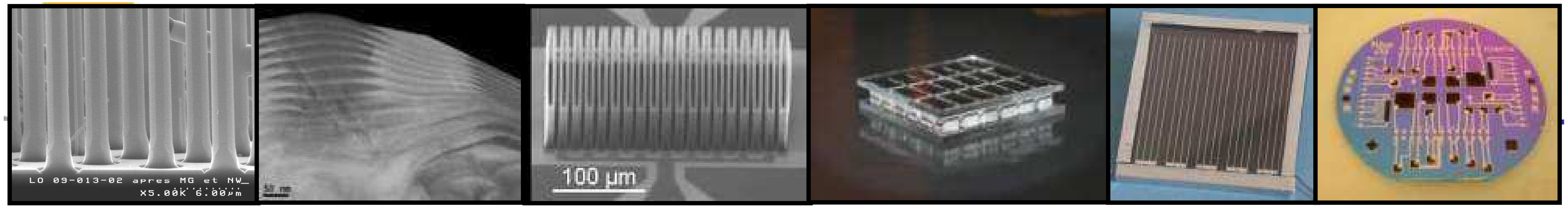


Photovoltaic convertors in thin film and nanoscale devices

Simon Perraud and Emmanuelle Rouvière

CEA LITEN, Grenoble, France

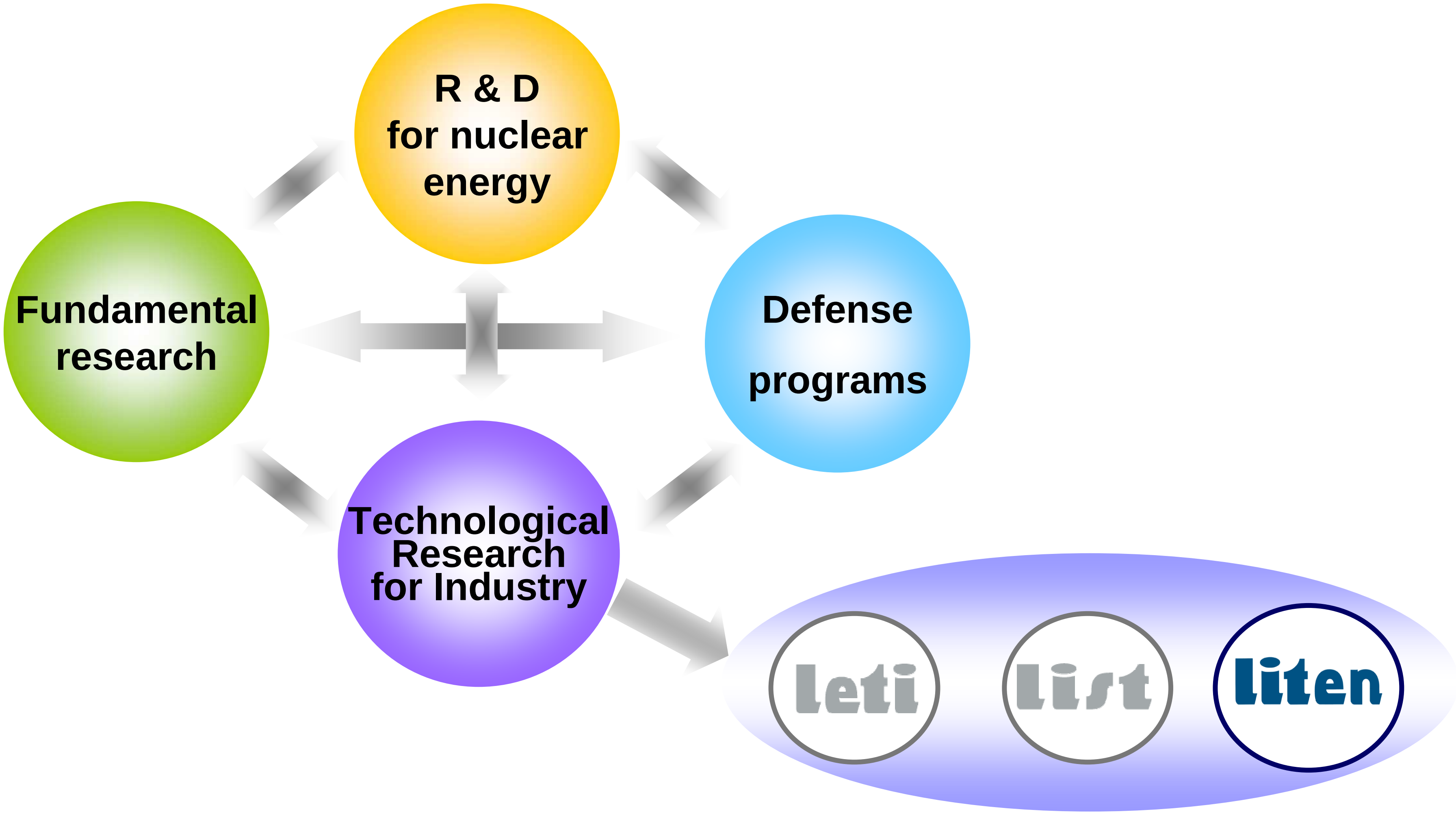
Séminaire organisé par l'ASPROM :

ÉNERGIE SOLAIRE PHOTOVOLTAÏQUE ET SON STOCKAGE

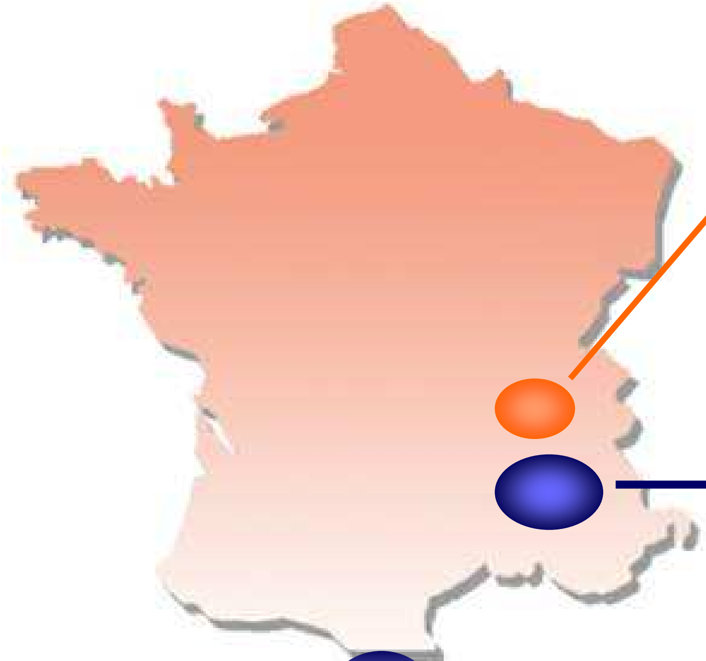
Technologies, enjeux et applications

Contents

CEA organization



The key points of LITEN



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

Grenoble : Electrical transports & Nanomaterials

550 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

INES
INSTITUT NATIONAL DE L'ENERGIE SOLAIRE

Biomass & Hydrogen

Solid storage

H2 Production
H2 Storage
Uses

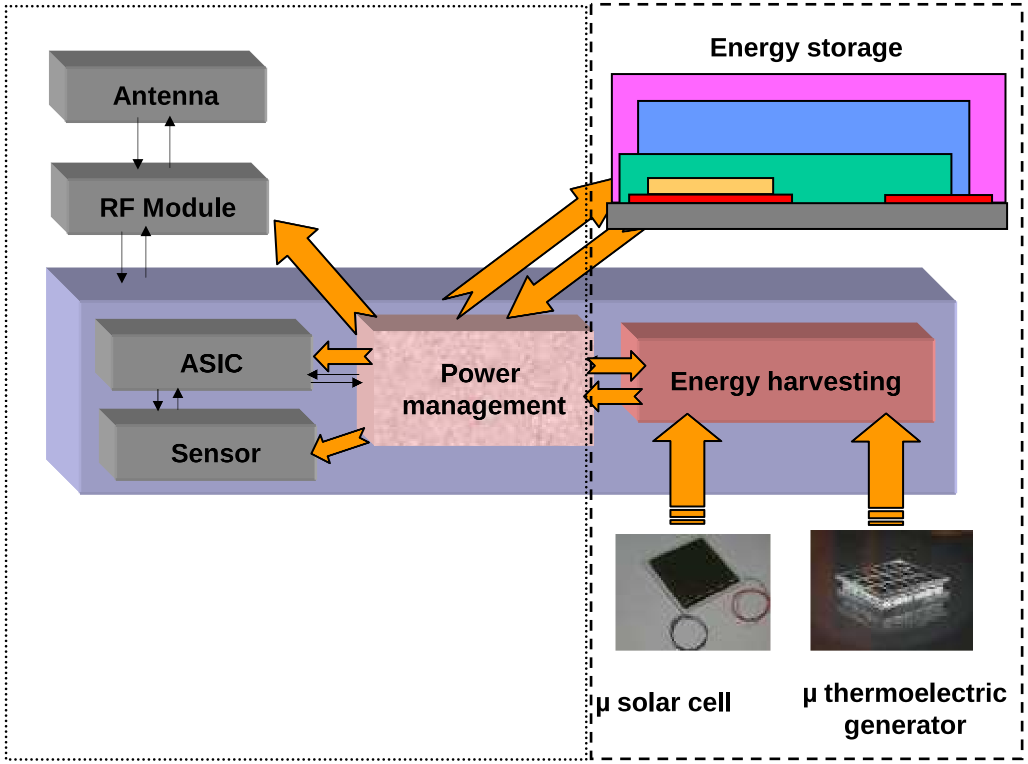
Large surface electronics

Nanomaterials

µ-sources
Energy recovery
Organic electronics

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

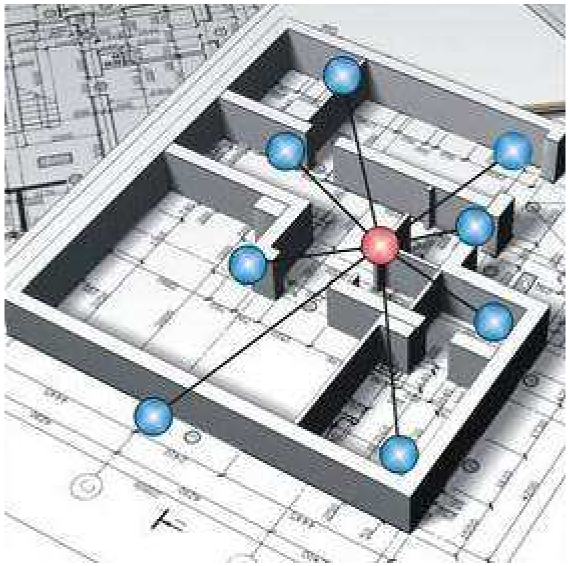
- Process temperature sensors
- Mechanical strain sensors
- Toxic gas sensors

