Recent Development of Thin Film Si Solar Cell Technologies for Commercialization

< Contents >

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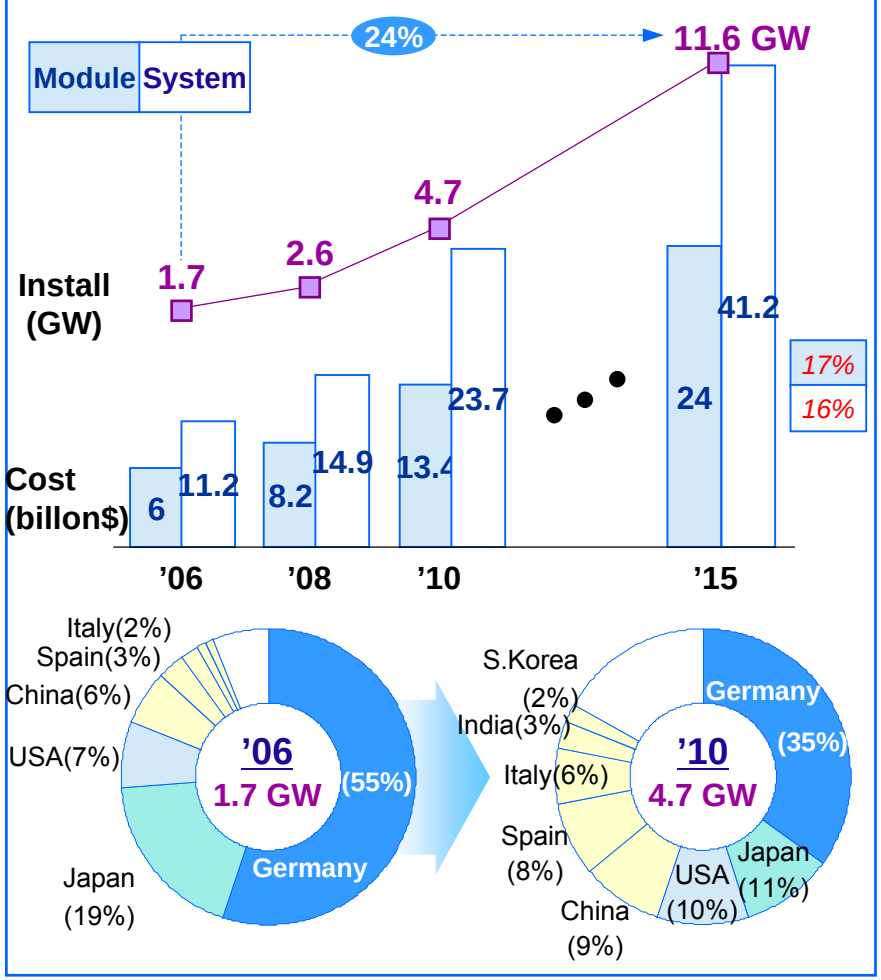
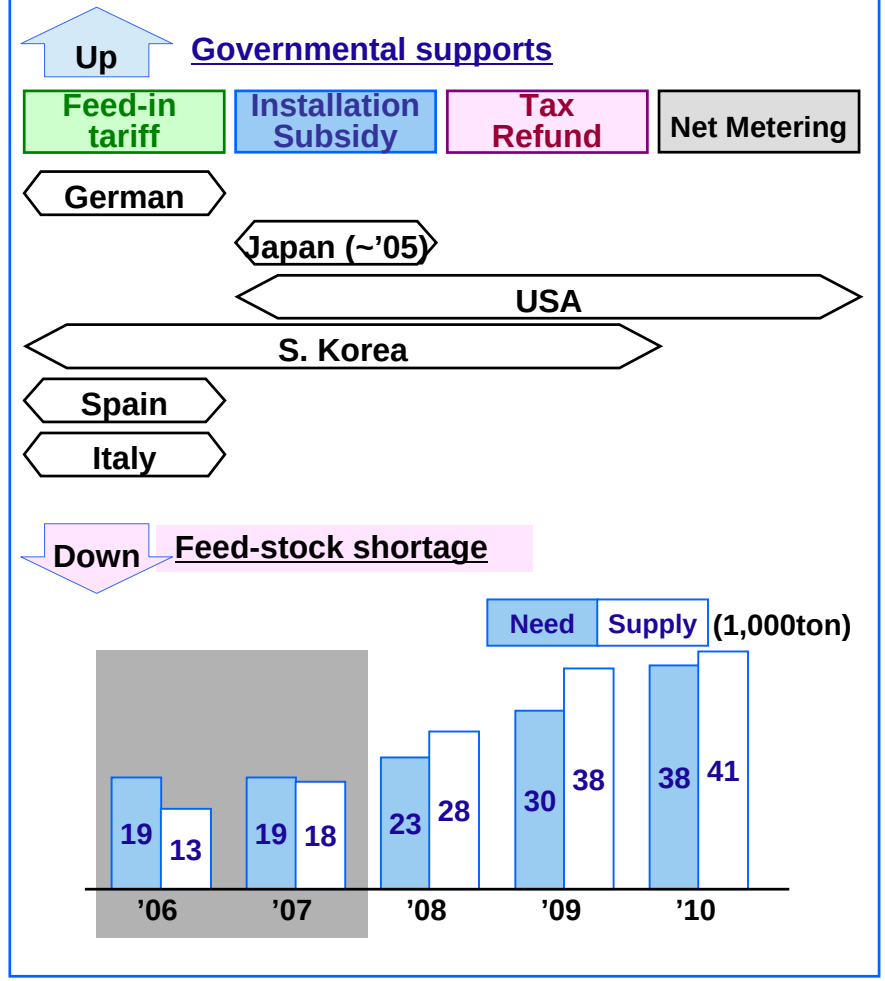
- Rapid increase of market size : governmental supports and policies
- Needs for low-cost solar cell development : Si feed-stock shortage

Market Perspectives



Market Driving Force



Products

Product (installation type)	Customer Needs [1]
 Roof	• Installation Space • Price ($/W) • Weight
 Ground	• Price ($/W) (needs to meet a base efficiency)
 BIPV [2]	• Price ($/m^2) • Appearance (Windows & building facings)
 Miscellaneous	• Power per Dimension

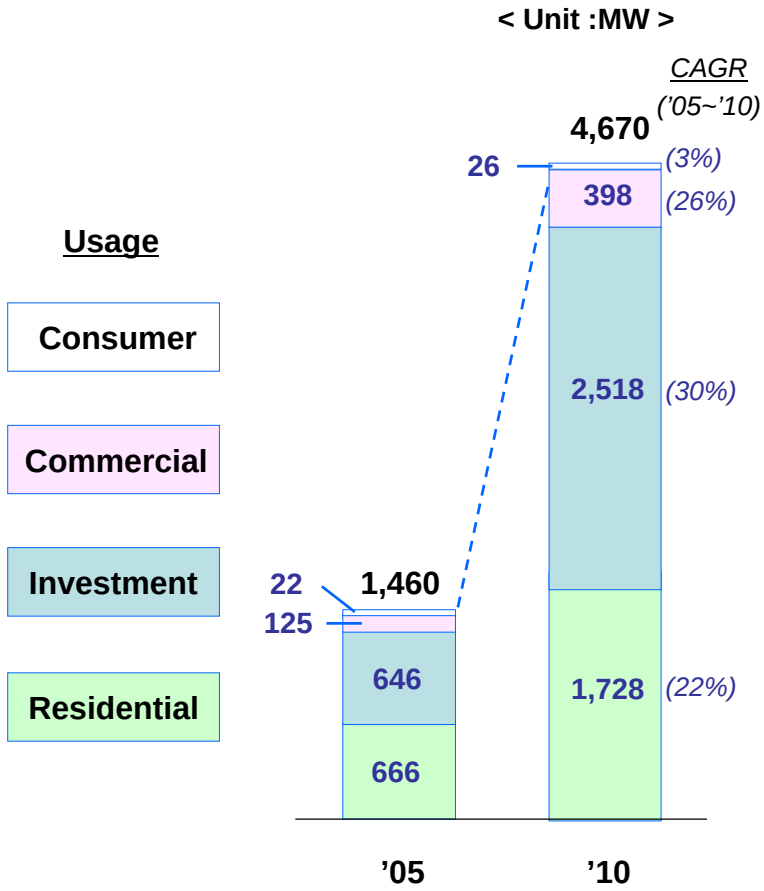
Usage

	Usage	Installation Place	Key decision Maker	Expectation
On-Grid	Residential	• Residential house • Apartment	• Customer • Installer • Constructor	• Investment collect through reduced electric bill
	Commercial	• Business building • Factory	• Building constructor & designer	• Ecological business brand image
	Investment	• Idle & rental space (roof/open space)	• Investor • Installer	• Profit from power generation
	Public building/ Utility	• Public building • Power plant • Public facility	• Contractor	• Profit from power generation • Public awareness
Off-Grid	Remote	• Remote area difficult to access electric supply	• Costumer/ Installer	• Power supply
	Consumer	• Product imbedded	• Application Manufacturer	• Auxiliary power supply

