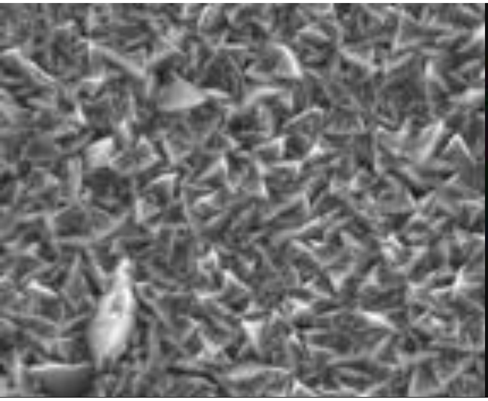
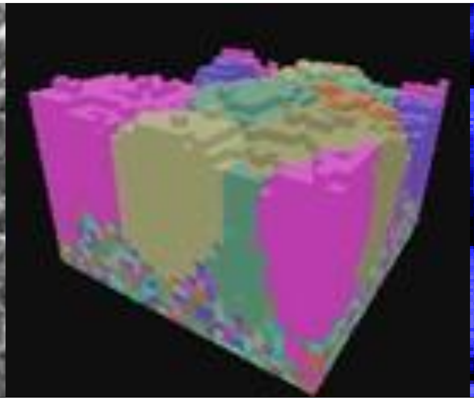
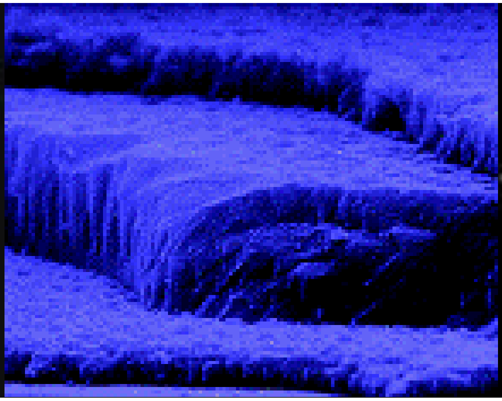
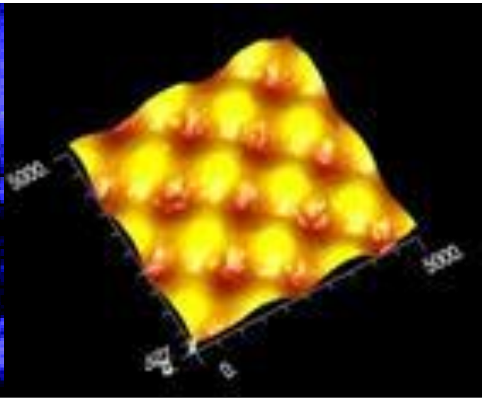
Thin-film silicon solar cells: the « micromorph » option

Arvind Shah
Institute of Microtechnology, IMT
University of Neuchâtel Switzerland

22nd European Photovoltaic Solar Energy Conference, Milano

Outline

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

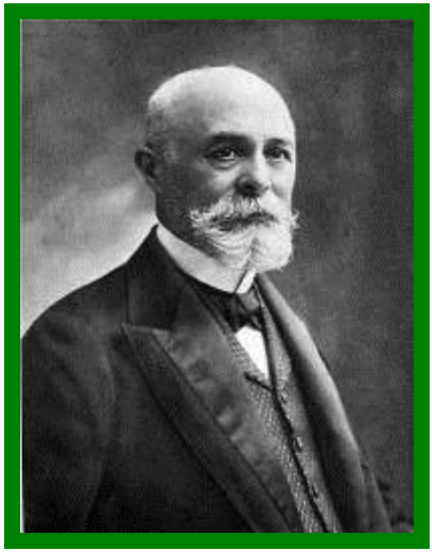
History of Photo*volta*ics: « Looking back »

