Photovoltaic convertors in thin film and nanoscale devices

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Séminaire organisé par l’ASPROM :
ÉNERGIE SOLAIRE PHOTOVOLTAÏQUE ET SON STOCKAGE
Technologies, enjeux et applications
Contents

• Introduction
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  ➢ Energy harvesting for wireless electronic devices
  ➢ Photovoltaic energy harvesting

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  ➢ Radial junction silicon nanowires cells and development
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• Conclusion
CEA organization

- R & D for nuclear energy
- Fundamental research
- Defense programs
- Technological Research for Industry

[Logos and text: CEA, Defense programs, Fundamental research, Technological Research for Industry, LETI, LIST, LITEN]
The key points of LITEN

Grenoble: Electrical transports & Nanomaterials
550 staffs

Chambery: Solar Energy & Building integration R&D
200 staffs

2009 Manpower
750 Staffs

Patents: 400 in portfolio
135 new patents in 2009

2010 Budget
120 M€
90 M€ turnover
30 M€ of CEA funding
Liten R&D focused

Electric Transports
- Electrical Powered
  - Batteries
  - Fuel Cells
  - Hybridation

Solar Energy & Buildings
- Solar energy
  - Solar PV, CSP, CPV
  - Electrical systems
  - Energetic efficiency

Biomass & Hydrogen
- Solid storage
  - H2 Production
  - H2 Storage
  - Uses

Large surface electronics

Nanomaterials
- μ-sources
- Energy recovery
- Organic electronics

Energy Harvesting Lab. Confidential information 24/11/2010
Energy harvesting for wireless electronic devices

System approach

Energy harvesting wireless sensing node
Wireless electronic devices

- Laptop computer
- Mobile phone
- Audio player
- Digital assistant
- Medical implant
- RFID tag
- Watch
- Calculator
Wireless sensor networks

Building
- Temperature sensors
- Humidity sensors
- Air quality sensors
- Light sensors
...

Industry
- Process temperature sensors
- Mechanical strain sensors
- Toxic gas sensors
...

Automotive
- Disc brake temperature sensors
- Tire pressure sensors
- Acceleration sensors
...

SenTec Elektronik
Photovoltaic cell principle

Open-circuit voltage $\sim 0.1 - 1$ V, depending on material bandgap and irradiance
### Light energy: what is available?

<table>
<thead>
<tr>
<th>Environment</th>
<th>Light source</th>
<th>Irradiance (mW/cm²)</th>
<th>Illuminance (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor</td>
<td>Sun</td>
<td>100</td>
<td>100,000</td>
</tr>
<tr>
<td>(clear sky at solar noon)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td>Sun</td>
<td>0.1 - 1</td>
<td></td>
</tr>
<tr>
<td>(usual lighting conditions)</td>
<td>Incandescent lamp</td>
<td>0.4 - 4</td>
<td>100 - 1000</td>
</tr>
<tr>
<td></td>
<td>Fluorescent lamp</td>
<td>0.04 - 0.4</td>
<td></td>
</tr>
</tbody>
</table>

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![Spectral irradiance graph](image-url)
The short-circuit current delivered by a photovoltaic cell is given by:

\[ J_{SC} = \int E(\lambda) R(\lambda) \, d\lambda \]

where \( E(\lambda) \) is the spectral irradiance and \( R(\lambda) \) the spectral response.

Materials

- Each material addresses a limited spectral range
- a-Si is adapted to applications with fluorescent lamps
- CIS is adapted to applications with sunlight and incandescent lamps

## Photovoltaic cell technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Bulk materials</th>
<th>Thin films</th>
</tr>
</thead>
</table>
|            | • Crystalline silicon wafers  
             • Multi-crystalline silicon wafers | • Inorganic: amorphous silicon, CdTe, CIGS  
                                           • Organic, dye sensitized |
|            | ![c-Si cell (~ 100 cm²)](image1)  
             ![c-Si module (~ 1 m²) for building integration](image2) | ![a-Si module on metal foil (~ 1 m²) for building integration](image3)  
                                           ![a-Si mini-module (~ 1 cm²) integrated in a calculator](image4) |
| Manufacturers | JA Solar, Suntech Power, Trina Solar, Yingli Green Energy (CN)  
                 Q-Cells, Solar World (DE)  
                 Kyocera, Sanyo, Sharp (JP)  
                 SunPower (US)  
                                                          Solems (FR)  
                                                          G24 Innovations (UK)  
                                                          First Solar, Global Solar, Konarka, Uni-Solar (US)  
                                                          Sunshine PV (TW) |
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• Photovoltaic activities at CEA Liten
  ➢ Strategy on thin film and “nano” photovoltaic generations
  ➢ CIGS development
  ➢ Radial junction silicon nanowires cells and development
  ➢ Silicon nanocrystal technology
  ➢ Partnership

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Thin film photovoltaic cell technology