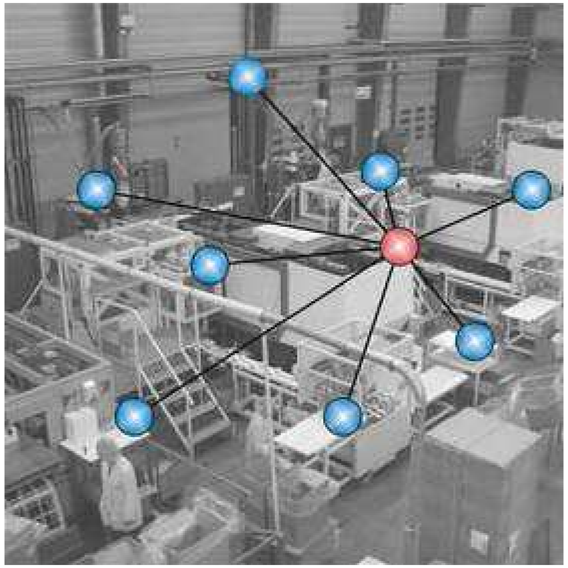
…

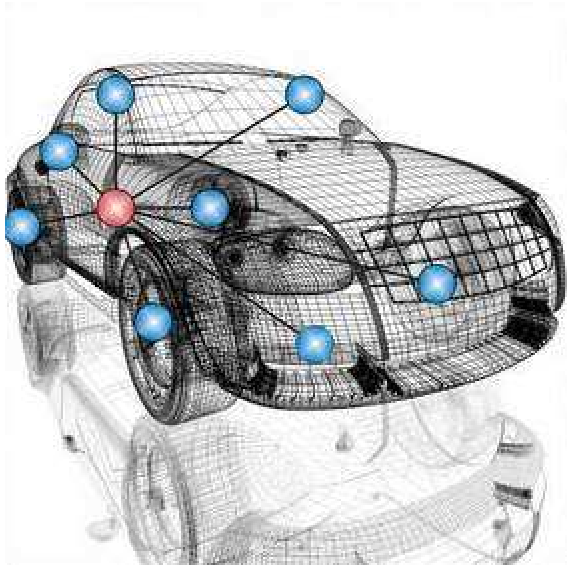
Automotive

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

…







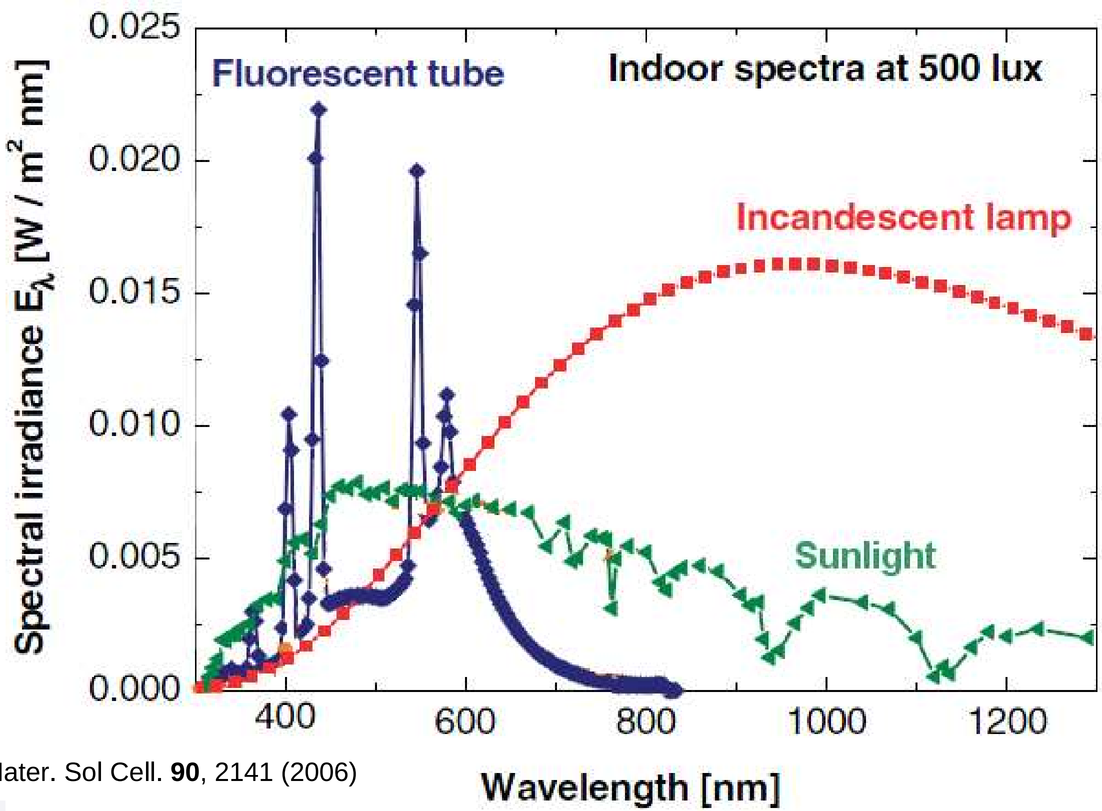
SenTec Elektronik

Photovoltaic cell principle

Open-circuit voltage ~ 0.1 - 1 V, depending on material bandgap and irradiance

Light energy: what is available?

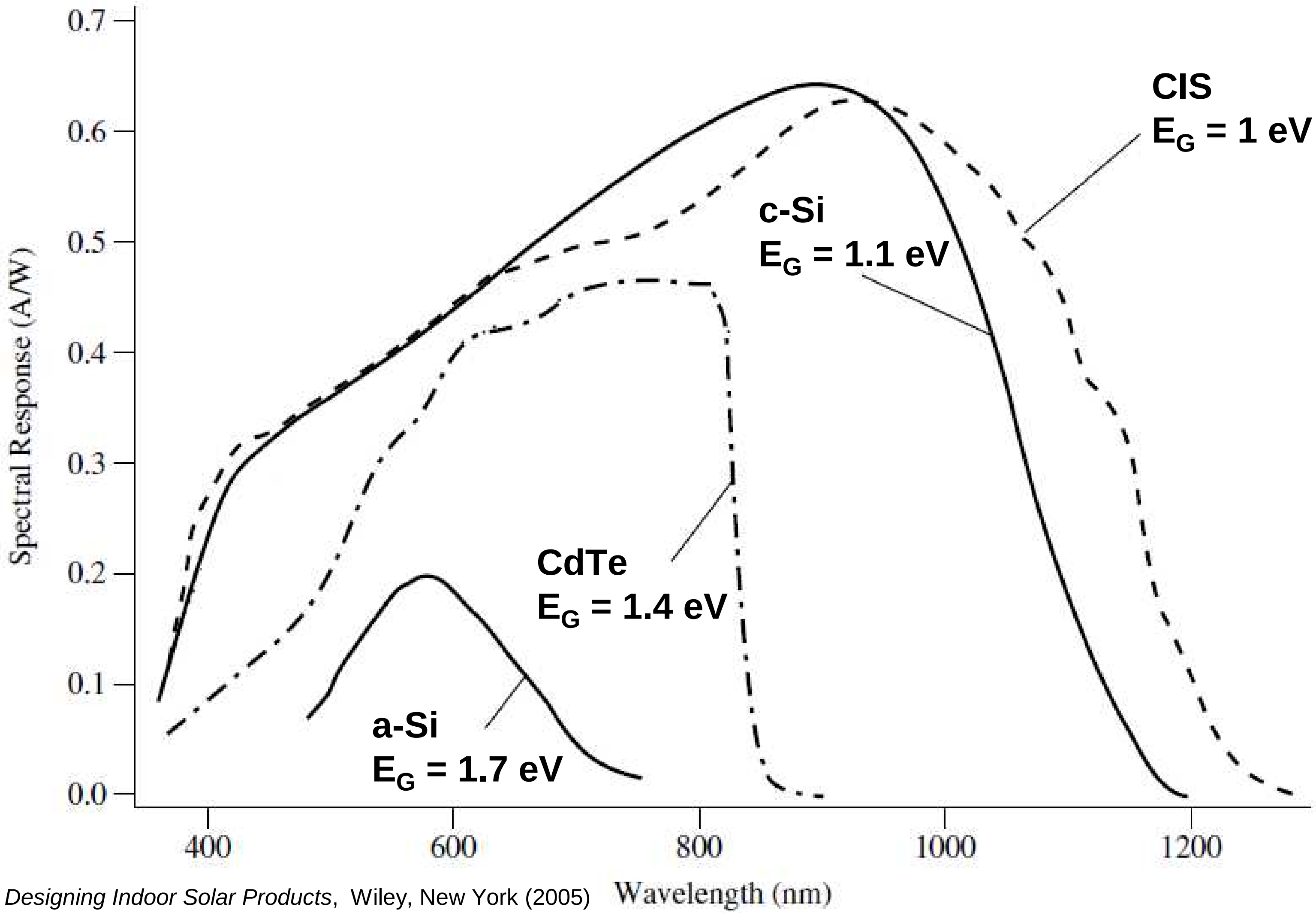
Environment	Light source	Irradiance (mW/cm²)	Illuminance (lux)
Outdoor (clear sky at solar noon)	Sun	100	100,000
Indoor (usual lighting conditions)	Sun	0.1 - 1	100 - 1000
	Incandescent lamp	0.4 - 4	
	Fluorescent lamp	0.04 - 0.4	