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

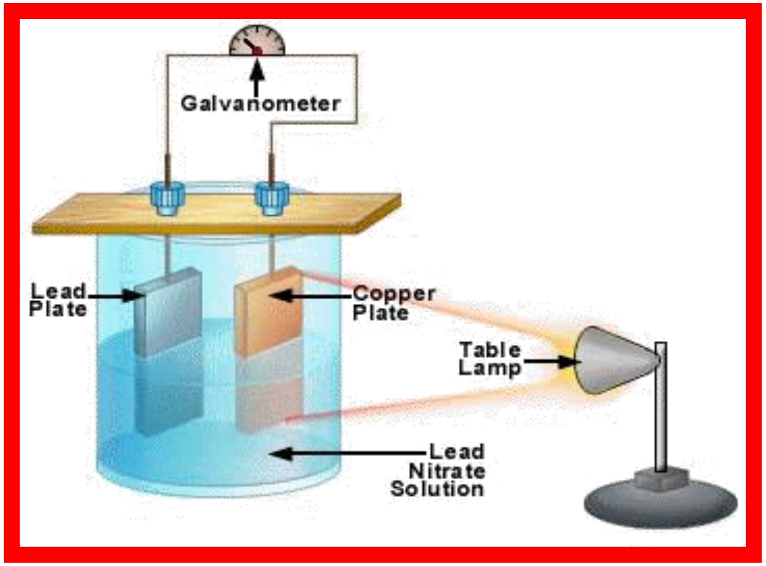


History of Photovoltaics: « Looking back »

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

History of Photovoltaics: « Looking back »

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"

History of Photovoltaics: « Looking back »

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 tarifs 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

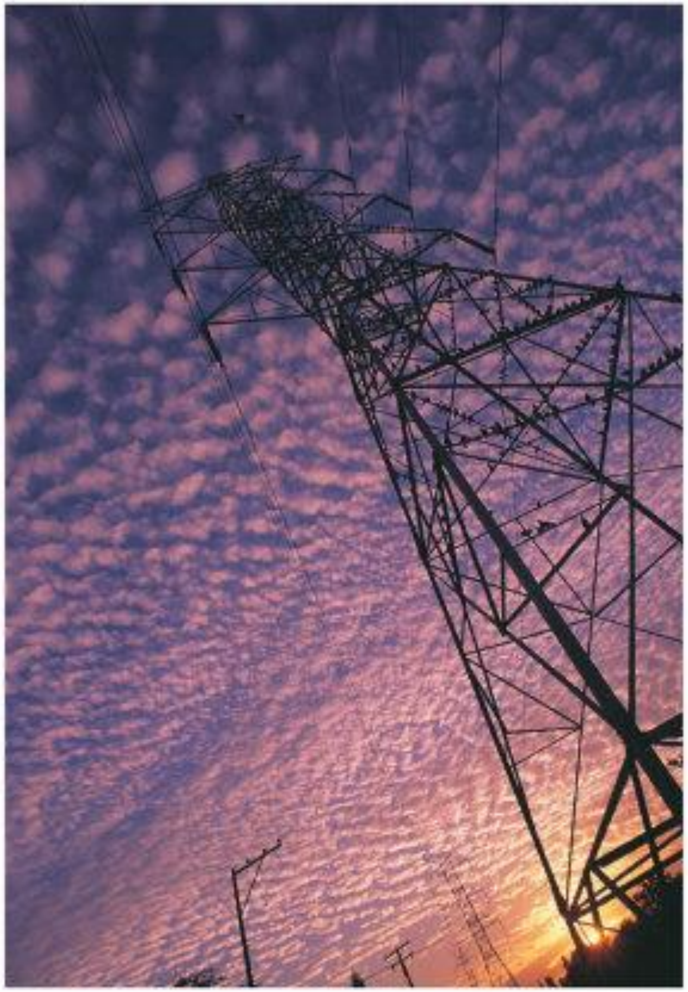
Photovoltaic Cell/Module Factory in Germany (Q-Cells)

Photovoltaics : present status

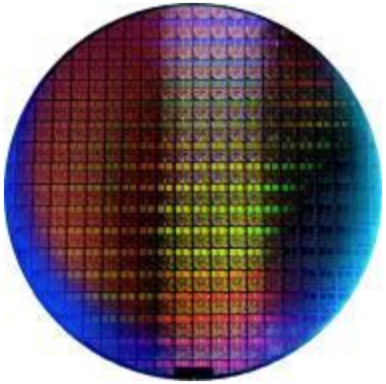
Today, solar electricity

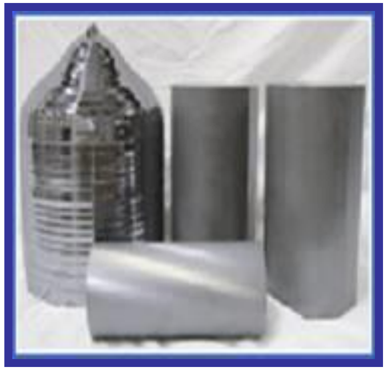
- costs around 0.50 €/kWh (in CH)
- but has to compete on the grid-connected electric power market, where the kWh is often sold for less than 10 € Cents/kWh