Energy harvesting components: advantages of thin films over bulk materials
1) Thin-film deposition and monolithic interconnection techniques
   ➔ Easy miniaturization & integration
   ➔ High voltages on small area (series connection of a large number of cells on a small area)

2) Low material usage (film thickness < 5 µm) & low-cost substrates (glass, metal, polymer)
   ➔ Low cost technology

Module fabrication by monolithic interconnection
   ➔ easy miniaturization
In contrast, bulk crystalline Si modules are fabricated by connecting individual cells with metallic strings ➔ miniaturization is difficult
Thin film photovoltaic cell technology

Amorphous silicon thin film

CIGS thin film

Light

ZnO

Buffer layer (n type)

CIGS (p type)

Mo

Substrate
Thin film photovoltaic cell technology

Organic material thin film

Dye sensitized technology


G24 Innovations
### Thin film photovoltaic cell state of the art

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency under sunlight at 100 mW/cm²</th>
<th>Max power under fluo lamp at 1000 lux$^{2,3}$</th>
<th>Max power under fluo lamp at 200 lux$^{2,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lab best cells$^1$</td>
<td>Commercial modules$^2$</td>
<td></td>
</tr>
<tr>
<td>a-Si</td>
<td>10.1%</td>
<td>6 - 7%</td>
<td>≈ 35 µW/cm²</td>
</tr>
<tr>
<td>CIGS</td>
<td>19.4%</td>
<td>7% - 12%</td>
<td>≈ 30 - 35 µW/cm²</td>
</tr>
<tr>
<td>Organic</td>
<td>5.15%</td>
<td>1.5%</td>
<td>≈ 10 µW/cm²</td>
</tr>
<tr>
<td>Dye</td>
<td>10.4%</td>
<td>1.5%</td>
<td>≈ 15 µW/cm²</td>
</tr>
</tbody>
</table>


- a-Si gives the best performances for indoor conditions
- CIGS gives the best performances for outdoor conditions
- The CIGS performances for indoor conditions could be improved by increasing the bandgap (increasing the Ga/In ratio)
Efficiency of laboratory & commercial PV devices

Largest Potential for Improvement

- R&D Cell
- 2012 Module
- 2009 Module

a-Si, CdTe, CIGS, mc-Si, c-Si

Generation thin film
Generation bulk silicon

Veeco, Photon’s PV Production Equipment Conf. (2009)
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Photovoltaics at CEA LITEN

1st generation

- Bulk silicon
  - Crystalline Si
  - Multicrystalline Si
  - Metallurgical Si
  - Heterojunction

2nd generation

- Thin films
  - CIGS
  - CZTS
  - a-Si, a-SiGe
  - organic

3rd generation

- Nanomaterials
  - Si nanowires: radial junction
  - Si nanowires and Si nanocrystals: quantum effects
CEA LITEN strategy on TF and Nano generation PV

Energy conversion efficiency

Nano generation (tandem)
Quantum effect in Si nanostructure

Si nanocrystal
Si nanowire

Low-cost substrate
Low-cost substrate

25%
20%
15%
10%

TF generation:
a-Si, a-SiGe, CIGS, CZTS

Thin film
Low-cost substrate (glass, metal, plastics)

Low
High

Fabrication cost

Nano generation (single junction)
Radial junction Si nanowire

Low-cost substrate

Si nanowire

20%
15%
10%

Silicon generation

Crystalline silicon wafer

Low-cost substrate

Nano generation (single junction)
Radial junction Si nanowire

Low-cost substrate

25%
CIGS thin film technology

- Tunable band gap (In/Ga ratio)
- High efficiency (> 10% for commercial devices, up to 20% for best laboratory cells)
- Low cost (thin film technology)
CIGS thin film elaboration

Vacuum processes

PVD tool for CIGS deposition

CIGS absorber
Mo back contact

Wet processes

Screen Solar
Le PV multifonctionnel en couches minces
Wide bandgap CIGS cells

- CIGS bandgap can be tuned between 1.1 eV and 1.7 eV by adjusting In/Ga ratio
- Wide bandgap CIGS is useful for tandem architecture & indoor applications

Wide bandgap CIGS material (~1.35 eV) by an optimized co-evaporation process

- CIGS bandgap can be tuned between 1.1 eV and 1.7 eV by adjusting In/Ga ratio
- Wide bandgap CIGS is useful for tandem architecture & indoor applications

→ Open-circuit voltage 797 mV

→ Efficiency 15%

MRS Spring Meeting (2009)
CIGS mini-modules

<table>
<thead>
<tr>
<th>25 cm² module (5 cells in series, interconnection by wire bonding)</th>
<th>Halogen desk lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage at the MPP</td>
<td>1.5 V</td>
</tr>
<tr>
<td>Maximum power</td>
<td>14 mW</td>
</tr>
</tbody>
</table>

→ The mini-module was used as a proof-of-concept device, for developing power management electronics