A. Virtuani *et al.*, Sol. Energy Mater. Sol Cell. **90**, 2141 (2006)

Materials

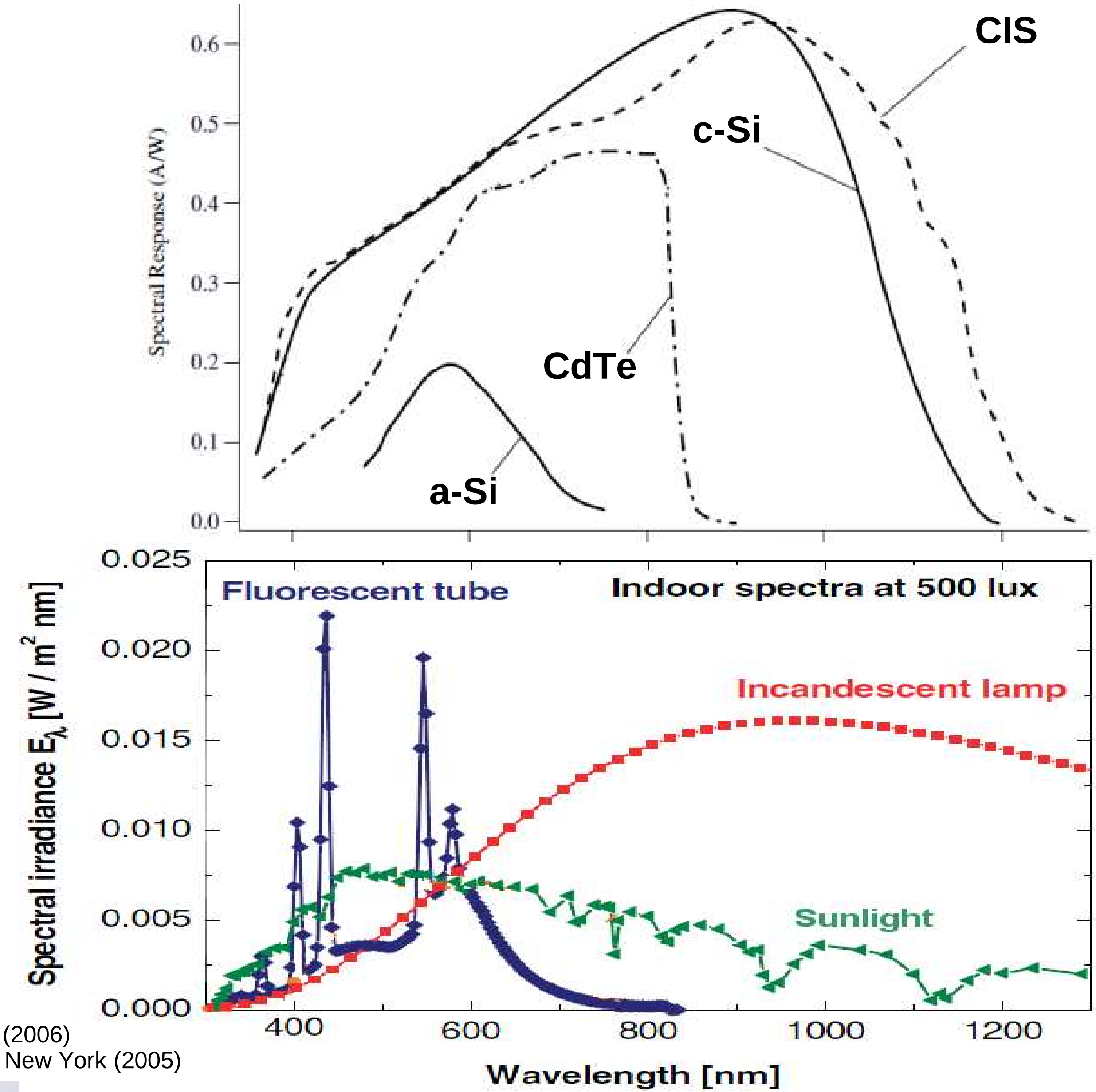
The short-circuit current delivered by a photovoltaic cell is given by:
$J_{SC} = \int E(\lambda)\, R(\lambda)\, d\lambda$ where $E(\lambda)$ is the spectral irradiance and $R(\lambda)$ the spectral response



J. F. Randall, *Designing Indoor Solar Products*, Wiley, New York (2005)

Materials

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



A. Virtuani *et al.*, Sol. Energy Mater. Sol Cell. **90**, 2141 (2006)
J. F. Randall, *Designing Indoor Solar Products*, Wiley, New York (2005)

Photovoltaic cell technology

	Bulk materials	Thin films
	• Crystalline silicon wafers • Multi-crystalline silicon wafers	• Inorganic: amorphous silicon, CdTe, CIGS • Organic, dye sensitized
Technology	 c-Si cell (~ 100 cm²)  c-Si module (~ 1 m²) for building integration	 a-Si module on metal foil (~ 1 m²) for building integration  a-Si mini-module (~ 1 cm²) integrated in a calculator
Manufacturers	JA Solar, Suntech Power, Trina Solar, Yingli Green Energy (CN) Q-Cells, Solar World (DE) Kyocera, Sanyo, Sharp (JP) SunPower (US) Gintech, Motech Solar, Neo Solar Power (TW)	Avancis, Bosch Solar, Q-Cells, Schott Solar, Würth Solar (DE) Solems (FR) Kaneka, Honda Soltec, MHI, Sanyo, Sharp, Solar Frontier (JP) G24 Innovations (UK) First Solar, Global Solar, Konarka, Uni-Solar (US) Sunshine PV (TW)

Contents

Thin film photovoltaic cell technology

Energy harvesting components: advantages of thin films over bulk materials

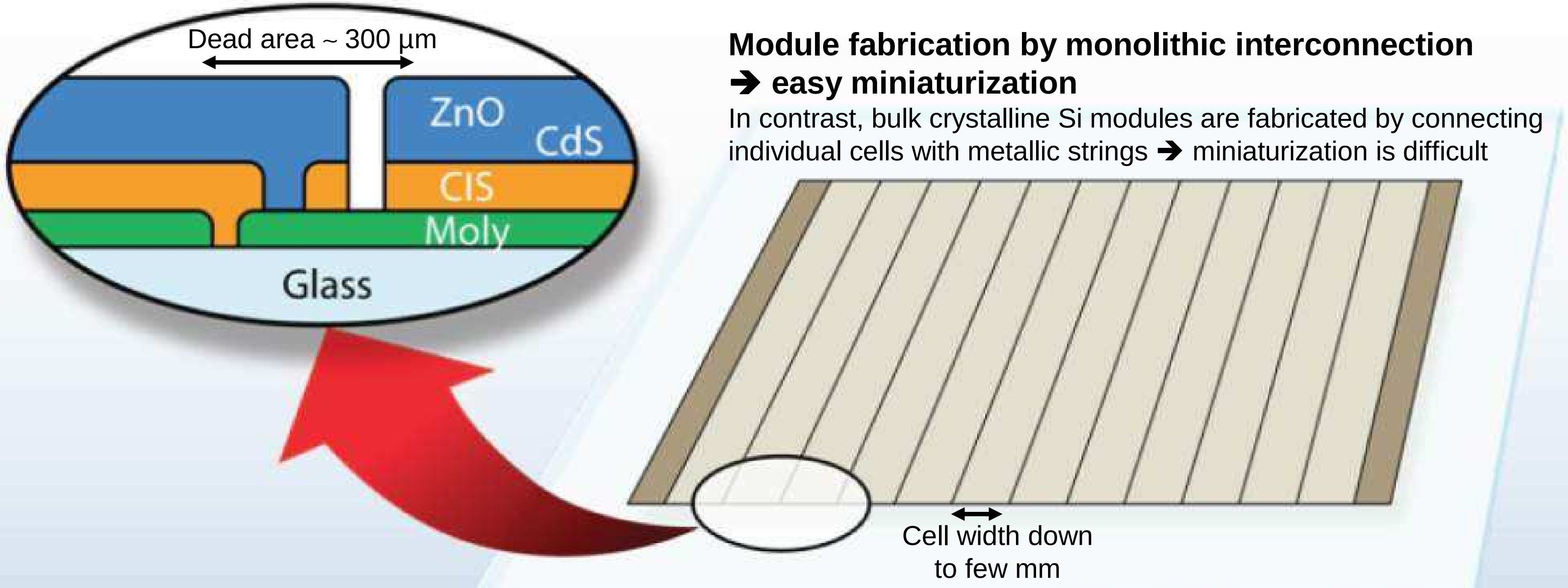
1) Thin-film deposition and monolithic interconnection techniques

➔ 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



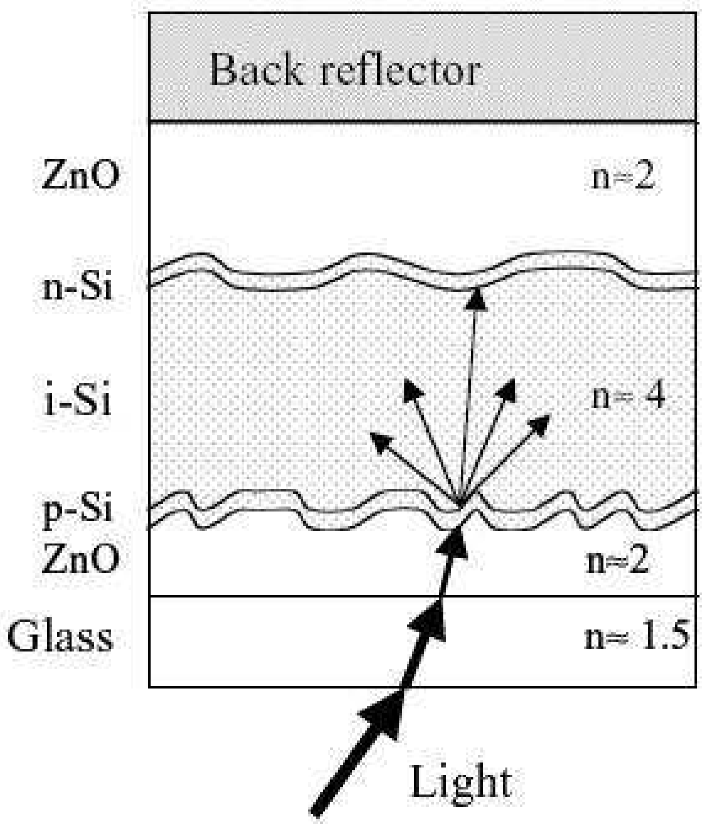
Courtesy of Dale Tarrant, Shell Solar

Module fabrication by monolithic interconnection
➔ easy miniaturization

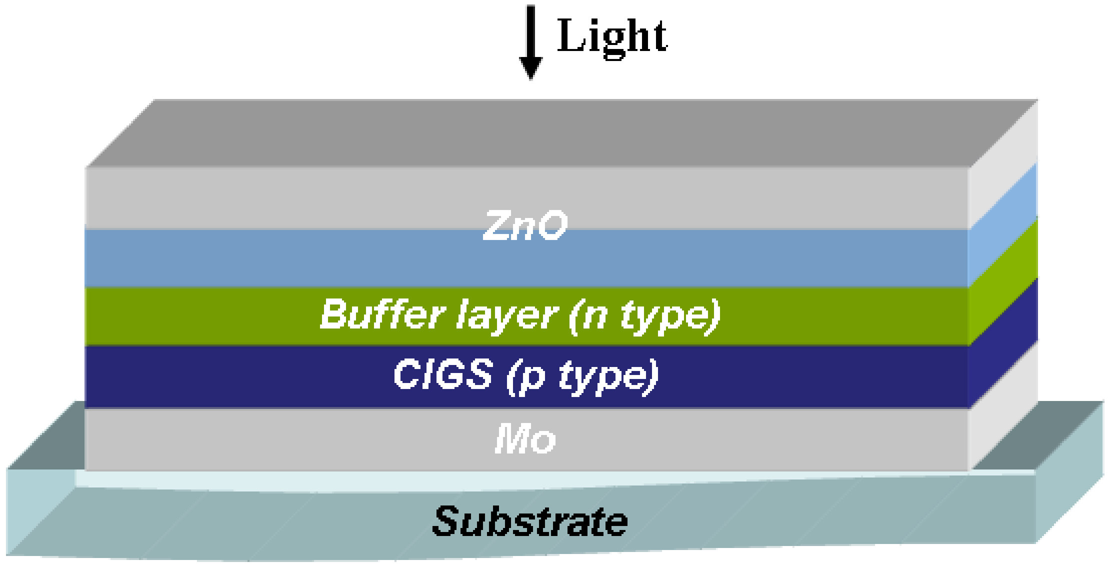
In contrast, bulk crystalline Si modules are fabricated by connecting individual cells with metallic strings ➔ miniaturization is difficult