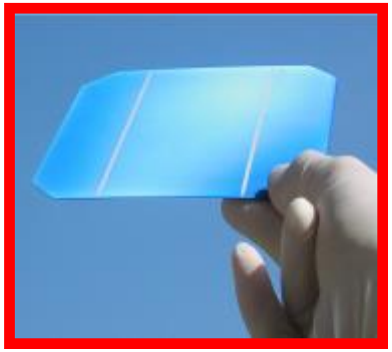
Solar electricity therefore needs continued political support And strong R&D support to be able to establish itself



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

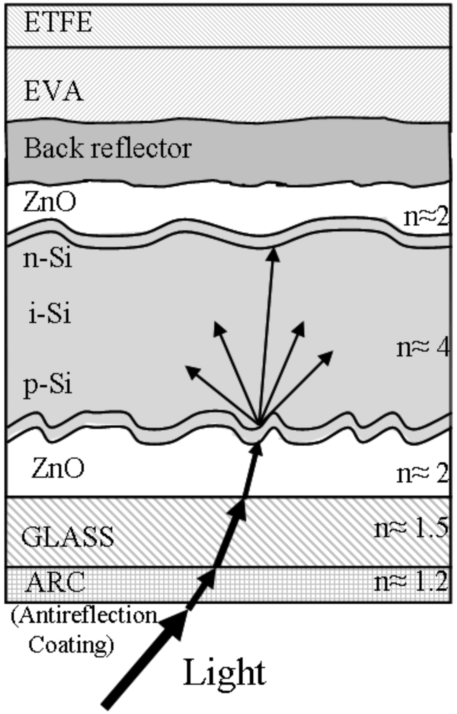
Low-temperature (≈200°C) plasma fabrication process

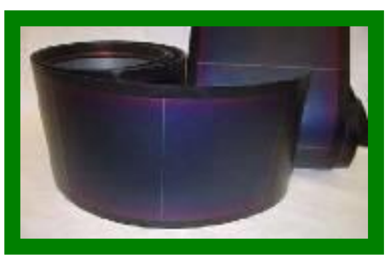
Low optical absorption in material

→ Light trapping needed in cells

Facade at the Bavarian Ministry for Environmental Protection (1993)

Amorphous silicon (a-Si:H) PV modules



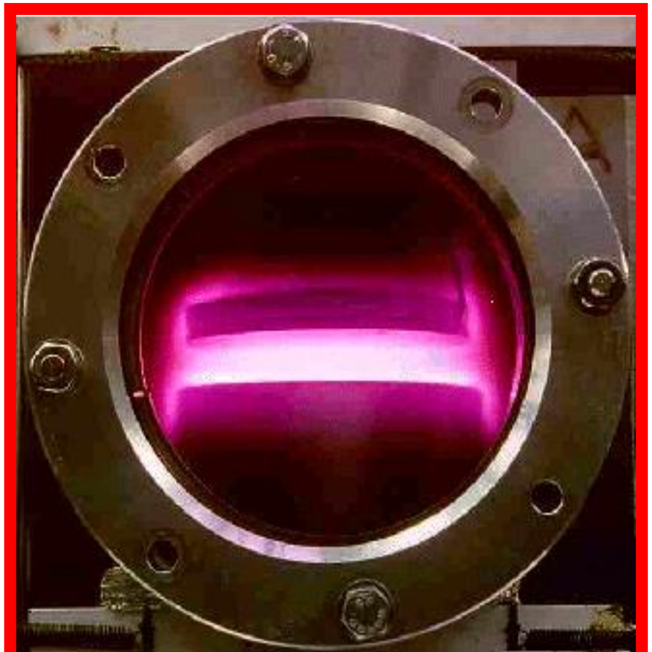


- Roughness of Layers, such as Transparent contact layers (SnO_2, ZnO) leads to scattering and trapping of light
- Amorphous silicon suffers from initial light-induced degradation

→ Stabilized module efficiencies only ≈ 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