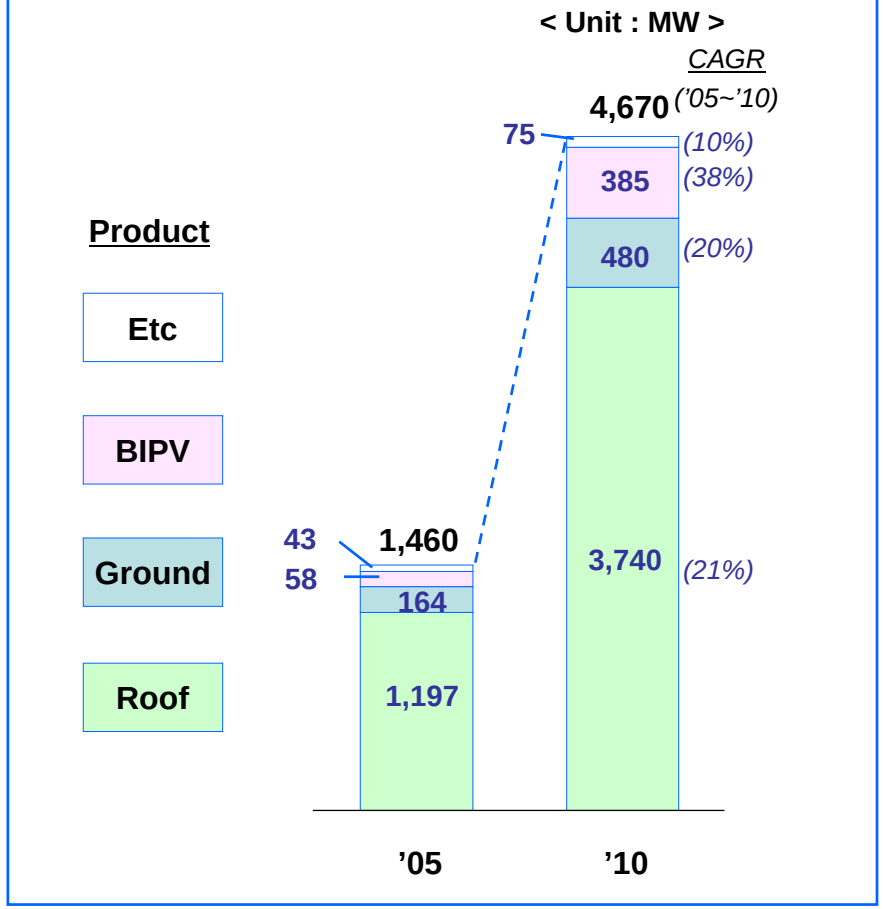
1) Interview data from SolarBuzz, Lahmeyer, domastic Installer, LGC BIPV TFT 2) Building Integrated Photovoltaic

- Residential house's roof is one of the largest potential usages
- BIPV market is expected to grow rapidly

Market per usage



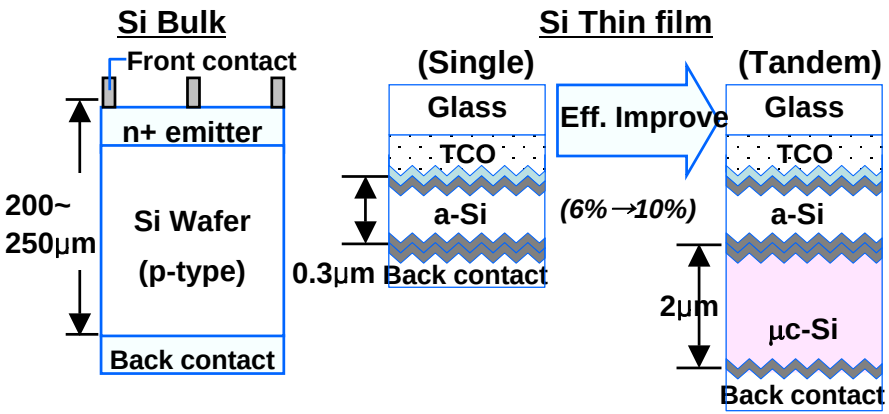
Market per product



1) Summary of Navigant, Lahmeyer Int'l, Solarbuzz

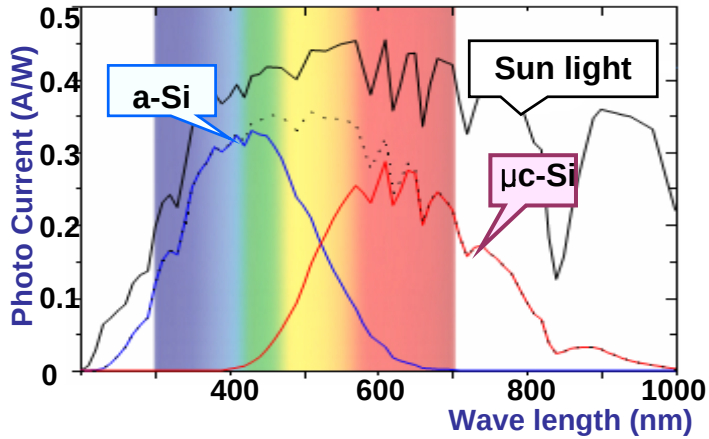
- Si bulk technology : Main stream in solar cell market
- Si thin film technology : High potential of efficiency improvement and low cost

Structures of bulk and thin film



High efficiency

Potential of Si thin film

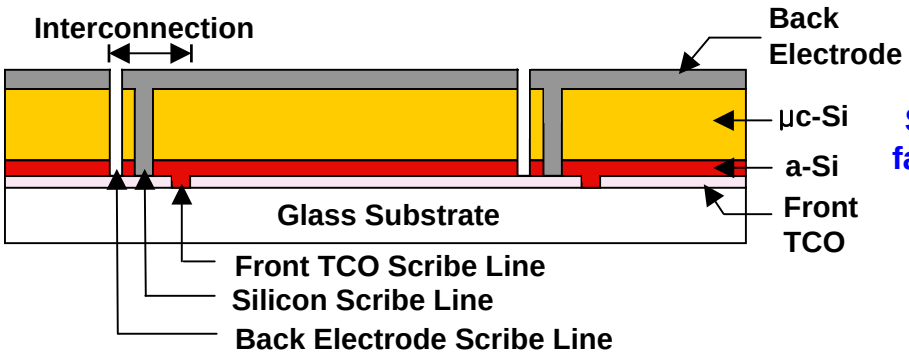


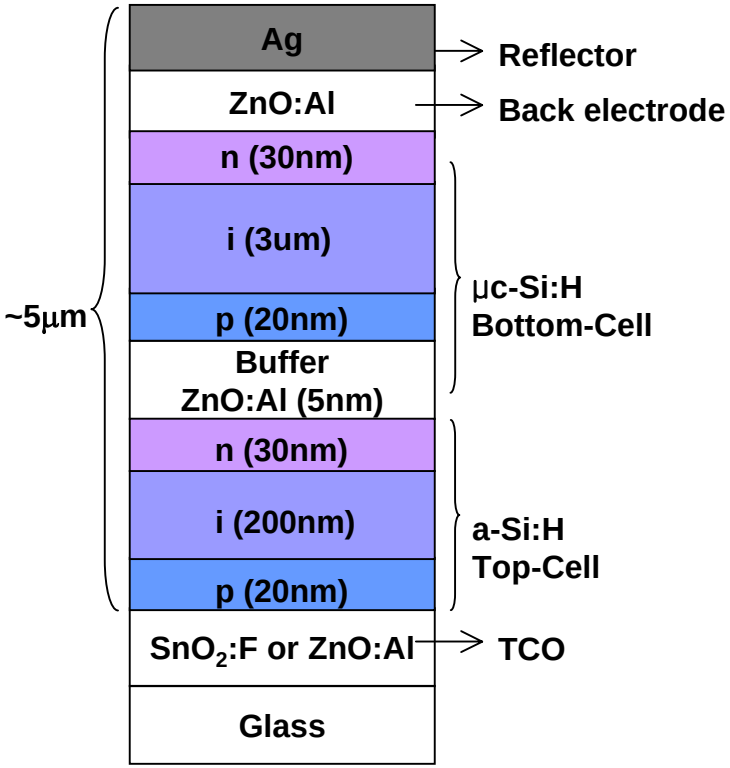
Type	Si Bulk	Si Thin Film
Adva-ntage	• Mass production • Easy achievement of base efficiency • High efficiency - 12 ~ 15% for module	• Low cost of raw materials (1/3 of Si bulk) • Power generation 10%↑ - weak effects from install angle and temperature • Good appearance (Color)
Chall-enge	• High consumptions of raw materials & energy	• Relatively low efficiency • High cost of production system 1)