Thin film photovoltaic cell technology

Amorphous silicon thin film

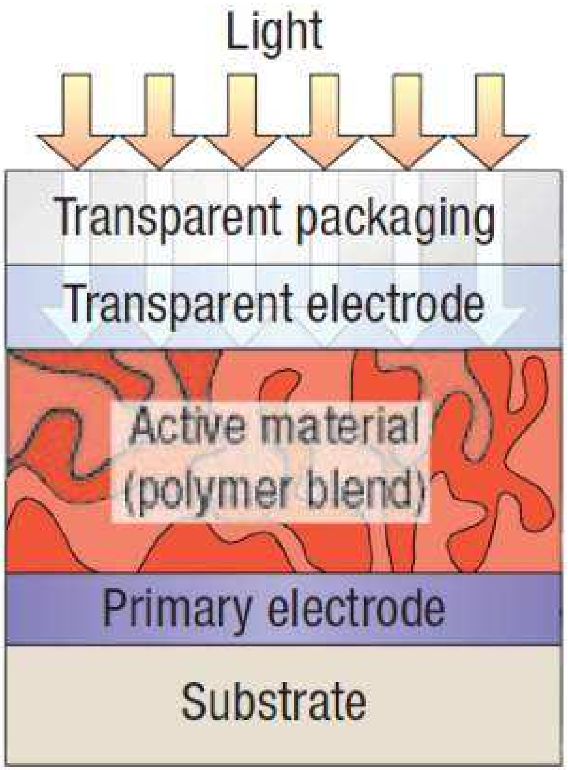


CIGS thin film



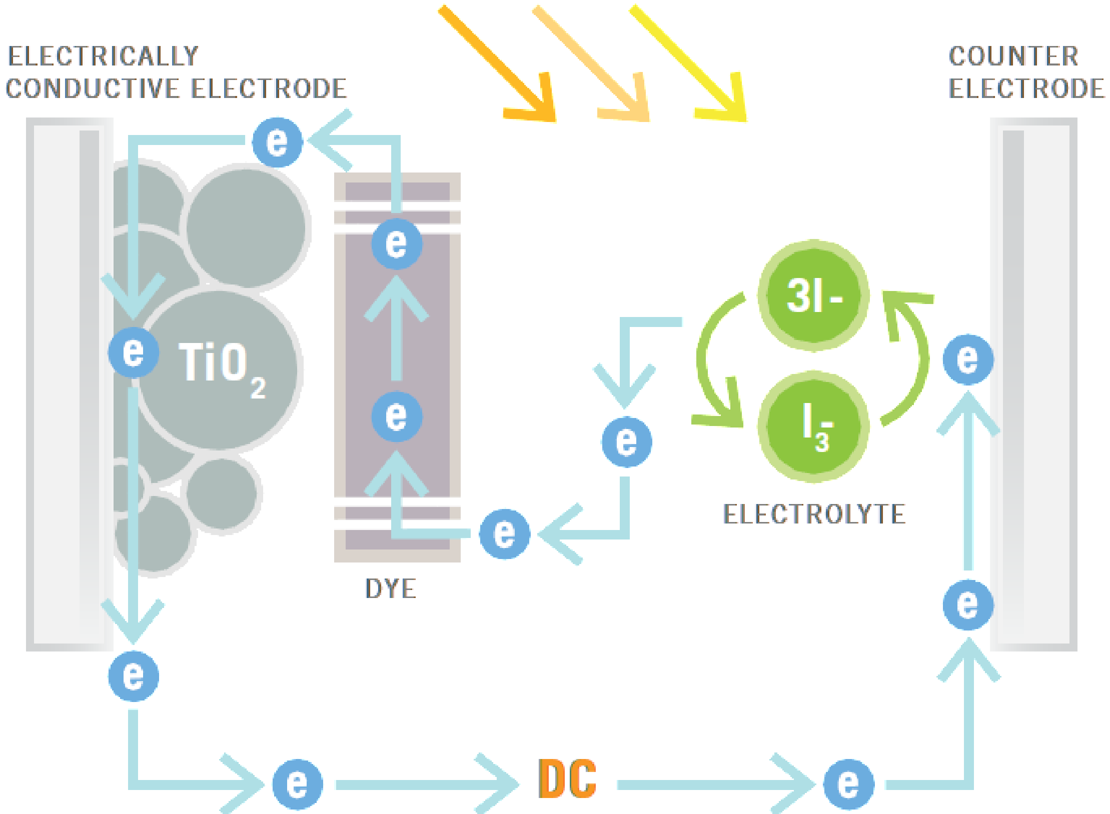
Thin film photovoltaic cell technology

Organic material thin film



R. Gaudiana and C. Brabec, Nature Photonics **2**, 287 (2008)

Dye sensitized technology



G24 Innovations

Thin film photovoltaic cell state of the art

Technology	Efficiency under sunlight at 100 mW/cm²		Max power under fluo lamp at 1000 lux[2,3]	Max power under fluo lamp at 200 lux[2,3]
	Lab best cells[1]	Commercial modules[2]		
a-Si	10.1%	6 - 7%	≈ 35 µW/cm²	≈ 6 - 7 µW/cm²
CIGS	19.4%	7% - 12%	≈ 30 - 35 µW/cm²	≈ 3 - 5 µW/cm²
Organic	5.15%	1.5%	≈ 10 µW/cm²	-
Dye	10.4%	1.5%	≈ 15 µW/cm²	≈ 3 µW/cm²

[1] M. A. Green et al., Prog. Photovolt. Res. Appl. **18**, 346 (2010).

[2] Manufacturer websites: Avancis, Bosch Solar, Q-Cells, Schott Solar, Würth Solar (DE), Solems (FR), Kaneka, Honda Soltec, MHI, Sanyo, Sharp, Solar Frontier (JP), G24 Innovations (UK), First Solar, Global Solar, Konarka, Uni-Solar (US), Sunshine PV (TW).

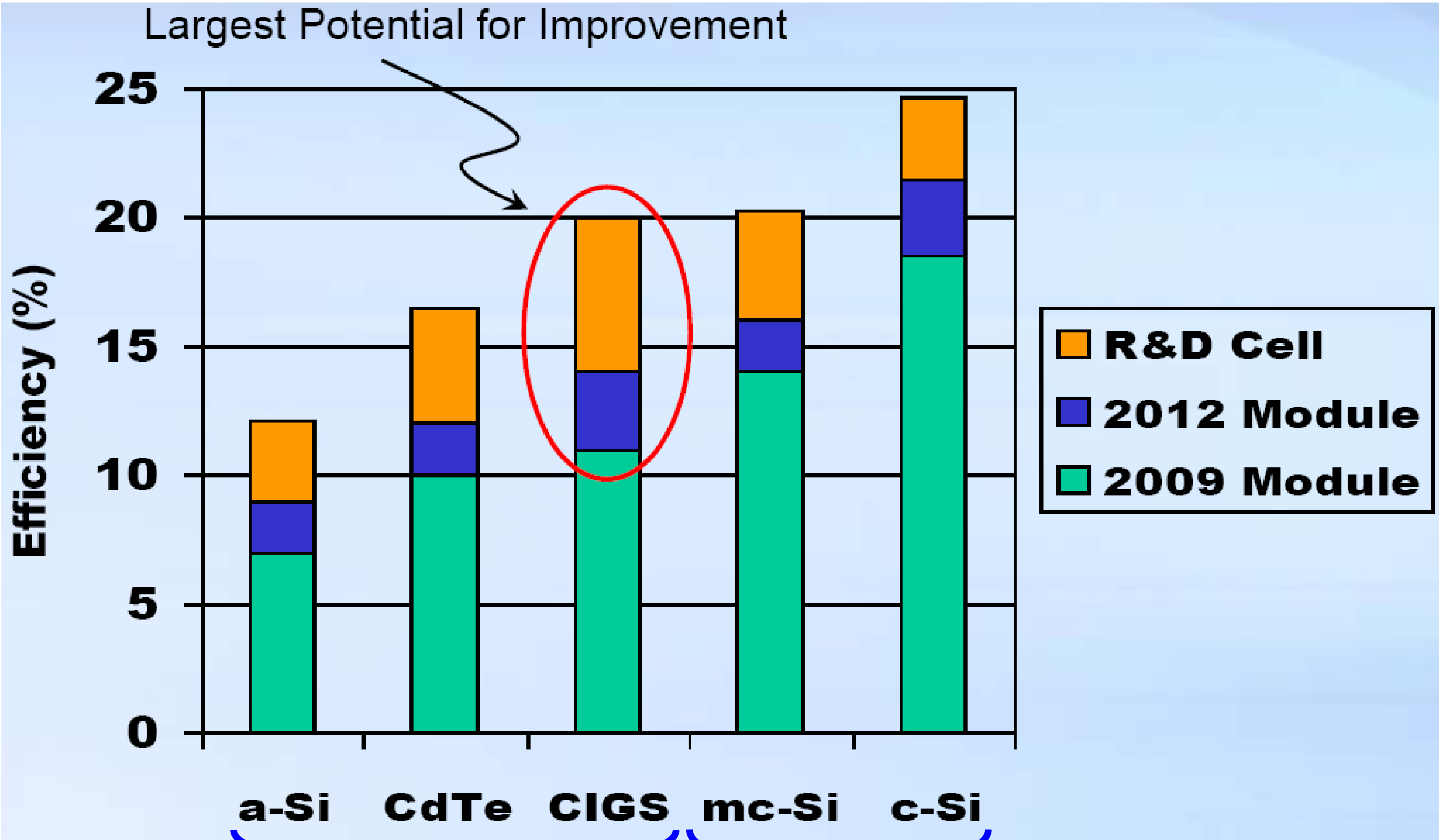
[3] N. H. Reich *et al.*, Sol. Energy Mater. Sol. Cell **93**, 1471 (2009); A. Virtuani *et al.*, Thin Solid Films **431-432**, 443 (2003); Thin Solid Films **451-452**, 160 (2004).