Introduction of microcrystalline silicon (μc-Si:H)

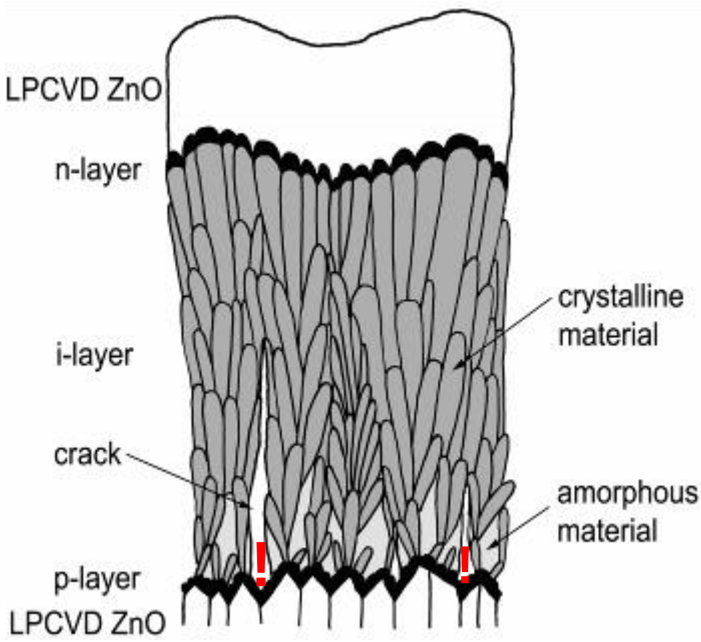
With VHF Plasma Deposition it became « easy » to produce high-quality **hydrogenated microcrystalline silicon (μc-Si:H)**

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

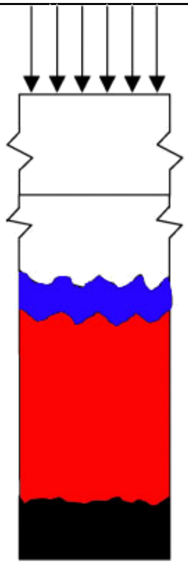
This form of thin-film silicon is complementary to amorphous silicon (gap 1.75 eV)

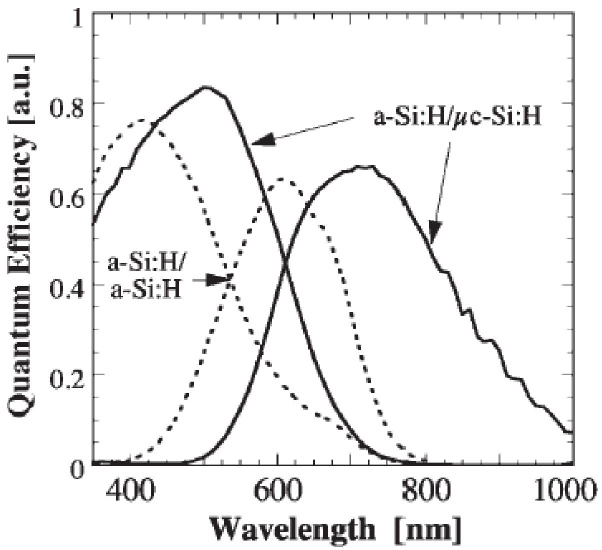


Microstructure of p-i-n μc-Si:H solar cell

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

The « micromorph » tandem:





