Development of Photovoltaic Power System toward Large Scale Application

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Outline

1. Solar cell (PV) development situation and generation efficiency limit of multijunction PV
2. Cost of Si PV module
3. Cost estimation of future PV module
4. Cost estimation of concentrator
Theoretical Efficiency

Thermodynamic efficiency of solar cells

Energy conversion through reversible process (Landsberg efficiency)

\[ W = (\hat{E}_s - \hat{E}_r) - T_r (\hat{S}_s - \hat{S}_r) = \sigma (T_s^4 - T_r^4) - T_r (4/3 \sigma T_s^3 - 4/3 \sigma T_r^3), \]

= 1 - (4/3)(T_r/T_s) + (1/3)(T_r/T_s)^4 = 93.3\% , T_s = 5700K, T_r = 300K

s: solar, r: room

The efficiency depends on the device Structure

Single junction

Tandem

Interband

Hot carrier

Sun light

Selective energy contact
Comparison of PV, Thermal Power Generation and Fuel Cell Systems

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>PV</th>
<th>TPG</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>present</td>
<td>15</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>(future)</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Investment cost (Yen/kWh/y)</th>
<th>PV</th>
<th>TPG</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>20</td>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>
Categories of Solar Cells

First generation
- bulk, high cost
  - single crystalline: <24%
  - poly crystalline: <19%
  - amorphous: <13%

Second generation
- Thin film, low cost
  - CIGS, CdTe: <20%
  - Dye-sensitized: <13%
  - organic: <5%

Third generation
- High efficiency, low cost

New category:
- tandem: ~42%
Highest efficiency for 2 layer cells have been recorded as 42.1% (2010, 454 sun), 35.8% (2009, 1 sun) by SHARP.
Single junction cell has the highest efficiency with the band gap of 1.4eV - \[ \eta = \frac{I_{sc} \times V_{oc} \times FF}{P_{incident}} \times 100\% \text{, FF: fill factor} \]

Key issues to improve the performance and decrease the cost:
- Increase the diffusion length of the minor carriers
- Decrease the thickness used
- Developing new production method (sheet growth techniques)

Resourceful and safe → Si-based cells become the mainstream

Control of the defects

Light-trapping, antireflection
Single Junction Solar Cell - Si

Highest efficiency reached in 1998 by UNSW group

Poly-crystalline Si : 19.8%
Single-crystal Si: 24.4%

- Honeycomb structure for reducing the reflection
- Inhibit the surface recombination by oxidation

almost reaching the theoretical efficiency of Si

Green, Appl. Phys. Lett. 73 (14) (1998)
CIGS solar cells are one of the most promising solar cells and expected as the third generation solar cells.

- High efficiency among the thin film cells
  - Lab. Cell (NREL, 0.5cm²) ~19.9%, 2008,
  - Flexible sub-module (AIST, 75.7cm²) 15.9%, 2010
  - Large Module (Showa Shell, 3600cm²) 13.6%, 2007

- Low cost, high production rate
  - module cost target <100¥/W, 1GW/year at 2010 (Showa Shell)

- Excellent long term stability

http://www.showa-shell.co.jp/products/solar/research/cis-0002.html
Fundamentals for CIGS Solar Cells

Basic structure of CIGS solar cells

- **CIGS**
- **Soda lime glass**
- **n⁺-ZnO**
- **CdS** buffer

**Band diagram**

- **CIGS**
- **ZnO**
- **CdS**

Showa Shell new buffer; Zn(O,S,OH)x

- Efficiency was achieved by using GICS with the $E_g \approx 1.2$eV.
- Further improvement can be expected for the GICS with $E_g = 1.4$eV.

- $E_g$ of CIGS can be varied by controlling the In/Ga ratio (1.0-1.7eV).
- The inversion at the junction reduces the recombination.