➔ 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



Generation thin film

Generation bulk silicon

Veeco, *Photon's PV Production Equipment Conf.* (2009)

Contents

Photovoltaics at CEA LITEN

1st generation

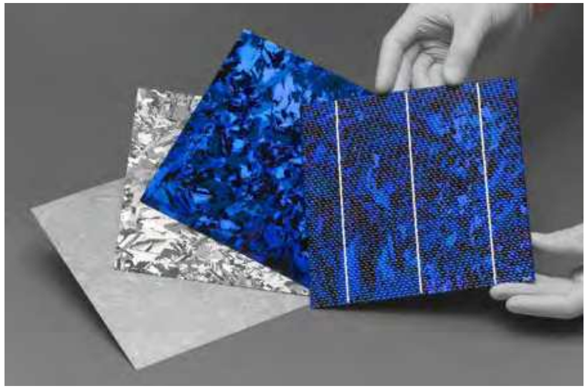
Bulk silicon
- ✓ Crystalline Si
- ✓ Multicrystalline Si
- ✓ Metallurgical Si
- ✓ Heterojunction

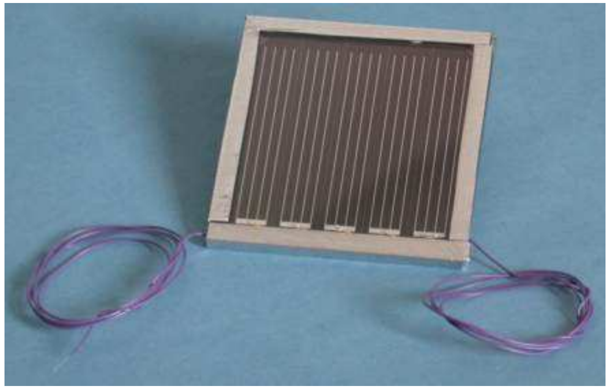
2nd generation

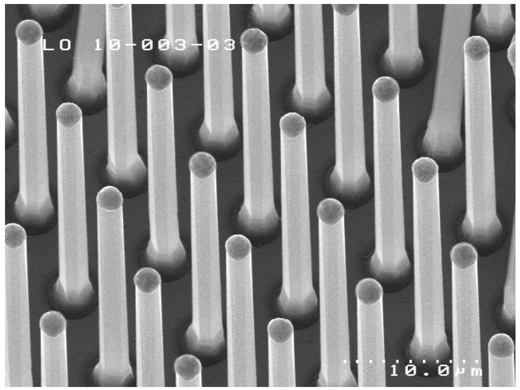
Thin films
- ✓ CIGS
- ✓ CZTS
- ✓ a-Si, a-SiGe
- ✓ organic

3rd generation

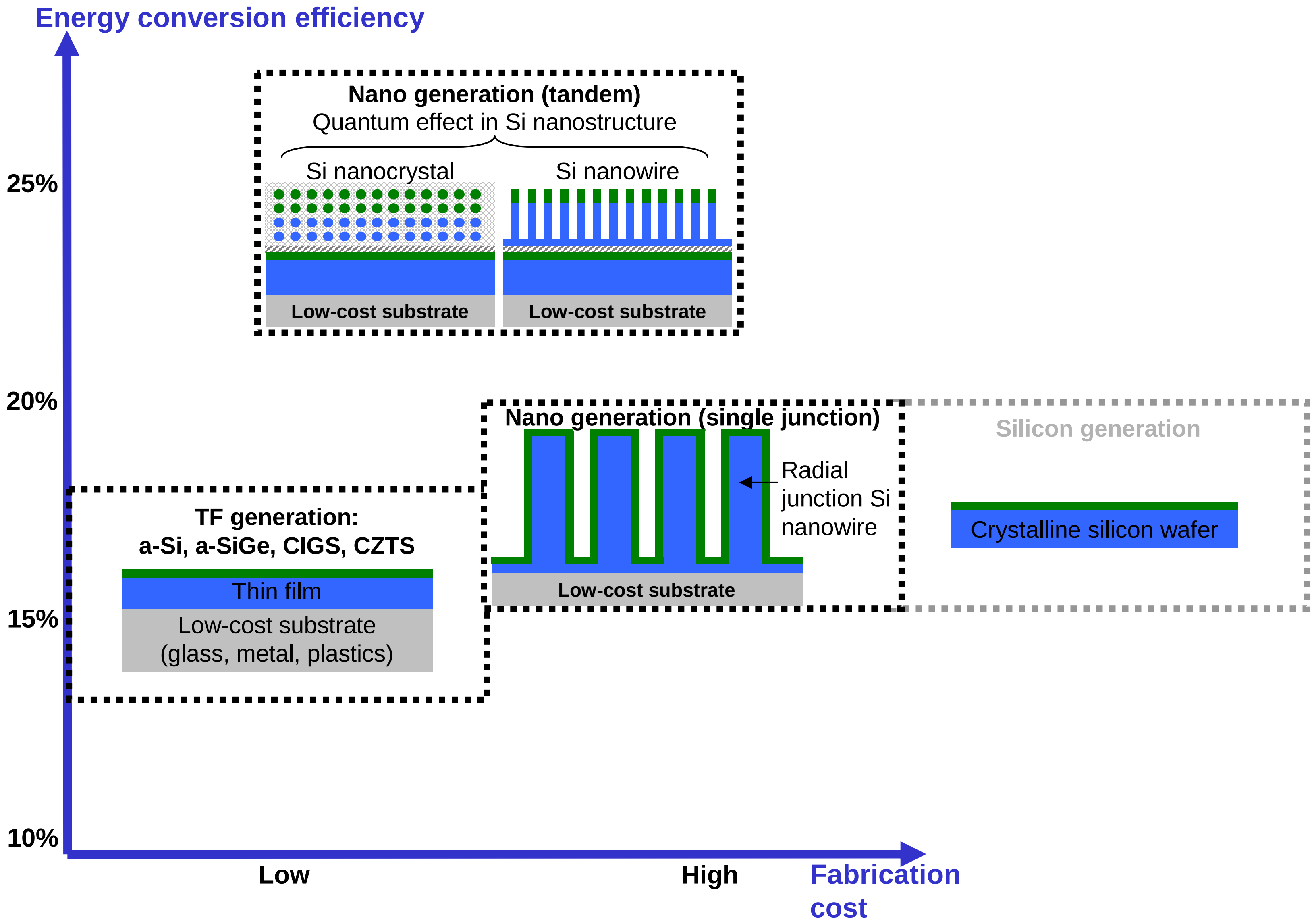
Nanomaterials
- ✓ Si nanowires: radial junction
- ✓ Si nanowires and Si nanocrystals: quantum effects



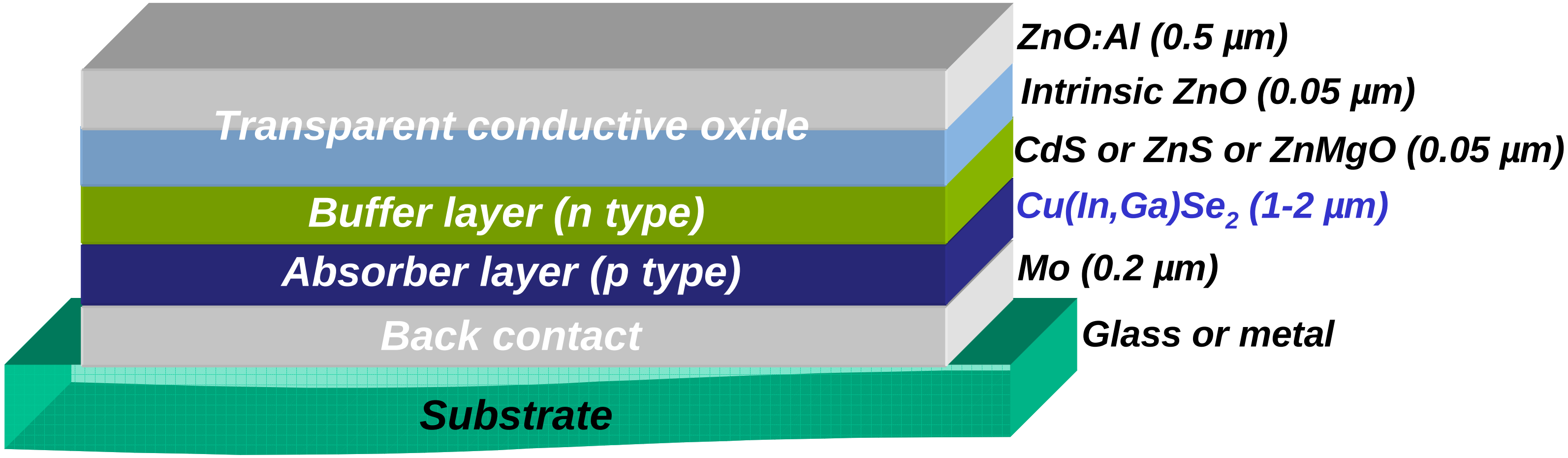




CEA LITEN strategy on TF and Nano generation PV



CIGS thin film technology



➔ **Tunable band gap (In/Ga ratio)**

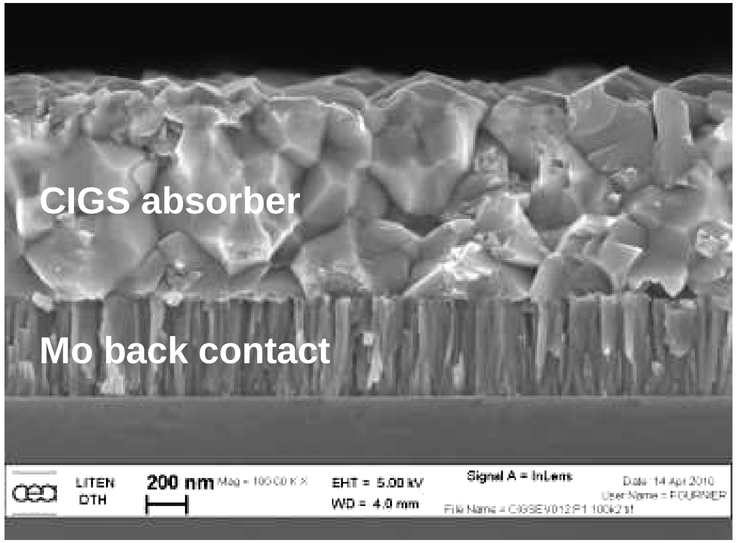
➔ **High efficiency (> 10% for commercial devices, up to 20% for best laboratory cells)**