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

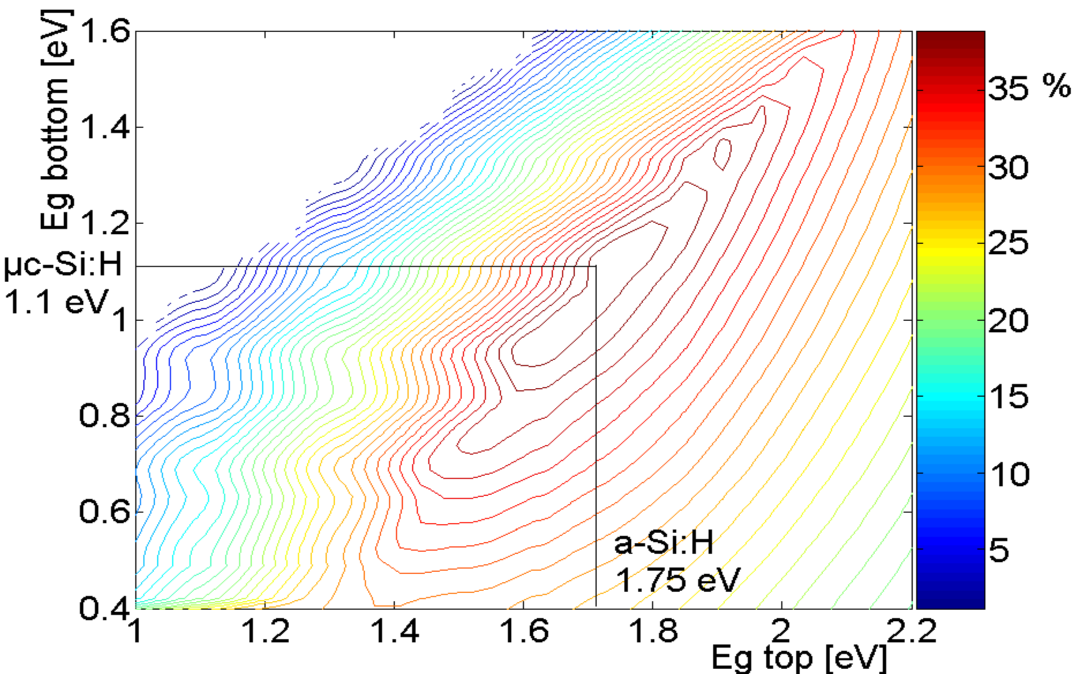
- IMT pioneered in 1994 the µc-Si:H/a-Si:H or « micromorph » tandem
- Today, stabilized cell efficiencies of 11 to 12 % can be obtained with these tandems

→ 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 Eg of μc-Si:H and a-Si:H form an almost ideal combination

Upper efficiency limit for micro-morph tandem cell:

η > 30 %

[A. Shah et al, J. of Non-Cryst. Solids, Vol 338-340C, pp 639-645.]

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/cm²
instead of 44 mA/cm²

Solution: **light trapping**

a-Si

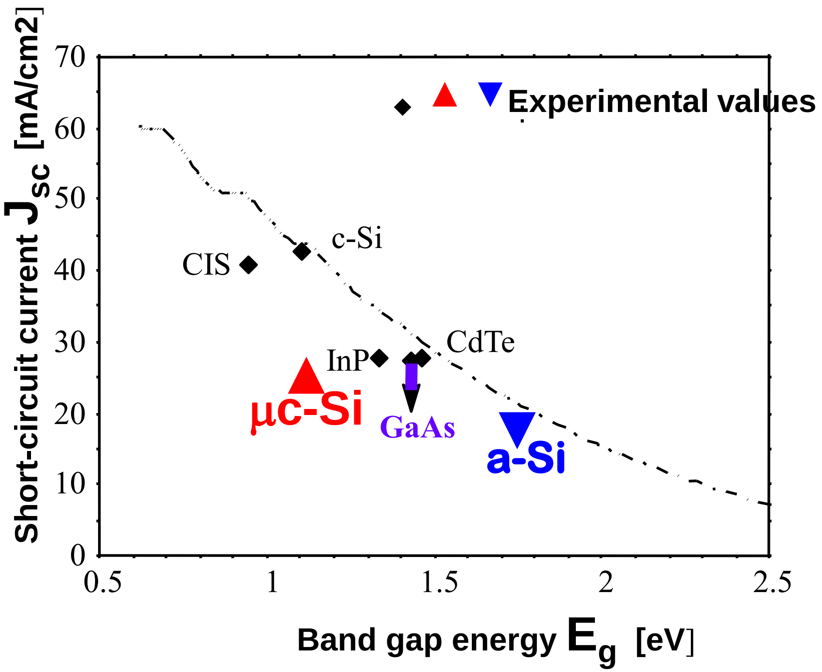
Individual cell (almost) OK

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 Eg, for AM1.5

The « micromorph » tandem: µc-Si + a-Si

→ **limitations in voltage V_{oc}**

µc-Si

(500-600 mV : almost OK)

