretical **limits**

<table>
<thead>
<tr>
<th></th>
<th>equation</th>
<th>Lab cell</th>
<th>Limit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J_{sc} )</td>
<td>( \min{J_{top}, J_{bottom}} )</td>
<td>( \frac{23}{2} = 11.5 ) [mA/cm(^2)]</td>
<td>20 [mA/cm(^2)]</td>
</tr>
<tr>
<td>( V_{oc} )</td>
<td>( V_{top} + V_{bottom} )</td>
<td>0.9 + 0.5 = 1.4 Volt</td>
<td>1.4 + 0.6 = 2.1 V</td>
</tr>
<tr>
<td>FF</td>
<td>Average{FF(<em>{top}), FF(</em>{bottom}}}</td>
<td>Aver{65%,75%} = 70%</td>
<td>76%</td>
</tr>
<tr>
<td>( \eta )</td>
<td></td>
<td>11.5 %</td>
<td>32 %</td>
</tr>
</tbody>
</table>
The « micromorph » tandem: μc-Si + a-Si

• Stabilized Efficiencies obtained today:
  11 to 12 % for laboratory cells
  8 to 8.5 % for commercial modules
  (Kaneka, Sharp, …)

• $V_{oc}$ & FF have nearly reached highest possible values for a-Si:H

To obtain higher efficiencies:
• Improve light trapping by using better transparent contact layers and back reflectors with low losses and, thereby, increase $J_{sc}$
• Find new top cell design to increase $V_{oc}$ ?
Micromorph Production equipment

Several industries offer production equipment, originally designed for Liquid Crystal Display Production:

• OERLIKON successfully uses the KAI 1200, for simultaneous Plasma deposition of amorphous modules on twenty glass panels of 1.4 m² size; Deposition of micromorph modules is under development

• Applied Materials is currently developing plasma deposition for micromorph solar modules on 5.7 m² glass panels
Outlook

Thin-film silicon is economically and ecologically one of the most promising materials for future large-scale photovoltaics.

Low efficiencies are at present a limiting factor for a-Si based modules, with typical values of stabilized module efficiencies of 6 to 8% (commercially available).

With microcrystalline/amorphous (« micromorph ») tandem modules, one should be able to increase commercial efficiency to 10%, in the next 2 to 3 years.

Key equipment suppliers are entering the market, GWatts of production capacities announced by 2010.

Goal (2010-2012) are modules at a production cost < 1€/Wₚ, with an output power of 100 Wₚ/m² and an annual output energy (in Milano) of 100 kWh/m².
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Mont-Blanc and University of Neuchâtel at dawn

www.unine.ch/pv