➔ **Low cost (thin film technology)**

CIGS thin film elaboration

Vacuum processes


PVD tool for CIGS deposition

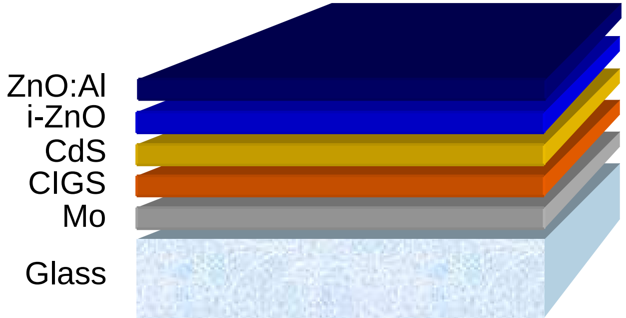


Wet processes

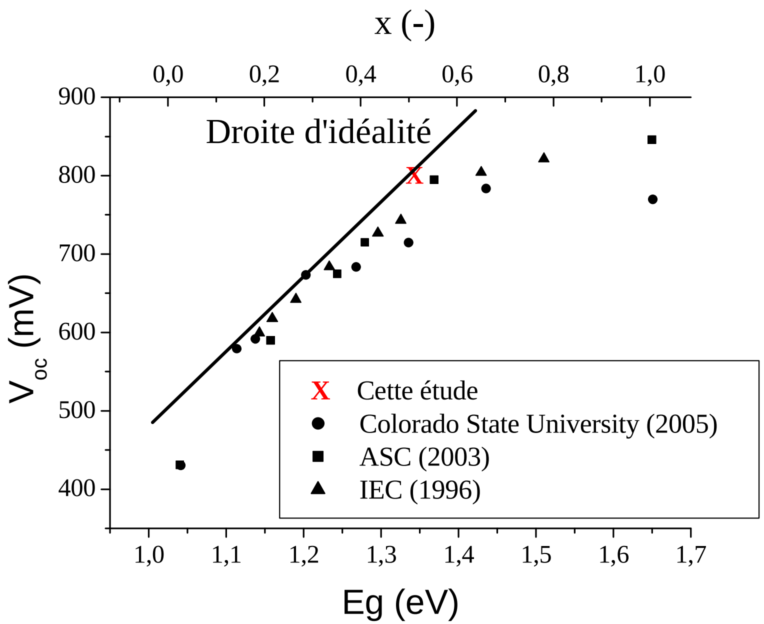
Screen Solar
Le PV multifonctionnel en couches minces

Wide bandgap CIGS cells

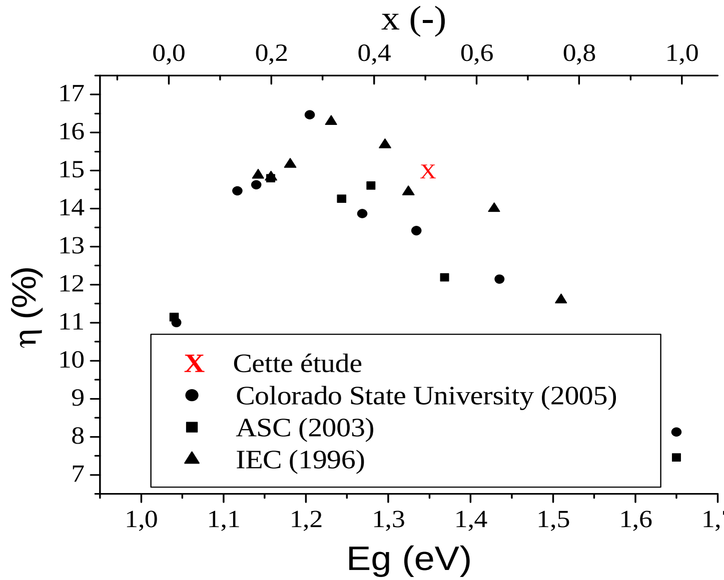
- CIGS bandgap can be tuned between 1.1 eV and 1.7 eV by adjusting In/Ga ratio
- Wide bandgap CIGS is useful for tandem architecture & indoor applications



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



➔ **Open-circuit voltage 797 mV**

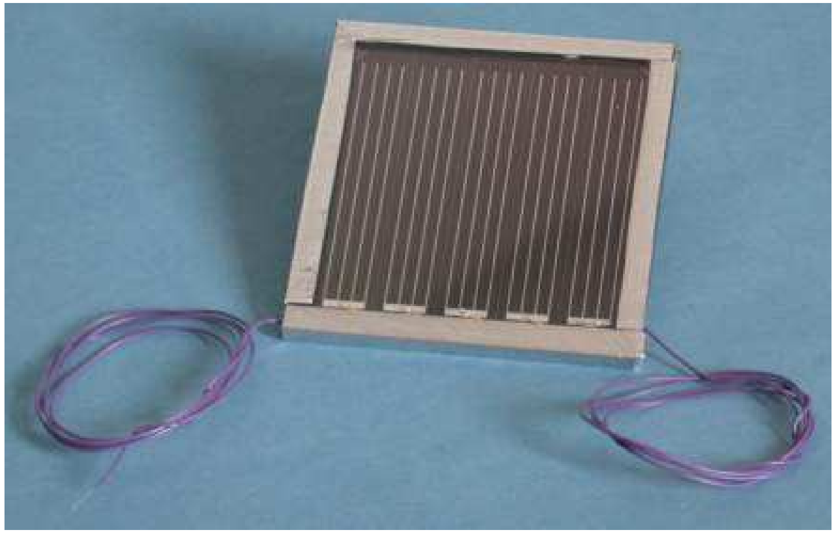


➔ **Efficiency 15%**

MRS Spring Meeting (2009)

CIGS mini-modules

25 cm² module (5 cells in series, interconnection by wire bonding)	Halogen desk lamp
Voltage at the MPP	1.5 V
Maximum power	14 mW



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

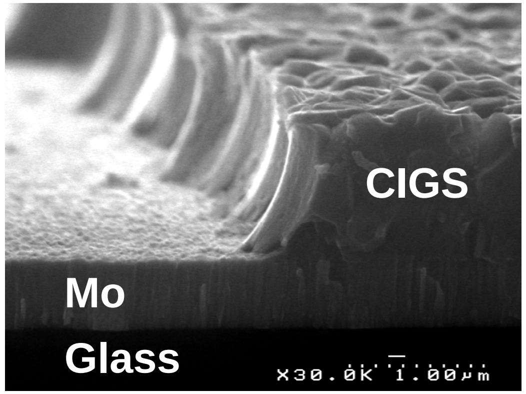
➔ The mini-module has been successfully integrated into a demonstrator of wireless audio player

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

CIGS mini-modules

10 cm² module (14 cells in series, monolithic interconnection)	Fluo office lamp
Voltage at the MPP	2.3 V
Maximum power	51 µW

Preliminary results



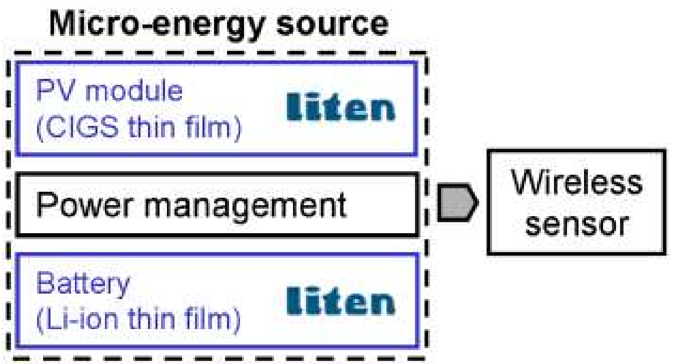
Work in progress:

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

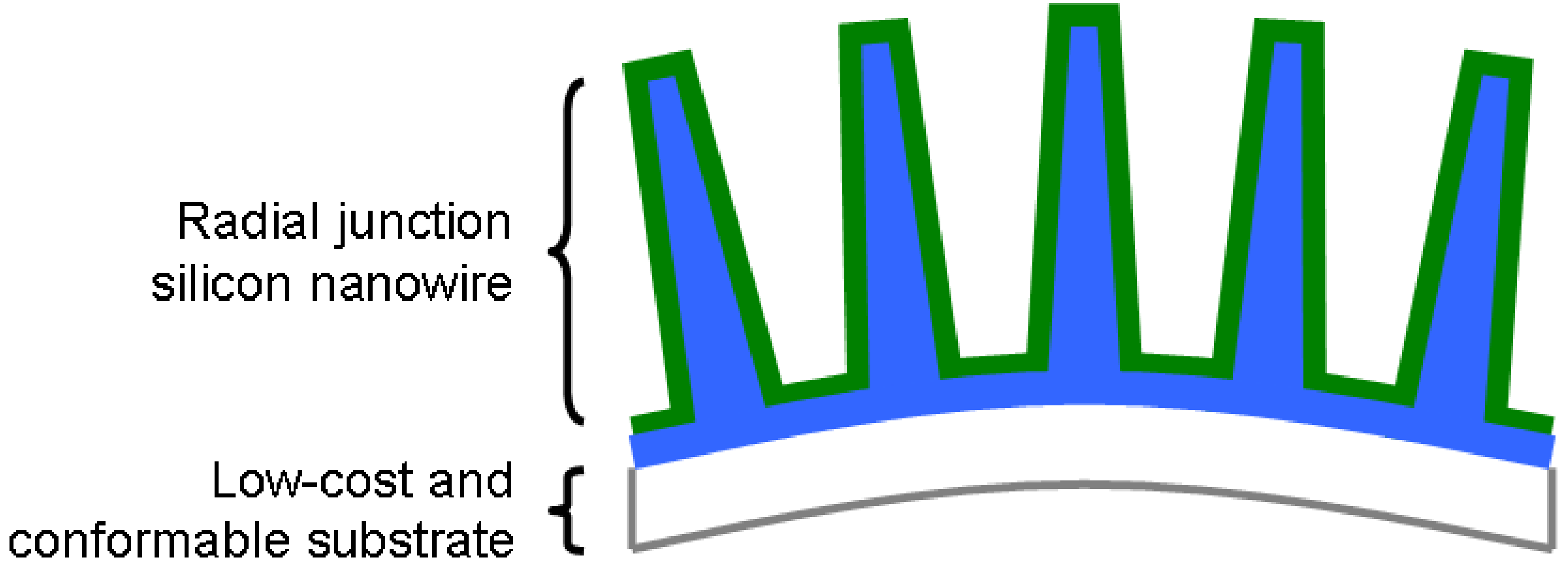
CEA LITEN patent pending

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

• Integration of the module into a demonstrator of wireless sensor (temperature, CO_2)