Type inversion at the interface reduces the recombination.
Challenge for Chalcopyrite Based Cells

- Improvement of Voc
- Development of high quality crystalline CIGS thin film (Ga/(In+Ga)≈0.6, Eg=1.4 eV)
- Optimize the junction structure
  - Buffer layer, wide gap window...
- Reducing the In,Ga content used

Developing a process for the thin film preparation is important

<table>
<thead>
<tr>
<th>物質名</th>
<th>Eg(eV)</th>
<th>a (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn–Ge–P₂</td>
<td>2.34</td>
<td>5.47</td>
</tr>
<tr>
<td>Zn–Sn–P₂</td>
<td>1.66</td>
<td>5.67</td>
</tr>
<tr>
<td>Zn–Ge–As₂</td>
<td>1.15</td>
<td>5.65</td>
</tr>
<tr>
<td>Zn–Sn–As₂</td>
<td>0.73</td>
<td>5.85</td>
</tr>
<tr>
<td>Zn–Sn–Sb₂</td>
<td>0.3</td>
<td>6.28</td>
</tr>
<tr>
<td>Cu–Al–Te₂</td>
<td>2.06</td>
<td>5.96</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Approach to Third Generation Solar Cells

Approach to high efficiency (50%) with low cost

- **Tandem solar cells**: expand the absorption band using multilayer cells
  
  - Increasing $E_g$

- **Quantum dot solar cells**
  
  - Use of size effect for controlling band gaps of tandem cells
  
  - Use of the interband absorption for expanded absorption band
  
  - Use of the hot carriers with long relaxation time for high energy utilization
To form high efficiency multijunction cells monolithically:

- The lattice constant must be matched.
- The bandgap (Eg) of each cell must be optimized regarding V and I.

Conventional three layers of InGaP/GaAs/Ge are adopted due to their accordance in the lattice constant:

- **Top** layer: InGaP, Eg = 1.85 eV
- **Middle** layer: GaAs, Eg = 1.42 eV
- **Bottom** layer: Ge, Eg = 0.67 eV
Multijunction Cell Approach

Ideal 3 layers of 0.74eV/1.2eV/1.8eV cell is calculated to be the efficiency limit of 59% based on $E_g$.

A conventional cell (0.67eV/1.4eV/1.85eV, eff. limit=47%) is not the best combination.

Developing a new material with smaller $E_g$ to replace GaAs

Developing a new material with larger $E_g$ to replace Ge

The photo-induced current is limited by the series-connected GaAs cell composition

devolving a new material with smaller $E_g$ to replace GaAs
devolving a new material with larger $E_g$ to replace Ge
3 layers of (0.74eV/1.2eV/1.8eV) tandem cell has the efficiency limit of 59%
Efficiency can be improved by optimizing the combination of junctions. Efficiency limits are as follows:

- 61% (36 cells, 1 sun) by C. H. Henry
- 71% (36 cells, 1000 sun)

In Sep., 2010, highest efficiency of 42.1% was achieved by the cooperation of TODAI&SHARP.
Multijunction Cells Approach

Increasing Voc

Voc=4.24V

2009, Sharp
35.8%

19.5mA/cm² (limit eff. 59%)

Ideal 3 layers: 0.74eV/1.2eV/1.8eV

Voc=3V

Isc=13.94mA/cm²

Voc=3.98V

Conventional
32%

Voc=3.62V

Increasing photo-current

InGaP Eg = 1.85 eV

GaAs Eg = 1.42 eV

InGaAs Eg = 0.97 eV

InGaP Eg = 1.75 eV

InGaAs Eg = 1.2 eV

Ge Eg = 0.67 eV

2009, Fraunhofer-ISE
41.1%(454sun)

Increasing Voc

InGaP Eg = 1.88 eV

GaAs Eg = 1.42 eV

Ge Eg = 0.67 eV

InGaP Eg = 1.85 eV

GaAs Eg = 1.42 eV

InGaAs Eg = 0.97 eV

InGaP Eg = 1.88 eV

GaAs Eg = 1.42 eV

Ge Eg = 0.67 eV

Increasing photo-current
InGaP

GaAs

InGaAs

GaAs

InGaP

Supporting substrate

$E_g = 1.85 \text{ eV}$

$E_g = 1.42 \text{ eV}$

$E_g = 0.97 \text{ eV}$

2009, Sharp:35.8%

To realize the junctions

Inversion of the depositing processes: forming top, middle and finally bottom cells by inserting a buffer layer
Selection of material combination to increase Voc is important
Increasing the number of cell layers is an effective way to improve the efficiency. However, the mismatch of the lattice constant limits the combinations.