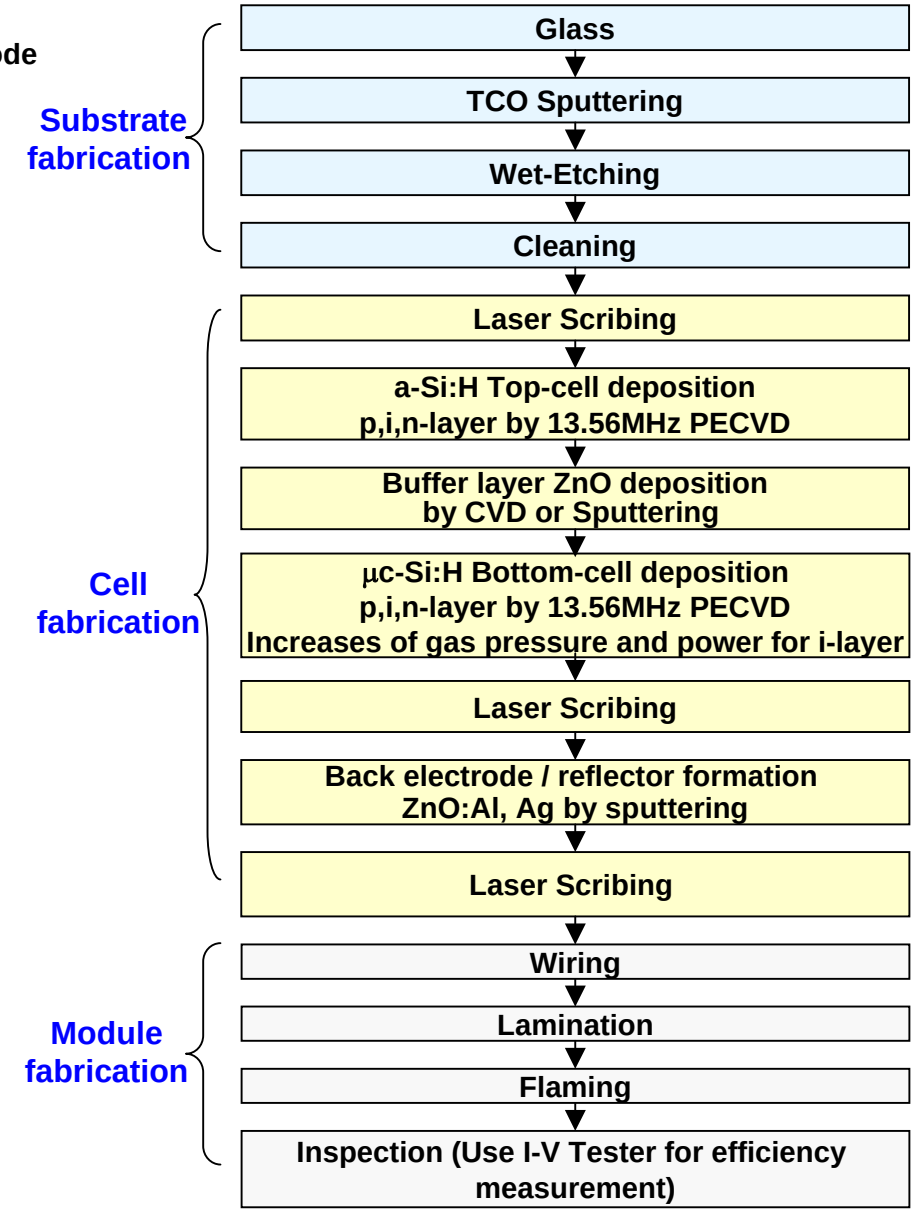
Power Generation

Type	Si Bulk	Si Thin film
Efficiency	14%	6% *(Single)*
Actual power generation (per 1m²-year)	152kWh	72kWh
Actual power generation (per1kW-year)	1,086kWh	1,203kWh

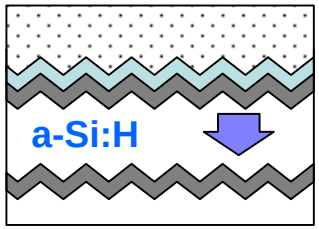
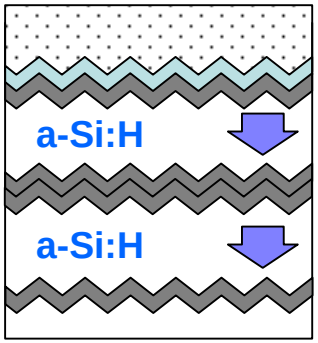
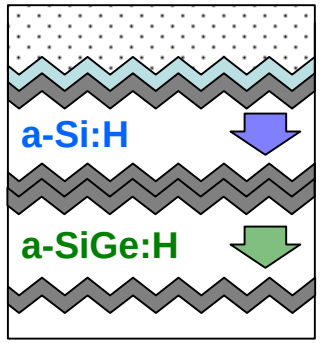
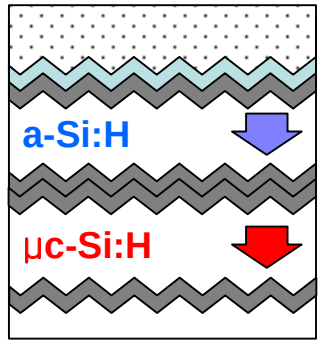
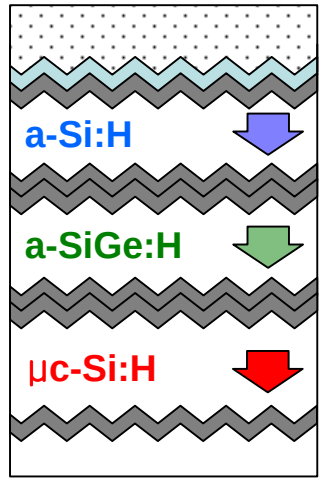
1) Investment costs : Bulk Cell($0.5/W)+Module($0.1/W), Si Tandem - $2.2/W, Compound semiconductor thin film - $3.0/W *(Kaneka's data)*


Interconnection
Back Electrode
µc-Si
a-Si
Front TCO
Glass Substrate
Front TCO Scribe Line
Silicon Scribe Line
Back Electrode Scribe Line


Ag
Reflector
ZnO:Al
Back electrode
n (30nm)
i (3um)
p (20nm)
µc-Si:H Bottom-Cell
~5µm
Buffer ZnO:Al (5nm)
n (30nm)
i (200nm)
p (20nm)
a-Si:H Top-Cell
SnO2:F or ZnO:Al
TCO
Glass


Substrate fabrication
Glass
TCO Sputtering
Wet-Etching
Cleaning
Cell fabrication
Laser Scribing
a-Si:H Top-cell deposition
p,i,n-layer by 13.56MHz PECVD
Buffer layer ZnO deposition
by CVD or Sputtering
µc-Si:H Bottom-cell deposition
p,i,n-layer by 13.56MHz PECVD
Increases of gas pressure and power for i-layer
Laser Scribing
Back electrode / reflector formation
ZnO:Al, Ag by sputtering
Laser Scribing
Module fabrication
Wiring
Lamination
Flaming
Inspection (Use I-V Tester for efficiency measurement)

