Innovative materials for micromorph solar cells

Lucia Vittoria Mercaldo
ENEA - Centro Ricerche Portici
Unità Tecnica Tecnologie Portici
Laboratorio MDB

L’ENEA e la ricerca di sistema elettrico: il fotovoltaico innovativo
ENEA CR Portici, 12 luglio 2011
Activities on advanced thin film Si PV

- Optimization of micromorph tandem cells by means of silicon oxide based intermediate and back reflectors;
- Development of innovative absorber layers for utilization in tandem cells;
- Evaluation of new architectures for an optical improvement of the thin film Si device performance;
- Development of appropriate substrates also with alternative techniques

Outline

- Advantages of thin film Si PV
- The micromorph structure
- Innovative n-doped layers
- Thinner simplified cells and mini-modules
- Micro-SiGe absorbers
- Si-ncs in dielectric matrix (SiNₓ, SiCₓ, SiOₓ)
Advantages of thin film Si PV

Very thin layers on appropriate supports.
No sawing loss of precious material.

Monolithic interconnections to form modules
Highly automated process: glass in – module out
Good outdoor performance at higher temperature.

Advantages of thin film Si PV

Energy Pay-back Time

\[ EPT = \frac{E_0}{E_g} \]

- \( E_0 \): Energy for manufacturing PV
- \( E_g \): Generated power by PV for one year

- Poly-crystalline silicon: 2.2 years
- Thin-film amorphous silicon: 1.6 years

Reduced energy production needs

- Production capacity (MW per year)
- Energy Pay-back Time (years)
Turn-key production lines on large area

1.4 m² solar modules
Lightweight and flexible products

Rome Trade Fair
1.4 MW
See-through capability

City Hall
Suzuka
Japan
See-through capability

City Hall
Suzuka
Japan
Micromorph tandem solar cells

Amorphous top cell + microcrystalline bottom cell

Advantages:

✓ The light-induced degradation typical of a-Si is effectively reduced
✓ Better utilization of the solar spectrum: the spectral sensitivity of the device is enlarged towards the near-infrared region
Gaps of $\mu$c-Si:H (1.1 eV) and a-Si:H (1.75 eV) form an almost ideal combination.

Upper efficiency limit for **micro-morph tandem** cell:

$\eta > 30\%$


Present **record efficiency: 11.9% (stabilized)** by Oerlikon Solar Lab, Switzerland (2010)
The light trapping issue

... to enhance the photocurrent of the top cell without increasing the thickness, thus improving the device stability!

Possible materials as intermediate reflectors:

- Zinc oxide ➔ Drawback: ex situ deposition
- Doped silicon oxide ➔ Very promising

P. Buehlmann et al., APL 91, 143505 (2007)
PECVD grown n-SiO$_x$:H films

Gas mixture: SiH$_4$, H$_2$, CO$_2$, PH$_3$ @ fixed doping ratio

<table>
<thead>
<tr>
<th>Series</th>
<th>H$_2$/SiH$_4$</th>
<th>Pressure (Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>100</td>
<td>1.9</td>
</tr>
<tr>
<td>N2</td>
<td>200</td>
<td>1.9</td>
</tr>
<tr>
<td>N3</td>
<td>200</td>
<td>3</td>
</tr>
</tbody>
</table>

Conductivity (S/cm)

Series H$_2$/SiH$_4$ Pressure (Torr)

N1 100 1.9
N2 200 1.9
N3 200 3

PECVD grown n-SiO$_x$:H films

Gas mixture: SiH$_4$, H$_2$, CO$_2$, PH$_3$ @ fixed doping ratio
Innovative n-doped layers

A simplification of the back contact/reflectors has been achieved

n-SiO$_x$:H in micromorph devices

P. Delli Veneri, L.V. Mercaldo, I. Usatii, to be published in Progress in Photovoltaics (2011)
Simplified cells with reduced thickness

**Goal:**
Realization of micromorph cells with thinner absorber layers and similar initial efficiencies (~ 11%).

### Performance Metrics
- **Area:** 1 cm²
- **$V_{OC}$:** 1.3 V
- **$J_{SC}$:** 12.1 mA/cm²
- **FF:** 71.9%
- **$\eta$:** 11.3%

#### Diagram Details
- **Simplified tandem cell** (no extra intermediate and back layers)
- **Thinner absorbers**
- **No IL**
- **No ZnO**
- **270 nm**
- **1.5 μm**
Micromorph mini-modules

obtained by scribing the sequential layers with appropriate lasers ($\lambda = 1064$ nm and $\lambda = 523$ nm)

- The laser cuts selectively remove narrow regions (30 – 130 $\mu$m) of a specific layer.
- Area loss due to scribing: 4%

$V_{oc} = 8.9$ V
$J_{sc} = 95.5$ mA
FF = 61.6%
$\eta = 8.4%$
µc-SiGe:H bottom absorber

µc-SiGe:H: more efficient infrared absorber

significant thickness reduction allowed

VHF-PECVD @ 100 MHz
Gas mixture: SiH₄, GeH₄, H₂

Costly GeH₄ is used in small amounts:
GeH₄/(GeH₄+SiH₄) = 5 – 15%

Increasing GeH₄/SiH₄
Nanostructured top absorbers

The discrete energy levels depend on the dot size.

Mighty Small Dots

... nanoscience and nanotechnology will change the nature of almost every human-made object in the next century.

—The Interagency Working Group on Nanotechnology, January 1999

LLNL - USA

Si and Ge QDs with size 1-6 nm
Nanostructured top absorbers

Si QDs in dielectric matrix

The discrete energy levels depend on the dot size.

With an array of closely spaced QDs the confined energy levels would overlap, forming minibands.

New materials made of “artificial atoms”

Tunable gap by changing the dot size.
Si-ncs in silicon nitride

PECVD grown a-SiNₓ films

Gas mixture: SiH₄ + N₂ @300°C

Si 2p XPS
@ Univ. of Catania

partial phase separation

Si4⁺
E = 102.89 eV
W = 2.04 eV

Si1⁺
E = 100.67 eV
W = 1.29 eV

Intensity (arb. units)
B.E. (eV)

18%
Si excess
11%

Annealing @1100°C formation of Si-ncs

EFTEM @ CNR IMM Catania


Optical properties

Films with different Si excess
Ellipsometry + PDS analysis

Sample A: ~30%
Sample B: ~57%

Optical model

Sample B annealed @1100°C
μc-Si

Sample A
Increasing $T_A$
1100°C --> 0

quantum confinement

Si-necs in silicon sub-oxide

EFTEM

LAADF-STEM

n doped SiO_x:H layers

Phase separated in as-grown condition

Si-necs density (x10^11 cm^-2 nm^-1)

diameter (nm)

A deposited @ 3 Torr
B deposited @ 1.9 Torr

TEM analysis @ CNR – IMM Catania

Conclusions

- Innovative SiO$_x$ based n-doped layers have been introduced.
- Thinner simplified micromorph cells and mini-modules have been developed [presently: $\eta=11.3\%$ (cells) & 8.4\% (modules)].
- Alternative bottom absorbers (μc-SiGe) are under study.
- Film of Si-ncs embedded in Si$_3$N$_4$ (after high-T annealing) and SiO (by low-T in-situ process) have been realized.