Developing the process for preparing new materials and forming junctions are important.
Multijunction Cell Approach in TODAI

Developing a novel bulk III-V crystal or using strain-compensated structures → technical process developing such as CVD is important

3 junctions:
- InGaP, $E_g = 1.75 \text{ eV}$
- InGaAs, $E_g = 1.2 \text{ eV}$
- Ge, $E_g = 0.67 \text{ eV}$

Fraunhofer:
- new material for 1 eV layer

4 junctions:
- AlInGaP, $E_g = 2.0 \text{ eV}$
- InGaAs, $E_g = 1.4 \text{ eV}$
- Ge, $E_g = 1.0 \text{ eV}$
- Ge, $E_g = 0.67 \text{ eV}$

Lattice const. matched

bulk quantum dots quantum wells

InGaAsN:Sb
InAs/GaAsN:Sb
InGaAsN/GaAs
InGaAs/GaAsP

By Okada and Sugiyama

use of strain compensation mechanism
The efficiency limit of 4 layers (0.67eV/1eV/1.4eV/2eV) cell is 52%

The current is limited by the top cell
4 layers of (0.52eV/0.98eV/1.4eV/1.92eV) tandem cell has the efficiency limit of 64%
Solar Cell with Quantum Dots Layer

Solar cells with quantum dots layer

At 1100°C in N2

Heating the layers of SiO$_2$ and SiO$_x$ (Si rich) to form Si quantum dots

Voc increase by the dot size decrease ($\eta \sim 10\%$)

size effect was confirmed

M. A Green, Nanotechnology 19 (2008) 245201
Outlook of Solar Cells with Quantum Dots Layer

Cell with Si quantum dots layer achieved efficiency of 1% (Konagai, TIT)

realize the tandem cells by developing novel quantum dots materials to optimize the bandgaps

By M. Konagai
Outlook of Solar Cells with Quantum Dots Layer

Using interband absorption can reach the efficiency higher than 60%

InAs QD in <20nm space

(Prof. Okada, TODAI)

researches to realize the ideal band structure

- Developing new materials
- Control of structure (barrier thickness < 10nm)
**Higher Performance CIGS Cell**

Multijunction cell of CIGS system

Eg of CIGS can be varied by controlling the In/Ga ratio (1.0-1.7 eV)

\[
E_g = 1.010 + 0.626x - 0.167x(1 - x), \quad x = \text{In/Ga}
\]

<table>
<thead>
<tr>
<th>Wider gap Eg ~1.8 eV</th>
<th>CuGaSe2 Eg ~1.7 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuInGaSe2 Eg ~1.4 eV</td>
<td>CuInGaSe2 Eg ~1.2 eV</td>
</tr>
<tr>
<td>CuInSe2 Eg ~1.0 eV</td>
<td>narrower gap ~0.7 eV</td>
</tr>
</tbody>
</table>

- **Eff. limit**: 45%
- **Eff. limit**: 50%
- **3j**: Max. 59%
- **4j**: Max. 63%

Compatible material of Eg ~1.8 eV or Eg ~0.7 eV is required

Developing of buffer layer and tunnel junction are important
New materials with multi-elements

3j:0.74/1.2/1.8, 4j:0.52/.98/1.4/1.92eV
## Calculation Basis of Poly-crystalline Si PV Module Production

<table>
<thead>
<tr>
<th>Production rate</th>
<th>Cell efficiency (Module)</th>
<th>Thickness</th>
<th>Si</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 : 10MW/y</td>
<td>15%(12)</td>
<td>250µm</td>
<td>3.2mm</td>
<td></td>
</tr>
<tr>
<td>Case 2 : 1GW/y</td>
<td>17%(15)</td>
<td>200</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Case 3 : 100GW/y</td>
<td>20%(17)</td>
<td>200</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>
Silica(SiO$_2$) → Reduction → Si → purification → SOG Si → Casting → Wafer production → Cell production → Inspection → PV Cell