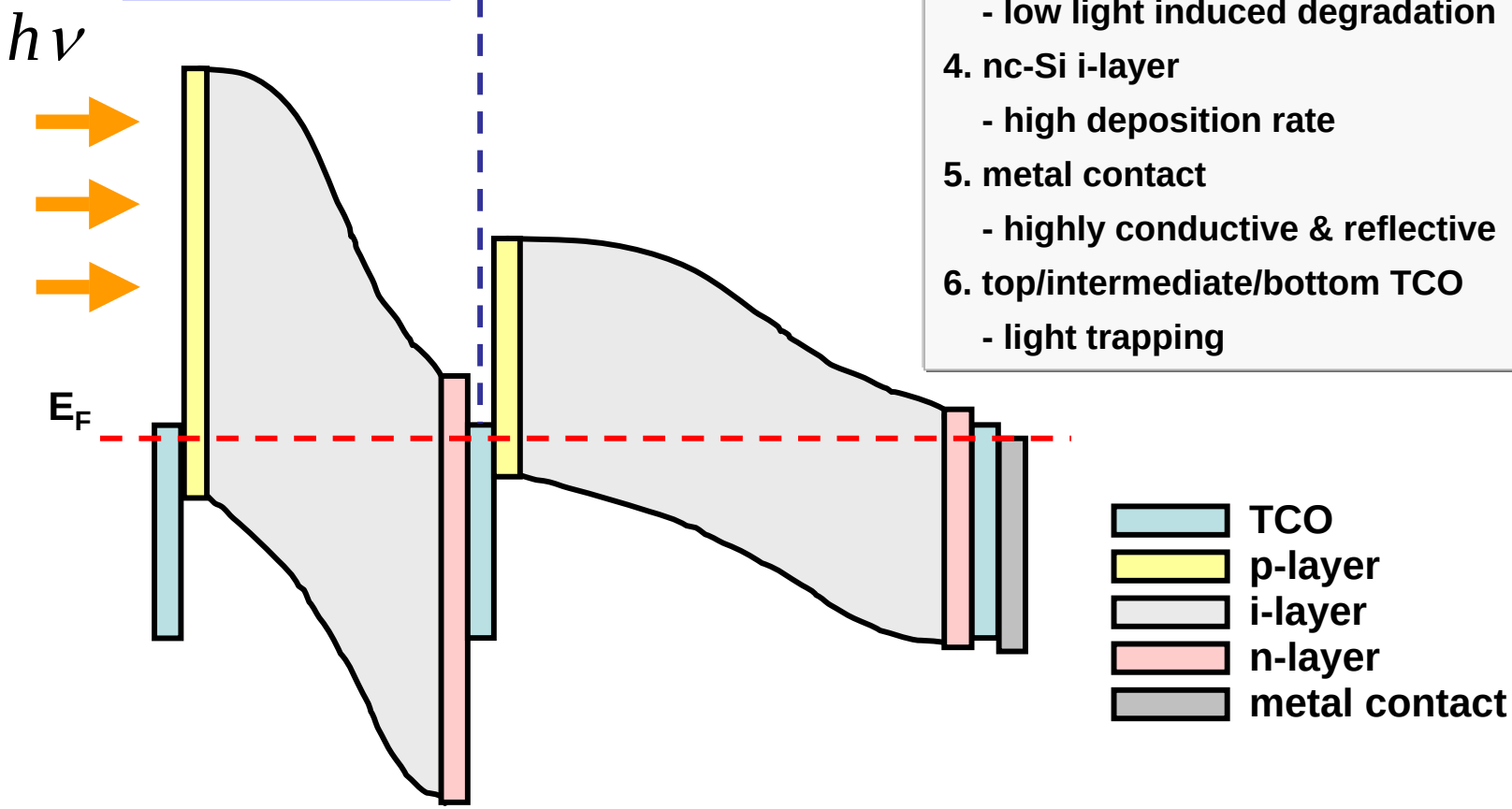
2. Si Thin Film Solar Cell Technologies

1st generation (single junction)	Tandem (double junction)			Triple Junction
	2nd generation	3rd generation	4th generation	5th generation
Efficiency: 5~6 %	Efficiency: 6~7 %	Efficiency: 7~8 %	Efficiency: 11~12 %	Efficiency: 13~14 %
				
Mass Production Stage			Pilot Stage	R&D Stage
- Japan: Kaneka(20MW), Sharp(15MW), Fuji Elec., Mitsubishi Heavy Ind., - US: Uni-Solar, EPV - EU: Oerlikon, Shott Solar			Kaneka, Sharp	Kaneka

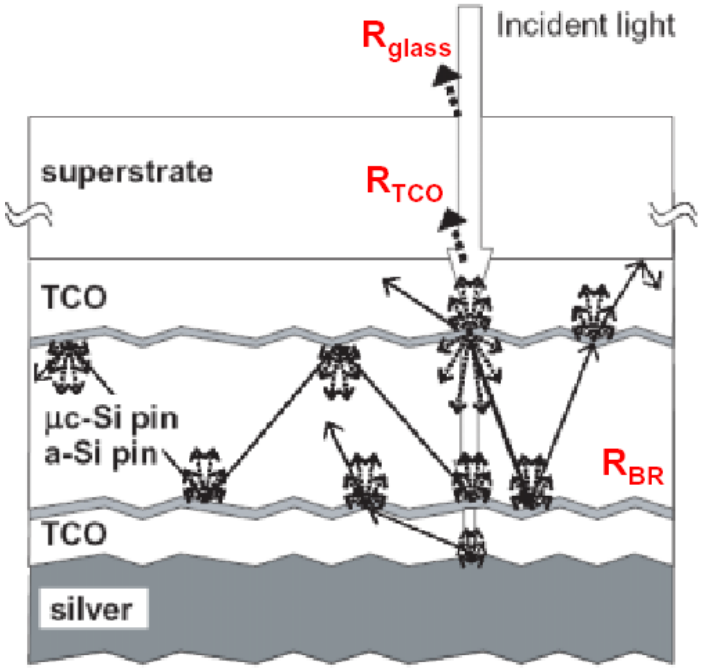
Top Cell
- i-layer=a-Si
- Eg=1.75 eV

Bottom Cell
- i-layer=uc-Si
- Eg=1.1 eV

1. TCO
   - Highly conductive & wide bandgap
2. p/i interface :
   - low recombination reduction
3. a-Si i-layer
   - low light induced degradation
4. nc-Si i-layer
   - high deposition rate
5. metal contact
   - highly conductive & reflective
6. top/intermediate/bottom TCO
   - light trapping

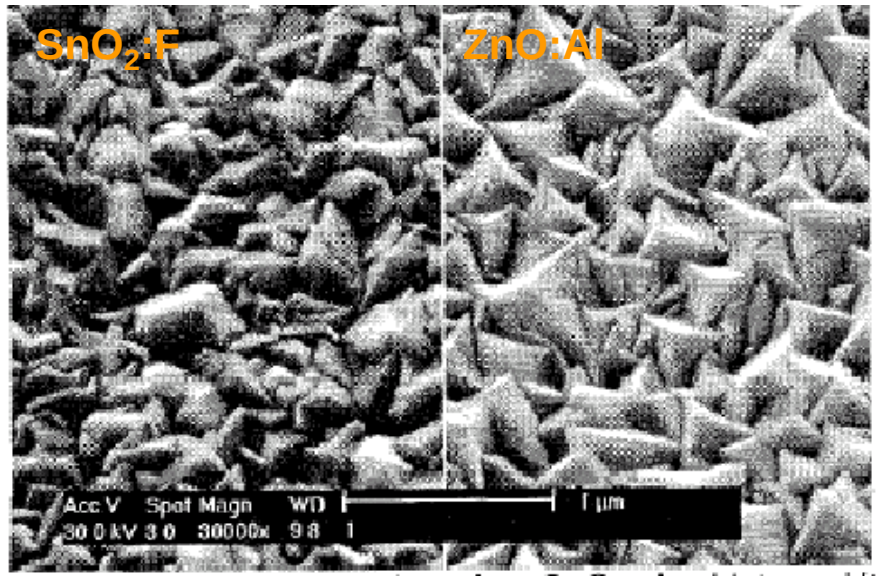


Light Trapping



- ✓ Reduced reflection
- ✓ Increased travel length
- ✓ Increased internal reflection

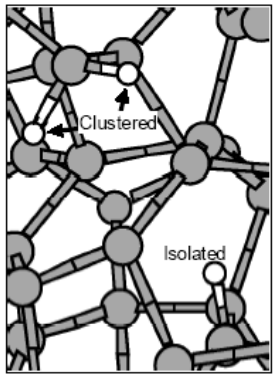
Surface Texturing

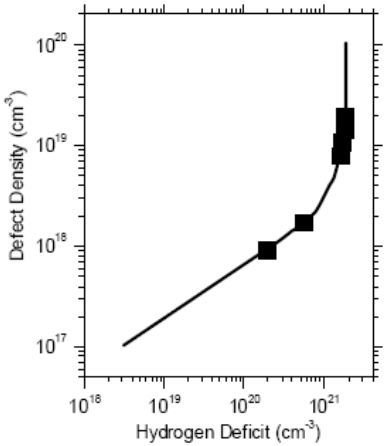


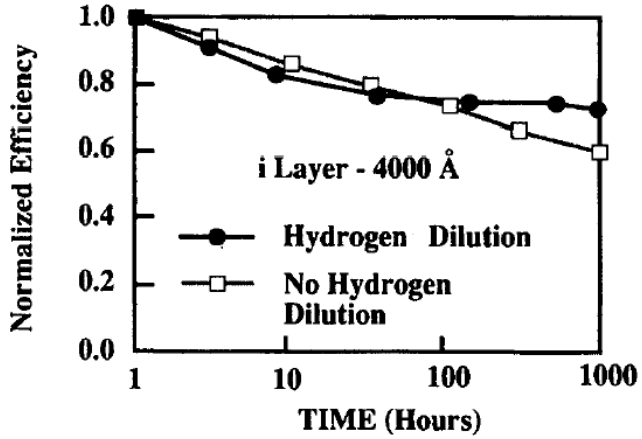
- ✓ Haze ratio (H)
  $H = T_{diffusion} / (T_{diffusion} + T_{specular})$
  H = 6~12% (Generally)
- ✓ Enhancement factor (F_E)
  $F_E = 4n^2$ (Theoretical Max)