→ The mini-module has been successfully integrated into a demonstrator of wireless audio player

→ When illuminated by a desk lamp, the mini-module supplies enough power to run the audio player without any battery
CIGS mini-modules

10 cm\(^2\) module
(14 cells in series, monolithic interconnection) | Fluo office lamp
---|---
Voltage at the MPP | 2.3 V
Maximum power | 51 µW

Preliminary results

Work in progress:

- Monolithic interconnection by chemical etching process, for increasing cell number and therefore obtaining higher voltage

**CEA LITEN patent pending**

- Increasing CIGS bandgap, for better matching to fluorescent light spectrum

- Integration of the module into a demonstrator of wireless sensor (temperature, CO\(_2\))

Micro-energy source

- PV module (CIGS thin film)
- Power management
- Battery (Li-ion thin film)

Wireless sensor
Radial junction silicon nanowire technology

- High efficiency (> 15%)
  - Enhanced optical absorption of silicon nanowire arrays
  - Effective extraction of photogenerated charges in the radial junction configuration
- Low cost
  - Low silicon material usage
  - Metal substrate
<table>
<thead>
<tr>
<th>Group</th>
<th>Substrate</th>
<th>Nanowire (or microwire)</th>
<th>Radial junction</th>
<th>Front contact</th>
<th>Energy conversion efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. Tsakalakos, General Electric, Appl. Phys. Lett. 91, 233117 (2007)</td>
<td>Metal</td>
<td>CVD</td>
<td>a-Si by PECVD</td>
<td>ITO by PVD</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Metal grid</td>
<td>1.8 cm²</td>
</tr>
<tr>
<td>P. Yang, Univ. California, Berkeley, J. Am. Chem. Soc. 130, 9224 (2008)</td>
<td>c-Si</td>
<td>Wet etching (AgNO₃ + HF)</td>
<td>c-Si by CVD + RTA</td>
<td>Metal grid</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 cm²</td>
</tr>
<tr>
<td>H. A. Atwater, CalTech, 33rd IEEE Photovoltaic Specialist Conf. (2008)</td>
<td>c-Si</td>
<td>RIE</td>
<td>Diffusion</td>
<td>Point contact</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.04 cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 cm²</td>
</tr>
<tr>
<td>P. Yang, Univ. California, Berkeley, Nano. Lett. 10, 1082 (2010)</td>
<td>c-Si</td>
<td>RIE</td>
<td>Diffusion</td>
<td>Metal grid</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25 cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.07 cm²</td>
</tr>
</tbody>
</table>
Growth of Si nanowires by CVD with high pattern fidelity

California Institute of Technology
SiCl₄ 1000°C

CEA Liten
SiH₄ + HCl 650°C
(potentially 400°C)

The use of SiH₄ + HCl instead of SiCl₄ allows to reduce the growth temperature

Growth temperature becomes compatible with low-cost substrates (glass, metal)

In-situ doping from B2H6 and PH3

EUPVSEC (2010)
Formation of radial junction by CVD

Shell: conformal $n$-type Si layer

Core: $p$-type Si nanowire

BF-STEM imaging of a radial junction Si nanowire (cross-section view)

Deposition of a conformal $n$-type Si layer for forming the radial junction
First results on aluminium-catalysed Si nanowires

Very high growth rate (about 2 µm/min)
For comparison, for obtaining vertical nanowires at similar temperature with gold catalyst, the maximum growth rate is about 0.2 µm/min

« Native » p-type doping level
Si nanocrystal Technology

European SNAPSUN project

- Tunable band gap (quantum confinement effects in silicon nanocrystals)
- High efficiency (>25%)
  - Tandem architecture
  - Crystalline silicon nanoparticle absorber
  - Semi-conductive host matrices (SiC, ZnO, In$_2$O$_3$)
- Low cost (low-temperature vacuum & wet processes)
Low-temperature processes for silicon nanocrystal elaboration

Vacuum nanotechnology

- nc:Si process
  - CVD Gas process for particle nucleation
  - CVD Gas process for host deposition

- host process

Atmospheric pressure nanotechnology

- c:Si synthesis + host precursor
  - Colloidal nanocrystals + TCO precursor

- Liquid injection head
  - Substrate chuck in atmospheric pressure

- Host PVD target
  - Nanoparticle source

- Substrate spin chuck

Vacuum nanotechnology

- Substrate chuck in CVD chamber

Atmospheric pressure nanotechnology

- Liquid injection head

- Substrate chuck in atmospheric pressure

- Substrate spin chuck
CEA LITEN main partners on TF and Nano generation PV

Academic partners

Suppliers

BIPV

Wireless electronics
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• Conclusion
Conclusion

• Thin films and nano technologies will be competitive when the conversion efficiencies will go over 13% on large area
  - Cost-effective,
  - High throughput

• Configuration of PV cells depending on application and its environment: building ≠ mobile electronic

• Large panel of application: autonomous sensors