Process of multi crystalline Si PV cell
case1 2,3 (top data)

- **Wafer thickness**: 250 → 200 µm → (100µm)
- **Cutting loss**: 280 → 200µm → (100µm)
- **Cutting velocity**: 300 → 500m/min

(30% cost down of cell by 100µm thinning)
## Cost and CO₂ Emissions of Multi C.-Si PV Module

<table>
<thead>
<tr>
<th>(Efficiency)</th>
<th>Case1-10MW (Cell;15%,Md;11.8%)</th>
<th>Case2-1GW (Cell;17%,Mod;14.2%)</th>
<th>Case3-100GW (Cell;20%,Mod;17.0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂ g-C/W % %/W</td>
<td>CO₂ g-C/W % %/W</td>
<td>CO₂ g-C/W % %/W</td>
</tr>
<tr>
<td>SOG-Si production</td>
<td>178 44 74 19</td>
<td>86 42 23 14</td>
<td>52 40 13 12</td>
</tr>
<tr>
<td>Wafer</td>
<td>99 25 94 24</td>
<td>47 23 41 24</td>
<td>22 17 20 18</td>
</tr>
<tr>
<td>Cell</td>
<td>32 8 111 28</td>
<td>15 7 33 20</td>
<td>9 7 18 17</td>
</tr>
<tr>
<td>Module</td>
<td>93 23 112 29</td>
<td>56 27 71 42</td>
<td>47 36 60 54</td>
</tr>
<tr>
<td>Total</td>
<td>402 100 391 100</td>
<td>204 100 168 100</td>
<td>130 100 111 100</td>
</tr>
</tbody>
</table>

Case3; 6g-C/kWh, 10Yen/kWh
Module Material Cost

Yen/W


- Glass
- EVA
- Al Flame
- Back sheet
- Cu lead
- Sealing material

Costs for Materials:
- Glass
- EVA
- Aluminum Flame
- Back sheet
- Copper Lead
- Sealing Material
Cost reduction of Poly-Si PV module by scale-up (SM), efficiency increase (EI), and technology improvement (TI)

<table>
<thead>
<tr>
<th>Case</th>
<th>Production rate(GW/y)</th>
<th>Total cost(Yen/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>0.01</td>
<td>391</td>
</tr>
<tr>
<td>Case2</td>
<td>1</td>
<td>169</td>
</tr>
<tr>
<td>Case3</td>
<td>100</td>
<td>111</td>
</tr>
</tbody>
</table>

Cost Reduction by SM, EI, TI

<table>
<thead>
<tr>
<th>Case</th>
<th>1→2</th>
<th>2→3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>43 Yen/W</td>
<td>3 Yen/W</td>
</tr>
<tr>
<td>EI</td>
<td>43</td>
<td>26</td>
</tr>
<tr>
<td>TI</td>
<td>136</td>
<td>29</td>
</tr>
</tbody>
</table>

Total Reduction:

- SM: 222 Yen/W
- EI: 58 Yen/W
Future 1kW PV module weight and cost

(17%) (110Yen/W)  
(14.4%)  

<table>
<thead>
<tr>
<th>Poly-crystalline Si</th>
<th>Glass</th>
<th>Amorphous Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4kg</td>
<td></td>
<td>42.7kg</td>
</tr>
<tr>
<td>2.5kg</td>
<td>Cell</td>
<td>0.04kg</td>
</tr>
<tr>
<td>(2.4kg)</td>
<td>Si</td>
<td>(0.005kg)</td>
</tr>
<tr>
<td>6.4kg</td>
<td>Filling material</td>
<td>4.7kg</td>
</tr>
<tr>
<td>1.3kg</td>
<td>Back sheet</td>
<td>2.0kg</td>
</tr>
<tr>
<td>0.6kg</td>
<td>Sealing materials</td>
<td>0.9kg</td>
</tr>
<tr>
<td>7.1kg</td>
<td>Al frame</td>
<td>14.1kg</td>
</tr>
<tr>
<td>47.3kg</td>
<td>Total</td>
<td>64.4kg</td>
</tr>
</tbody>
</table>