Hydrogen Dilution

Passivation of dangling bonds by H atoms

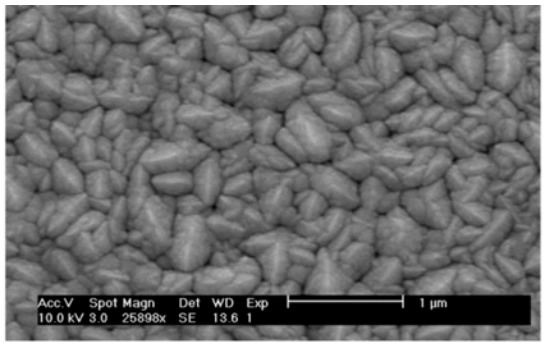






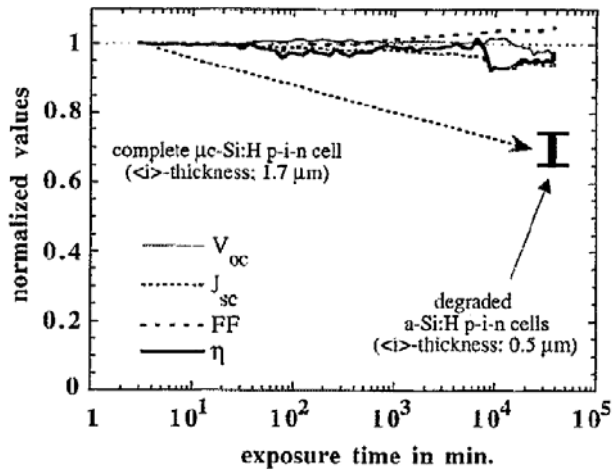
nc-Si:H Solar Cell

nc-Si:H Is more stable under light exposure than a-Si:H.

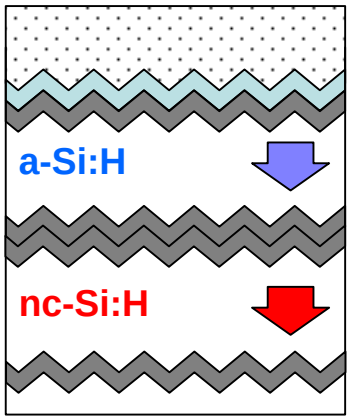


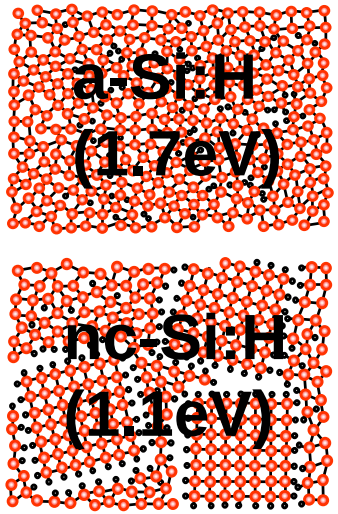
Franz *et al*, *Thin Solid Films* **383** (2001) 11-14.

Stability behavior of an all nc-Si:H p-i-n solar cell under long term light exposure.

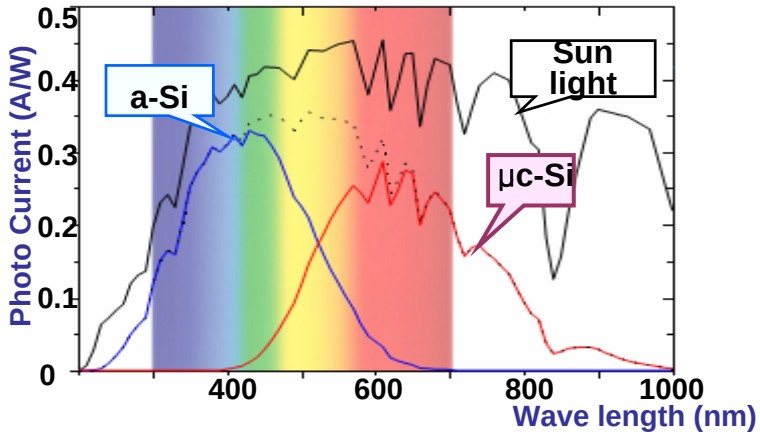


Meier J *et al*, *Appl. Phys. Lett.* **65** (1994) 7.





- ✓ Neuchatel pioneered in 1994 « micromorph » tandem
- ✓ Needs of a fast deposition technique for high-quality nc-Si:H

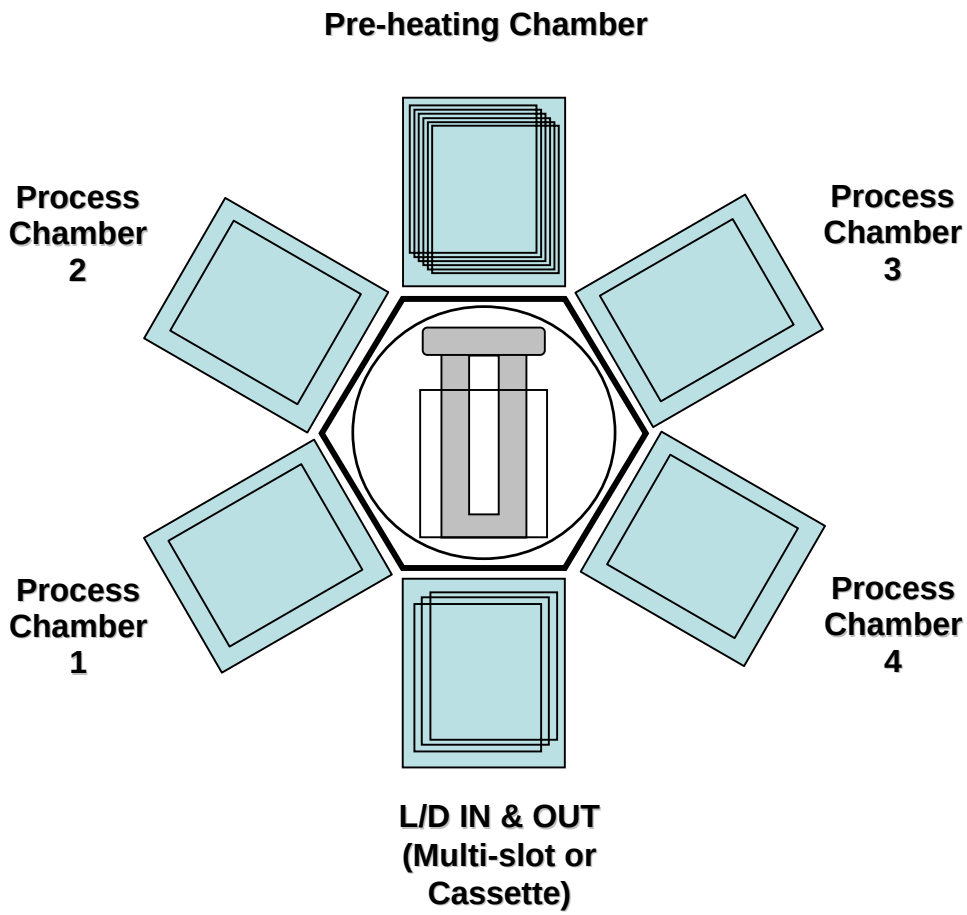


- ✓ In a micromorph tandem, the solar spectrum is ideally shared between top (a-Si:H) and bottom (nc-Si:H) cell

- SS/MC type PECVD system is suitable for R&D
- MS/MC type PECVD system is required for mass production

Chamber	Substrate: Single	Substrate: Multi
Single	**SS/SC Type** Adv. : Low cost of production facility Disadv. : Cross contamination between processes Manufacturer : EPV (USA)- for R&D	**MS/SC Type** Adv. : High productivity in mass production Disadv. : Cross contamination Manufacturer : EPV [USA], Oerlikon [Swiss]
Multi	**SS/MC Type** Adv. : High stability of each process Low cost of raw material Disadv. : Low productivity in mass production Manufacturer : MV Systems (USA) ▶ Suitable for R&D	**MS/MC Type** Adv. : High stability of each process Disadv. : Low perfection of production system development High cost of raw material Manufacturer : IHI (Japan), Centrotherm (Germany)

SS: Single Substrate, SC: Single Chamber, MS: Multi Substrate, MC: Multi Chamber

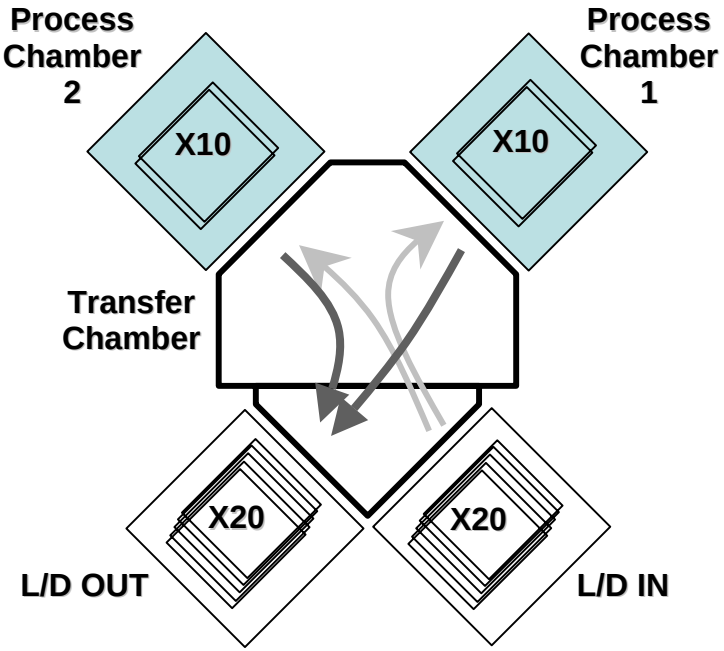


Basic Principle

- ✓ Capacitively-coupled parallel plate plasma reactor
- ✓ p-, i-, n-layer at each chamber
- ✓ Multiple i-chamber
- ✓ Plasma Cleaning (NF_3 or SF_6)
- ✓ VHF for nc-Si:H film