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**

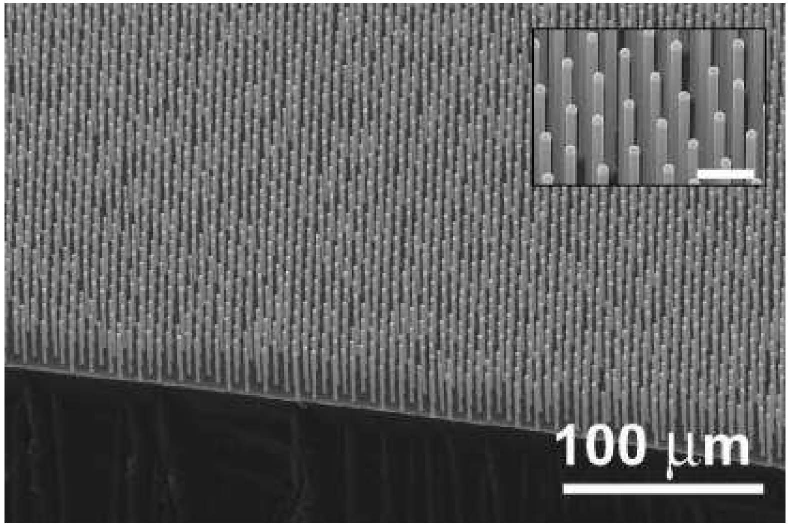
➔ **Low cost**
- **Low silicon material usage**
- **Metal substrate**

SOA : radial junction Si nanowire solar cells

Group	Substrate	Nanowire (or microwire)	Radial junction	Front contact	Energy conversion efficiency
L. Tsakalakos, General Electric, Appl. Phys. Lett. **91**, 233117 (2007)	Metal	CVD	a-Si by PECVD	ITO by PVD Metal grid	0.1% 1.8 cm²
P. Yang, Univ. California, Berkeley, J. Am. Chem. Soc. **130**, 9224 (2008)	c-Si	Wet etching ($AgNO_3$ + HF)	c-Si by CVD + RTA	Metal grid	0.5% 0.1 cm²
H. A. Atwater, CalTech, 33rd IEEE Photovoltaic Specialist Conf. (2008)	c-Si	RIE	Diffusion	Point contact	6% 0.04 cm²
O. Gunawan and S. Guha, IBM, Sol. Energy Mater. Sol. Cell. **93**, 1388 (2009)	c-Si	CVD	c-Si by CVD Al_2O_3 by ALD	Metal grid	2% 0.5 cm²
P. Yang, Univ. California, Berkeley, Nano. Lett. **10**, 1082 (2010)	c-Si	RIE	Diffusion	Metal grid	5% 0.25 cm²
T. S. Mayer, Pennsylvania State Univ., Appl. Phys. Lett. **96**, 213503 (2010)	c-Si	RIE	Diffusion	Point contact	9% 0.07 cm²

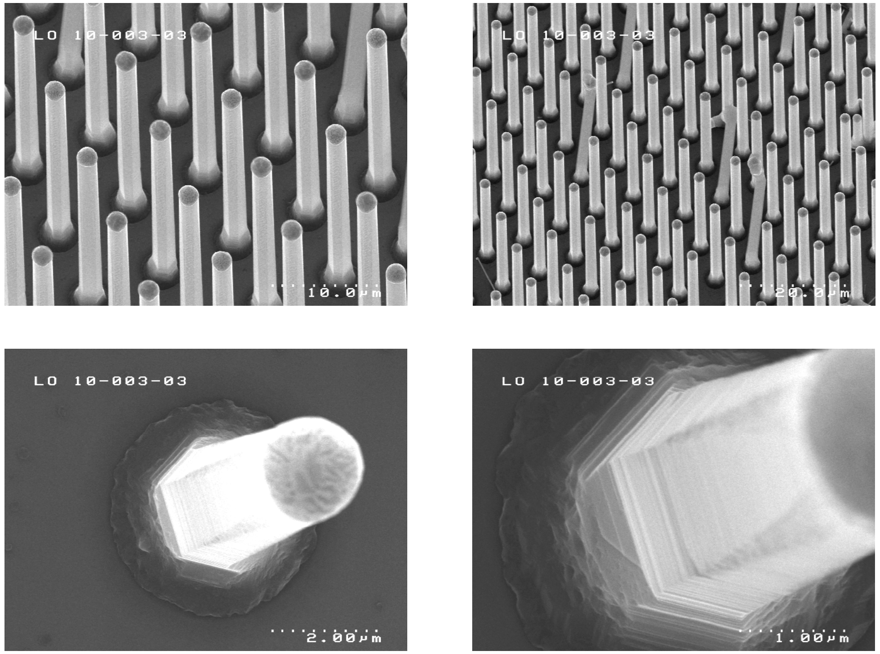
Growth of Si nanowires by CVD with high pattern fidelity

California Institute of Technology
$SiCl_4$ 1000℃



B. M. Kayes *et al.*, Appl. Phys. Lett. **91**, 103110 (2007).

CEA Liten
SiH_4 + HCl 650℃
(potentially 400℃)



➔ **The use of SiH_4 + HCl instead of $SiCl_4$ allows to reduce the growth temperature**

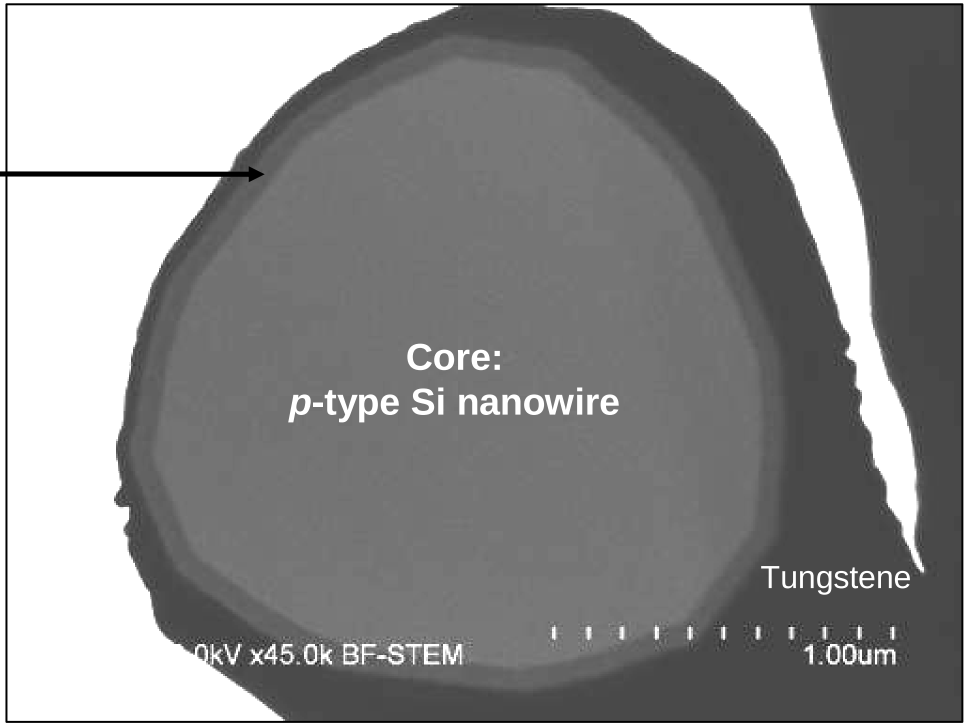
➔**Growth temperature becomes compatible with low-cost substrates (glass, metal)**

➔**In-situ doping from B2H6 and PH3**

EUPVSEC (2010)