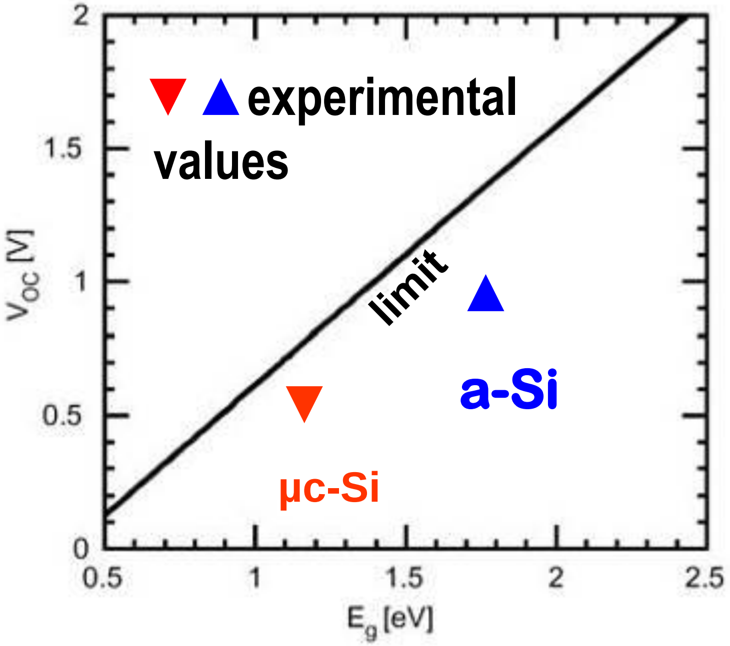
a-Si

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 !



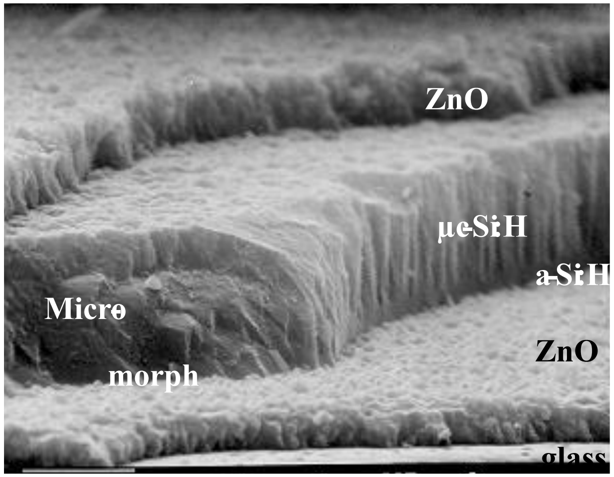
Semi-theoretical limit for V_{oc} as a function of gap E_g, for AM 1.5 illumination, calculated a/c to the diode equation with $J_o = 1.5 \times 10^5$ A/cm^2 x $\exp(-E_g/kT)$) reverse saturation current

The « micromorph » μc-Si + a-Si tandem: lab cells ↔ theoretical **limits**

	equation	Lab cell	**Limit** Value
J_{sc}	$\min\{J_{top}, J_{bottom}\}$	23/2 = 11.5 [mA/cm²]	20 [mA/cm2]
V_{oc}	$V_{top} + V_{bottom}$	0.9 + 0.5 = 1.4 Volt	1.4 + 0.6 = 2.1 V
FF	$\text{Average}\{FF_{top}, FF_{bottom}\}$	Aver{65%,75%} = 70%	76%
η		11.5 %	32 %

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 m^2 size; Deposition of micromorph modules is under development

• Applied Materials is currently developing plasma deposition for micromorph solar modules on 5.7m^2 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 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€/W_p, with an output power of 100 W_p/m^2 and an annual output energy (in Milano) of 100 kWh/m^2

Acknowledgements and Thanks

The work at IMT's PV Lab was financially supported by

- the Swiss Federal Government
  - Office féderal de l'énergie
  - Commission for Technology and Innovation (CTI)
- the European Commission
- IMT's Industrial Partners, especially:

IMT benefitted from close collaboration with many other groups:

Prague, Jülich, Konstanz, Polytechnique Paris, Princeton, AIST, …

With my deep thanks to :

All members of IMT's PV Team , since 1985, especially to
H. Curtins, H. Keppner, D. Fischer, J. Meier, N. Wyrsch, E. Vallat-Sauvain

…and my very best wishes to the present team under Christophe Ballif for the continuation of the work

Thanks for your attention

www.unine.ch/pv

Mont-Blanc and University of Neuchâtel at dawn