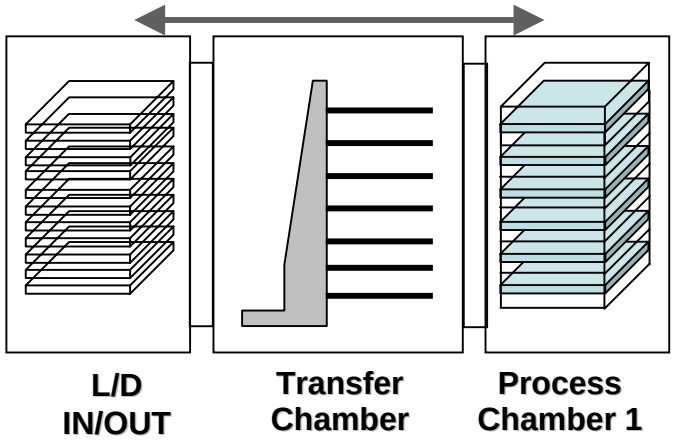
Consideration

- ✓ Pre-heating chamber
- ✓ Sputter system for BR-layer



System specification

- ✓ 2 Process chambers :
  - 40MHz VHF-PECVD
  - 10 reactors / 1 chamber
- ✓ Substrate size :
  - 520x410, 1250x1100 mm^2



Features

- ✓ High throughput equipment
- ✓Cross contamination problem between processes
- ✓Difficulty of maintenance

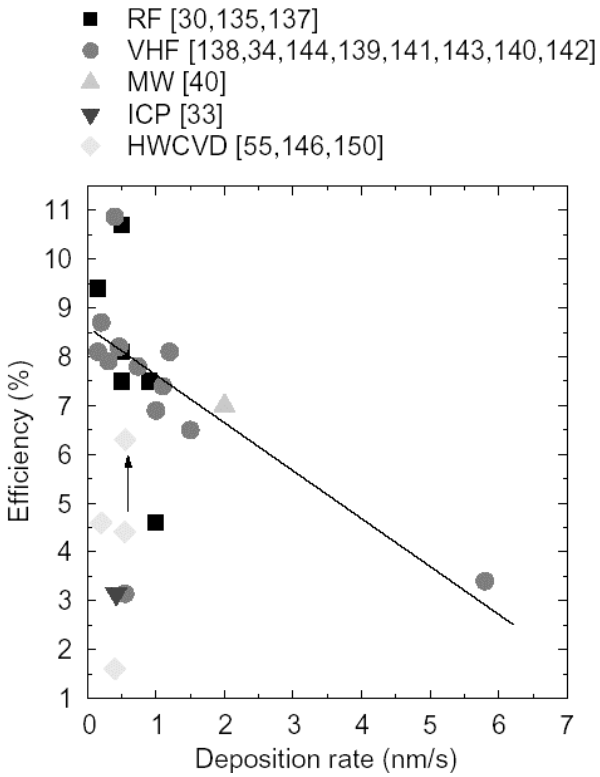
◆ **Requirements for nc-SI:H in tandem junction thin film solar cells**

- **High hydrogen dilution and denser films**
- **High material quality at high deposition rate**

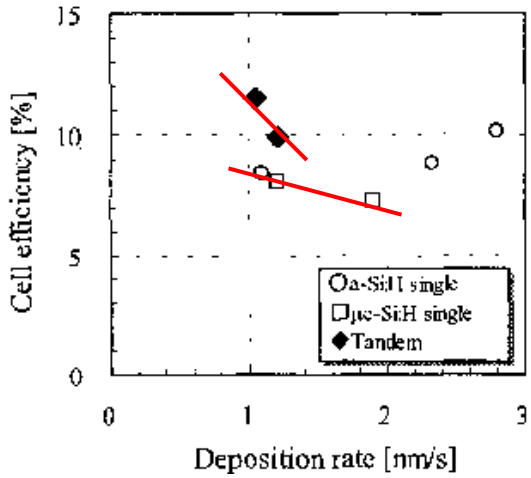
Low plasma damage

VHF-PECVD (40~120MHz)
High pressure & High Power

Efficiency > 12 %
nc-Si DR > 3 nm/s

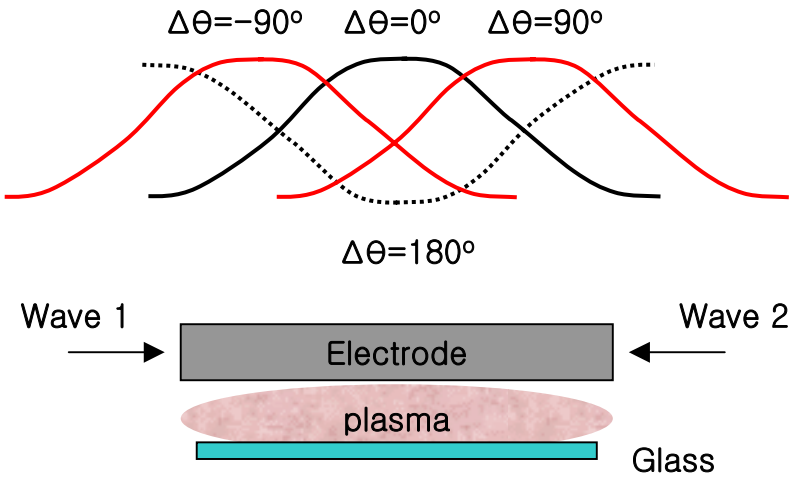


from J. K. Rath, *Solar Energy Materials & Solar Cells* **76,** 431, 2003



Kyocera, World Conf. 2003

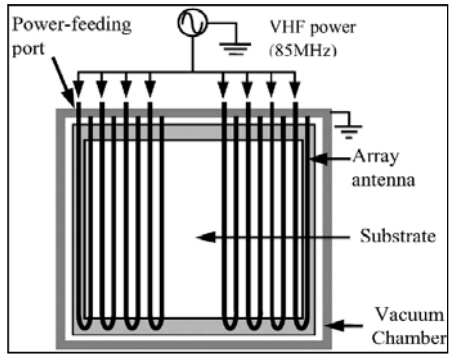
Phase Shift of Incidence Waves



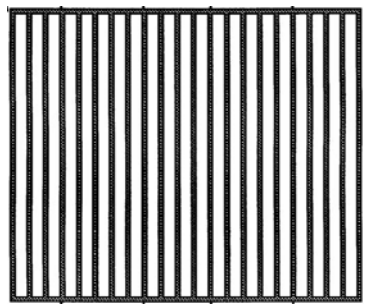
Control of standing-wave position by changing the phase difference of two waves with time