Present Module of SHARP; Polycrystalline Si, 13.3%, 95kg, 300Yen/W
PFD Example of Three Junction Cell

Back Electrode Sputtering

Laser Patterning

Bottom Layer MOCVD

Middle Layer MOCVD

Top Layer MOCVD

Laser Patterning

Transparent Electrode Sputtering

Laser Patterning

Module Process

Glass

Mo

MO1 (Ge)

MO2 (In, Ga, As)

MO3 (In, Ga, P)
Investment Cost of PV Module (1GW/y)

<table>
<thead>
<tr>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CIGS system, Efficiency = 13%)</td>
<td>（In-Ga-As-P system 3 layers, Eff. = 40%）</td>
</tr>
<tr>
<td>100BYen</td>
<td>① 30BYen (1 layer/min.)</td>
</tr>
<tr>
<td></td>
<td>② 300BYen (1 layer/100min.)</td>
</tr>
</tbody>
</table>
## Production Costs of PV Modules (Yen/W)

<table>
<thead>
<tr>
<th>Case Item</th>
<th>Present (CIGS)</th>
<th>Future(^1) (InGaAsP)</th>
<th>Future(^2) (InGaAsP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer Material</td>
<td>10</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Others Material</td>
<td>80</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Electricity</td>
<td>5</td>
<td>&lt;1</td>
<td>50</td>
</tr>
<tr>
<td>Labor</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Depreciation etc.</td>
<td>15</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>Total</td>
<td>112</td>
<td>51</td>
<td>145</td>
</tr>
</tbody>
</table>
Limits of **Ga** and **In** Resources

I  Required material weight

1  CIGS Cell (Efficiency = 15%, Layer thickness 2µm)
   - Ga weight = 9g/kW = 900 t/100GW
   - In weight = 26g/kW
     = 2,600 t/100GW

2  Ga system cell (3-junction, Eff. = 40%, Layer thickness = 2µm)
   - Ga weight = 15g/kW = 1,500 t/100GW

II  Present production rates and potential of **Ga**, **In** resources

<table>
<thead>
<tr>
<th></th>
<th>Production (2007 t/y)</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ga</strong></td>
<td>221 (96*)</td>
<td>110,000 t/y (Ca. 1,000 ** t/y)</td>
</tr>
<tr>
<td><strong>In</strong></td>
<td>1,340 (530* )</td>
<td>30,000</td>
</tr>
</tbody>
</table>

*Recycled in Japan  **From Bayer process
The Tracker Telescope Concept

Advantages:
- Stiff
- Low mass
- Simple tracker mechanism
- Minimal environmental impact
- 8 float glass sheets: Low self-shadowing in array “farm”
- Capacity 20KW
On-sun at 1000x
Investment Cost Estimation of 54 m² Concentrator (1000 sun)

Main device component and cost for the PV generation capacity of 27KW

1. Mirror: 3m×3m×6mm glass with Ag back coat, 6 plates(54 m²) 0.8tons, 1.5MYen
2. Steel supporter: 2tons, 0.5MYen
3. Cooling system: 1m², 1MYen
4. Tracking system: 2MYen
5. Others: 1MYen

Total 6MYen

Investment cost = 220Yen/W
Cost comparison of PV connected grids with and without battery

**Case 1** (19GWPV/60GWgrid)
Battery 38GWh=400BYen/y or
Without battery, 2% of PV electricity wasted=8BYen/y

**Case 2** (38GWPV/60GW)
Battery 152GWh=1500BYen/y or
Without battery, 10% of PV electricity wasted=80BYen/y

(based on PV elec.=20Yen/kWh, Battery=10Yen/Wh·y)

PV 発電による等価需要の低下（5月）
最大需要60GWに19GWのPV導入
PVは発電量の6％（全国では58GWのPV）

Figure by K. Ogimoto
Conclusion

Cost reduction measures

For the application of PV generation system on a large scale, following items are important:

- The generation efficiency higher than 40%
- New materials with variety of Eg and lattice const.
- The layer formation rate higher than 1 µm/min
- Lighter supporting materials
- Rational manufacturing equipment
- Application of rich and safe resource