Formation of radial junction by CVD

Shell: conformal *n*-type Si layer

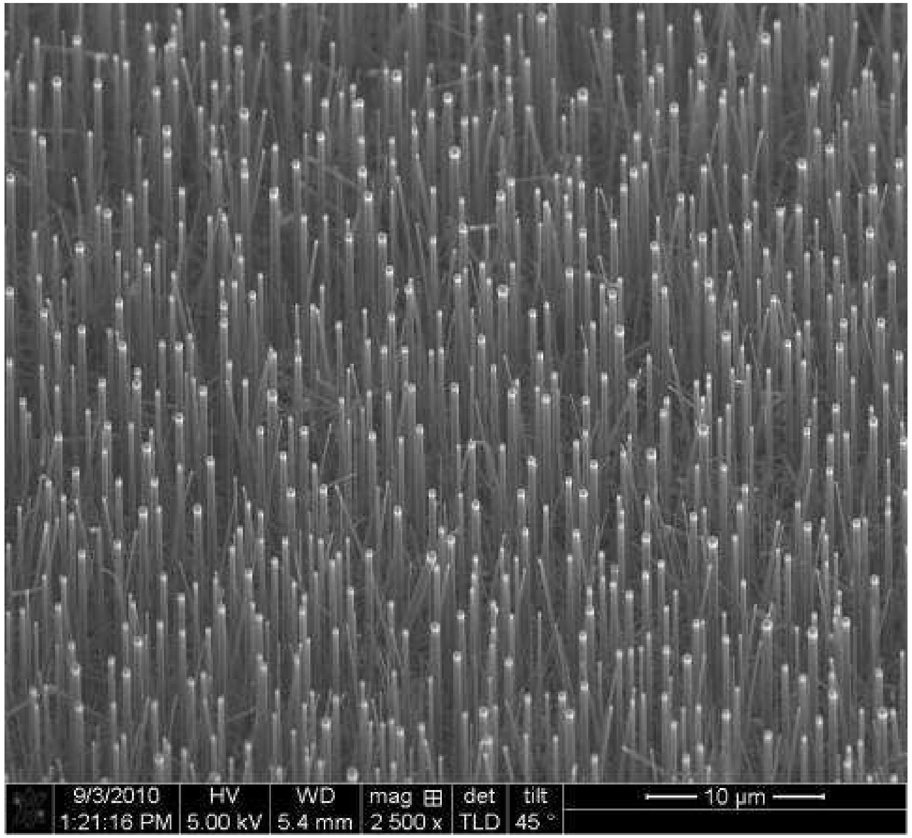


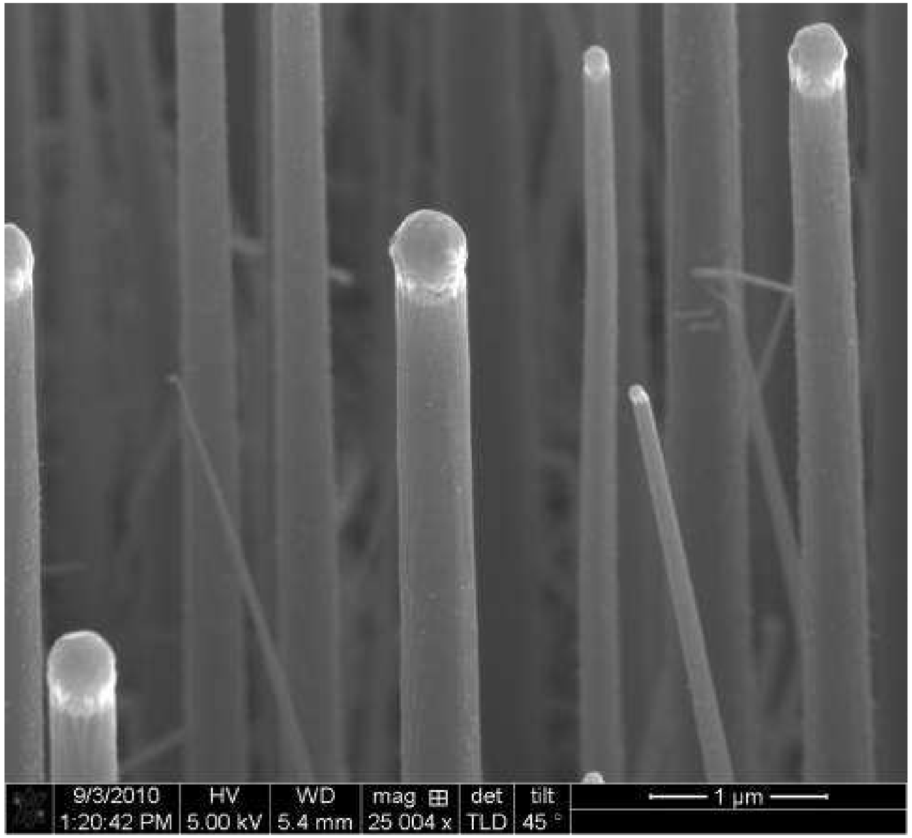
BF-STEM imaging of a radial junction Si nanowire (cross-section view)

➔ **Deposition of a conformal *n*-type Si layer for forming the radial junction**

First results on aluminium-catalysed Si nanowires

SiH_4 600℃



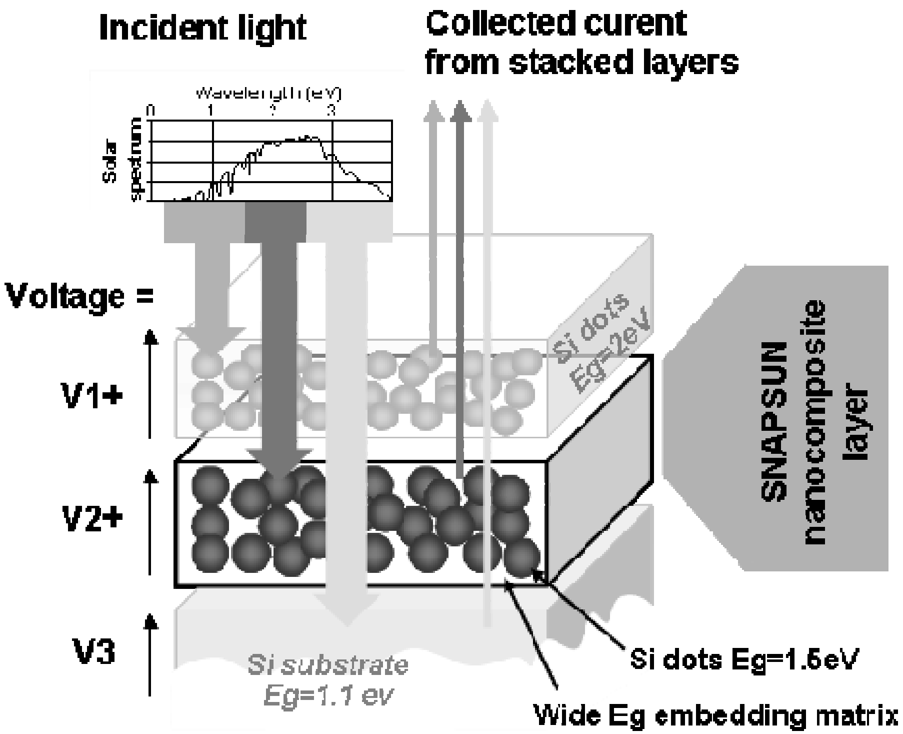


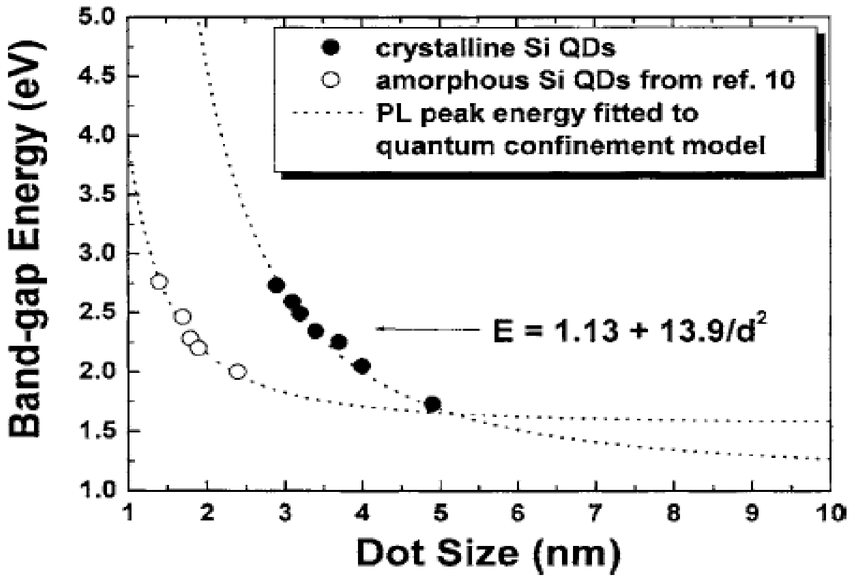
➔ **Very high growth rate (about 2 µm/min)**

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**

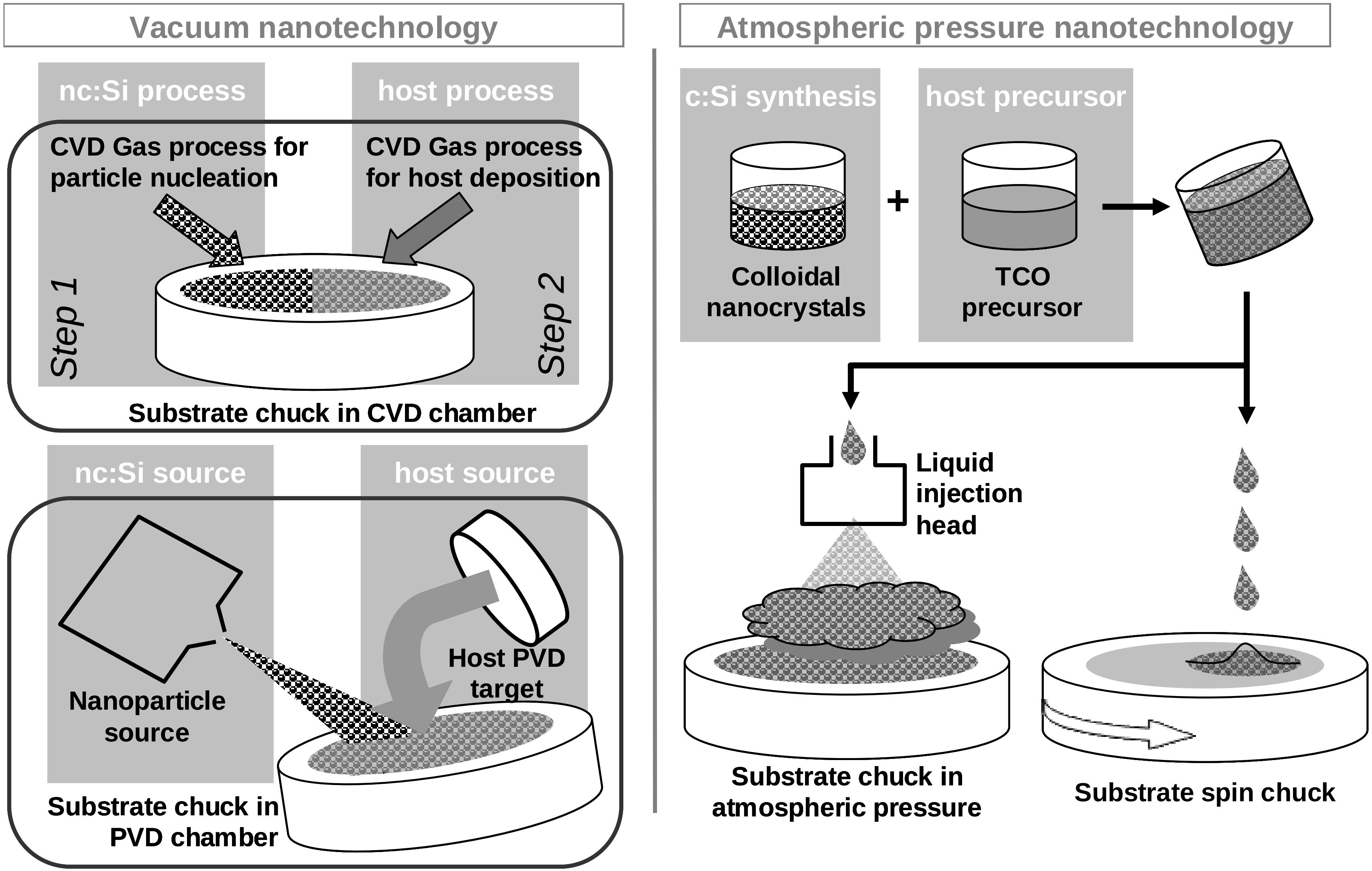
European SNAPSUN project





- ➔ 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_2O_3)
- ➔ Low cost (low-temperature vacuum & wet processes)

Low-temperature processes for silicon nanocrystal elaboration



CEA LITEN main partners on TF and Nano generation PV

Academic partners

Suppliers

BIPV

Wireless electronics

Contents

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

THANK YOU FOR YOUR ATTENTION

http://www.animaquark.com/