Specific Electrode Design

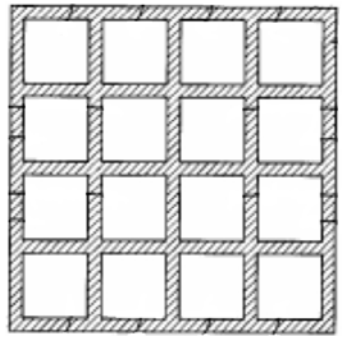
U shape : IHI



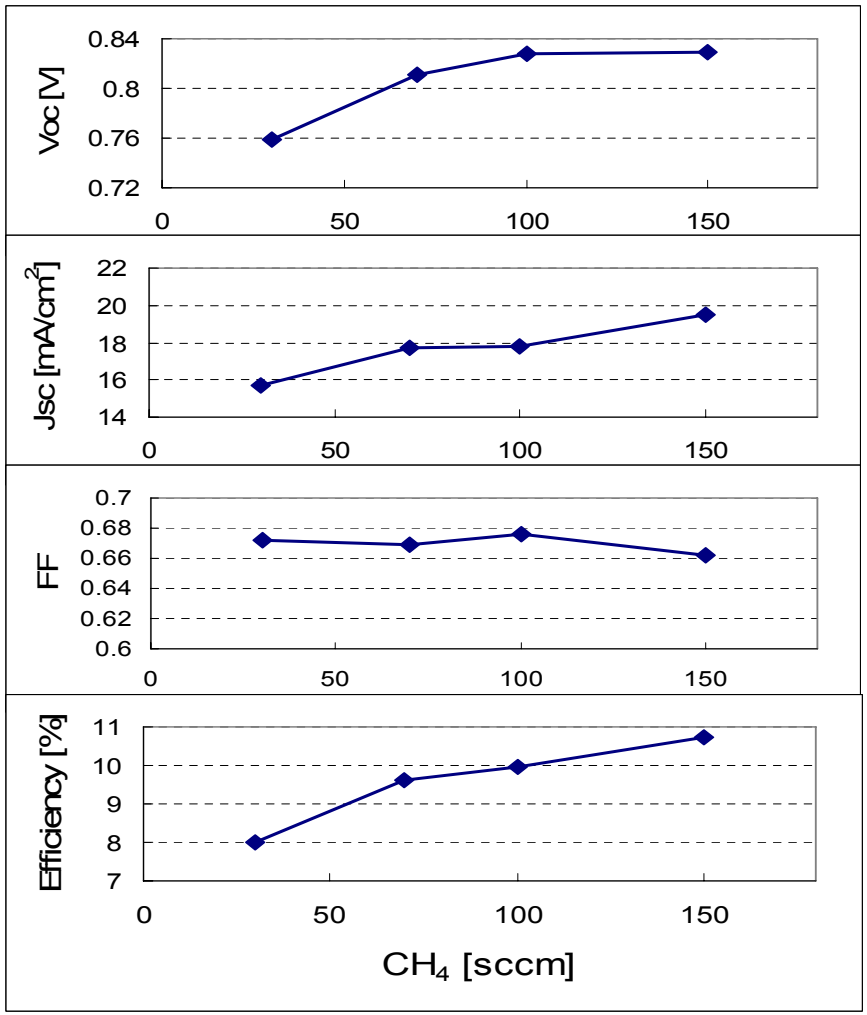
Ladder shape : MHI



Divided electrode : Sharp Inc.



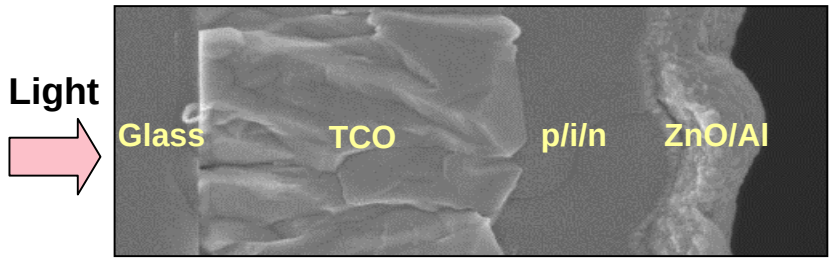
P-layer CH_4 Flow Dependences[1)]



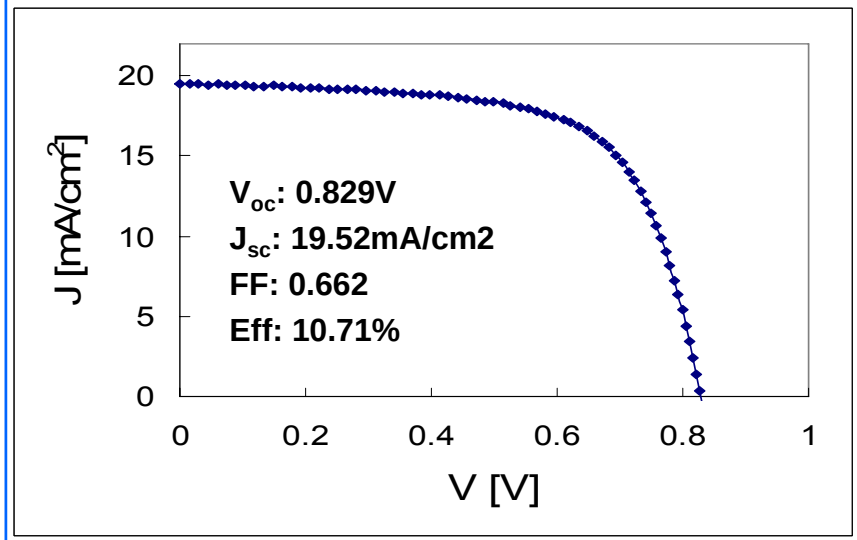
1) H_2:SiH_4:CH_4:B_2H_6 = 100:50:x:3, 20W, 0.2T

Cell Structure & Properties

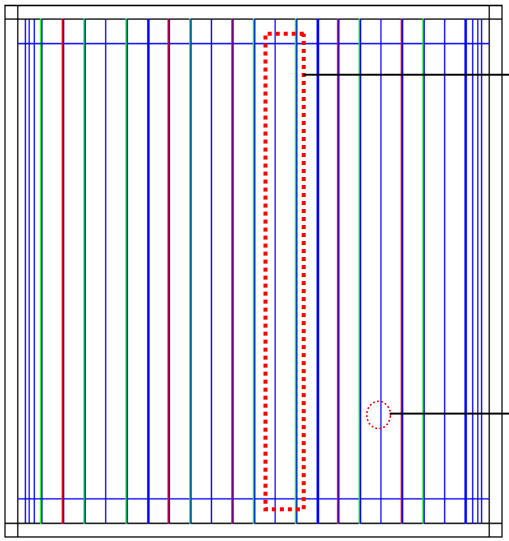
Cross sectional View



J-V Characteristics

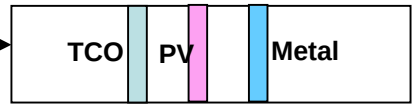


Module Design & Measured Results

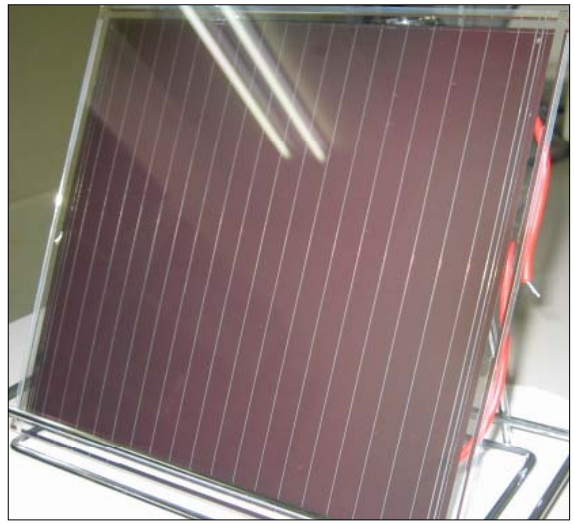


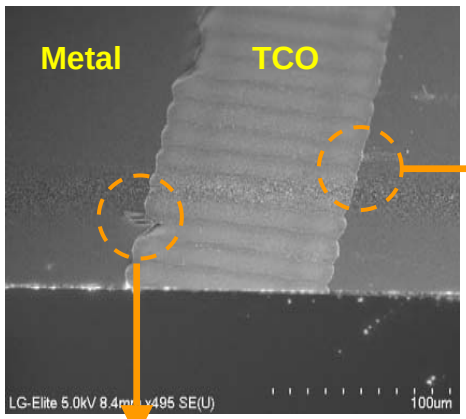
Cell No.: 17
Period: 9.75mm
Length: 182mm
Area: 17.74cm^2
Effective width: 9.35mm

Scribing pattern

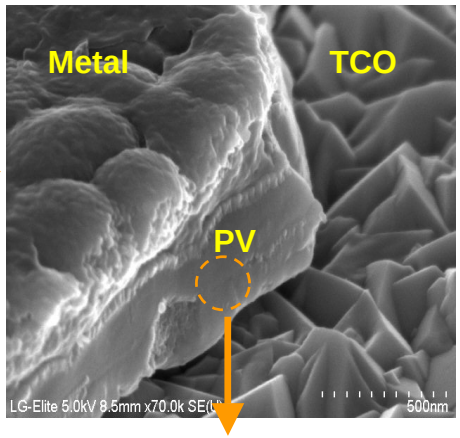


0.4 mm

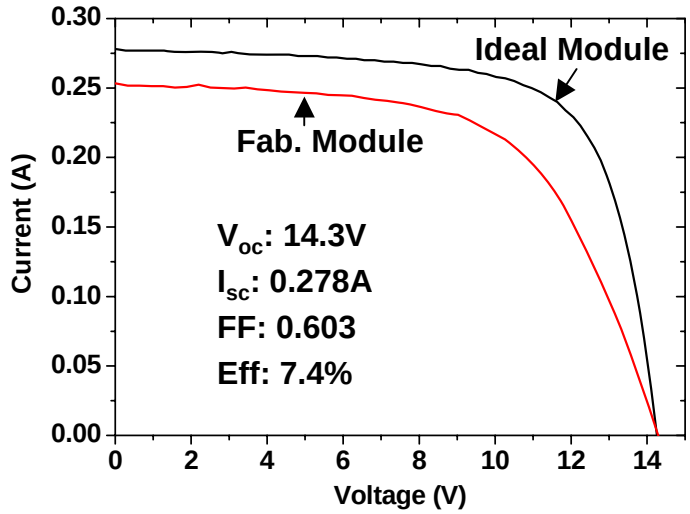




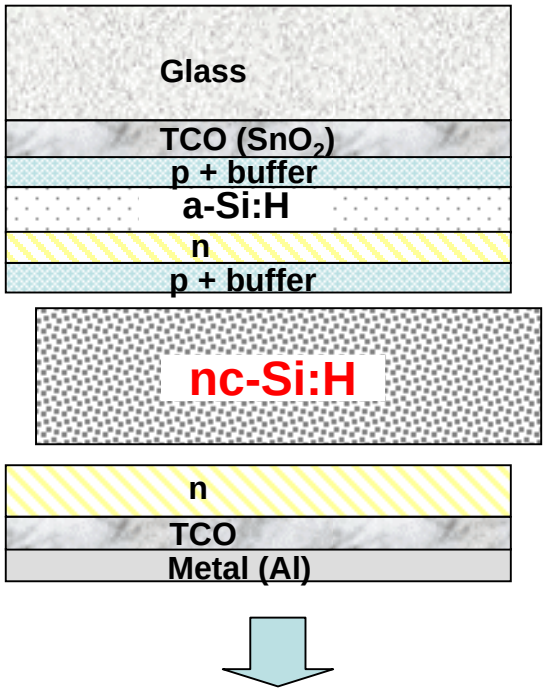
Burr formation



Sn detection (FE Auger analysis)



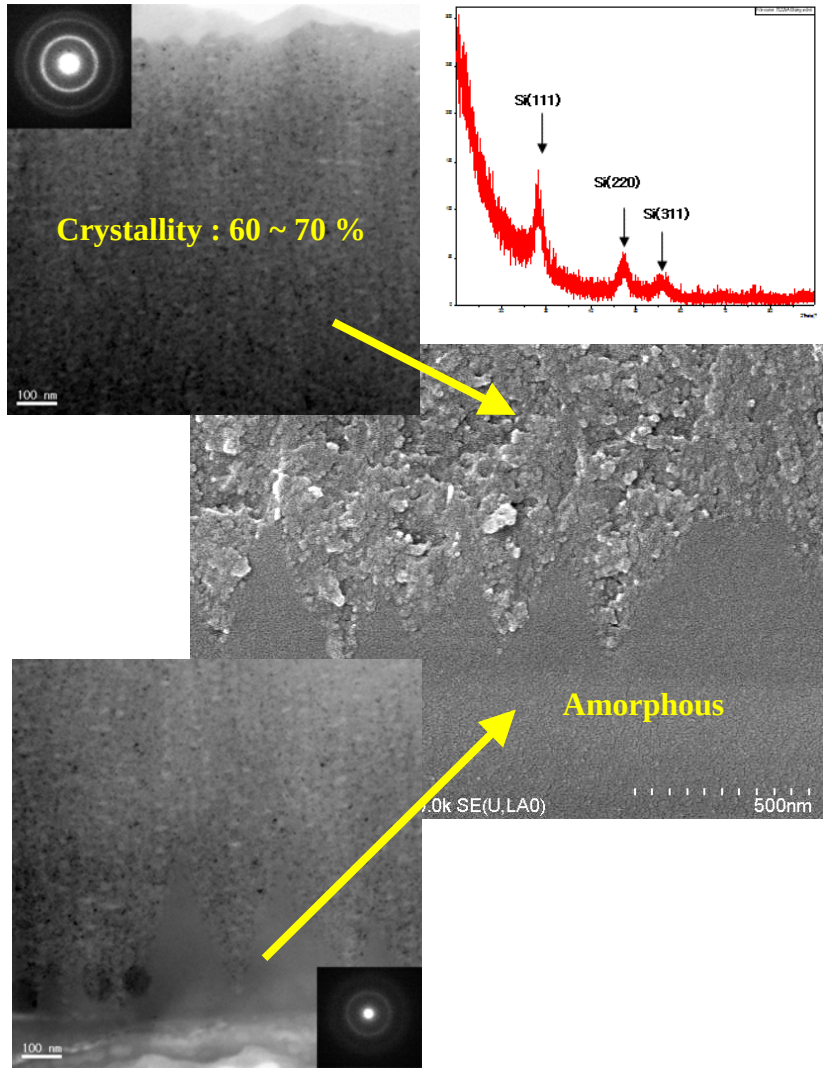
i a-Si:H optimization



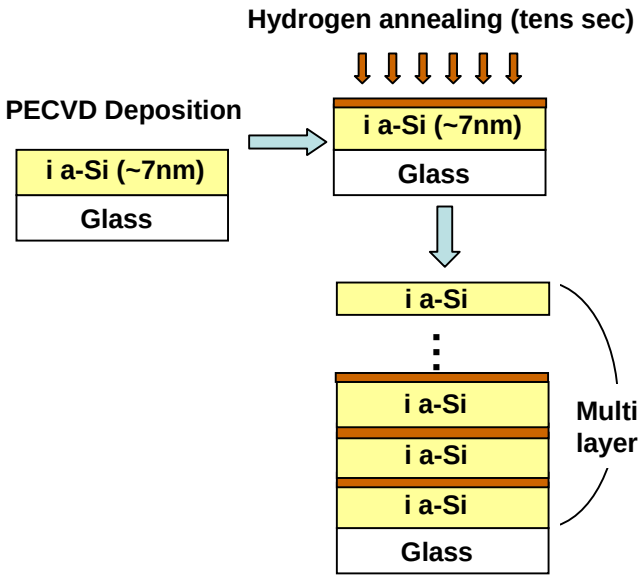
R&D subjects

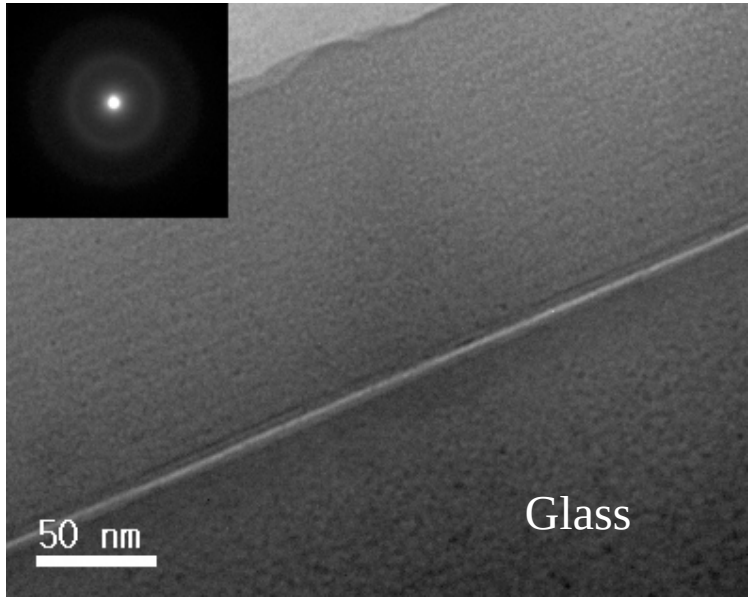
- Deposition Rate
- Crystallite and structure
- Incubation time control
- Low defect density

H_2/SiH_4 effects



Hydrogen Annealed Multi-layer





Expectations

- Low Defect density
  : High Initial Efficiency
- Low Photo-degradation
  : High Stabilized Efficiency

- s Dark: 1.30E-12, s Photo: 1.76E-5

- In investigation :

Bonding structure & Defect density

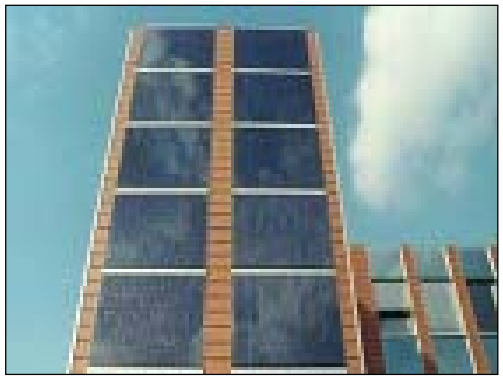
5. Conclusion

- **High potentials in thin film Si tandem solar cells**
  - ➔ Eventual raw material cost reduction (current problem in Si feed-stock)
  - ➔ Expectation of a high efficiency (more than 12%) via tandem cell technologies

- **For commercial success, high demands for the development of nano-crystalline Si thin films deposition technologies with a very high deposition rate**
  - ➔ Process-condition optimization technology
    - : Batch type PECVD and HpHP Process
  - ➔ VHF-PECVD technology : various electrode designs

- **LG Electronics is focusing on the key technology development of thin film Si solar cell and on its commercialization**

< Appendix > BIPV types



Facade

See-through