Emerging High-Efficiency Low-Cost Solar Cell Technologies

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DOE’s Sunshot Goal: $1/W by 2017

A module efficiency of 25% is wanted to enable the installation cost reductions.

Silicon is currently competitive in favorable locations with the current subsidies.

In 2017 the cost of silicon cells will probably be $0.65/W.
There are many approaches to making PV cells and experts do not agree on which one is the best.
Silicon PV

Silicon Feedstock → Ingot Growth → Slicing Wafers

Photovoltaic System ← Module Encapsulation ← Cell Fabrication
19.6% efficient planar cells on silicon

Source: J-H Lai, IEEE PVSC, June 2011
LOS is line of sight

<table>
<thead>
<tr>
<th>Table 2  Data table of cost analysis results as displayed in Fig. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Wafer</strong></td>
</tr>
<tr>
<td>Silicon feedstock</td>
</tr>
<tr>
<td>Depreciation</td>
</tr>
<tr>
<td>Labor</td>
</tr>
<tr>
<td>Wire sawing</td>
</tr>
<tr>
<td>Ingot casting</td>
</tr>
<tr>
<td>Maintenance</td>
</tr>
<tr>
<td>Yield loss</td>
</tr>
<tr>
<td>Input electricity</td>
</tr>
</tbody>
</table>

| **Cell**                                                     |
| Metal paste                                                 | 0.111 | 0.047 | 0.054 |
| Depreciation                                                | 0.063 | 0.061 | 0.051 |
| Chemicals                                                   | 0.045 | 0.039 | 0.017 |
| Labor                                                       | 0.034 | 0.020 | 0.013 |
| Yield loss                                                  | 0.030 | 0.020 | 0.011 |
| Input electricity                                           | 0.024 | 0.026 | 0.021 |
| Maintenance                                                 | 0.018 | 0.016 | 0.013 |
| Screens                                                     | 0.013 | 0.010 | 0.000 |

Table 2  Data table of cost analysis results as displayed in Fig. 2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>0.073</td>
<td>0.056</td>
<td>0.047</td>
</tr>
<tr>
<td>Frame</td>
<td>0.060</td>
<td>0.046</td>
<td>0.000</td>
</tr>
<tr>
<td>Back sheet</td>
<td>0.050</td>
<td>0.038</td>
<td>0.032</td>
</tr>
<tr>
<td>JB and cable</td>
<td>0.040</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>Encapsulant</td>
<td>0.039</td>
<td>0.030</td>
<td>0.025</td>
</tr>
<tr>
<td>Labor</td>
<td>0.034</td>
<td>0.020</td>
<td>0.013</td>
</tr>
<tr>
<td>Ribbon</td>
<td>0.032</td>
<td>0.025</td>
<td>0.000</td>
</tr>
<tr>
<td>Depreciation</td>
<td>0.028</td>
<td>0.028</td>
<td>0.023</td>
</tr>
<tr>
<td>Yield loss</td>
<td>0.025</td>
<td>0.017</td>
<td>0.010</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.009</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>Input electricity</td>
<td>0.003</td>
<td>0.004</td>
<td>0.003</td>
</tr>
<tr>
<td>Packaging</td>
<td>0.003</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.293</strong></td>
<td><strong>0.890</strong></td>
<td><strong>0.523</strong></td>
</tr>
</tbody>
</table>
Fig. 3  Sensitivity study for the 2012 module cost structure. Input variables that strongly determine module cost are shown toward the top of the plot, while variables that have a large cost reduction potential are shown toward the right.
156 x 156 mm² full-square cell (242.6 cm²)
43 µm epitaxial Si cell, FSRV < 10 cm/s
Voc = 681.7 mV
Jsc = 38.14 mA/cm²
FF = 77.41%
Cell Max Power = 4.88 Wp; Isc = 9.25 A

Device ID: V4-Supreme-16-4106
Oct 11, 2012 12:51
Spectrum: ASTM G173 global

Device Temperature: 24.5 ± 0.5 °C
Device Area: 242.6 cm²
Irradiance: 1000.0 W/m²

NREL-Certified Full-Area Cell Efficiency = 20.13%
Lightweight BIPV solution:
- 7 kg/m² for BIPV shingle demo system
- BIPV is < half the weight of typical framed glass-covered modules
- 2/3 the weight of asphalt shingles
- Distributed shade management

Simple, flat box packaging for shipment and storage

Capability of supporting walking
Using nanocones to enable complete light absorption in thin Si

Gallium Arsenide

- The 1.4 eV band gap is ideal for solar cells.
- High quality films are grown on single crystal substrates with MOCVD.
Alta Devices 28.8% efficient thin-film GaAs cell

a) MOCVD growth of device structure on reusable GaAs substrate.

b) Deposition of back contact metals and bonding of sample to flexible handle.

c) Dissolution of AlAs release layer to produce thin-film device on metal and flexible backing.

d) Completion of device fabrication.

Source: B. Kayes, IEEE PVSC, June 2011
Photon recycling

Why thin film GaAs is better

- Remitted photons are weakly absorbed and can easily travel more than a carrier diffusion length away from the junction in a wafer-based device.
- In a thin cell, a mirror keeps photons near the pn junction.

Theoretical limits

TABLE I

$V_{OC}$, $J_{SC}$, and Efficiency Values for Three Possible Geometries and Relevant Cell Thicknesses

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Textured, good mirror</th>
<th>Untextured, good mirror</th>
<th>Untextured, bad mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>$500\text{nm}$</td>
<td>1.14</td>
<td>1.16</td>
<td>1.08</td>
</tr>
<tr>
<td>$1\mu\text{m}$</td>
<td>1.13</td>
<td>1.15</td>
<td>1.08</td>
</tr>
<tr>
<td>$10\mu\text{m}$</td>
<td>1.12</td>
<td>1.14</td>
<td>1.07</td>
</tr>
<tr>
<td>Voc (volts)</td>
<td>32.3</td>
<td>29.5</td>
<td>25.2</td>
</tr>
<tr>
<td>Jsc (mA/cm$^2$)</td>
<td>32.7</td>
<td>31.6</td>
<td>29.5</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>efficiency %</td>
<td>32.8</td>
<td>30.6</td>
<td>24.3</td>
</tr>
</tbody>
</table>

A good rear mirror is crucial to a high open-circuit voltage and, consequently, to efficiencies above 30%.

A Manufacturing Cost Analysis Relevant to Photovoltaic Cells Fabricated with III-Vs

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
An Example Process Flow for Making Single-Junction III-V Devices by ELO

1. Unpack and clean GaAs epi-wafer.

2. MOVPE of AlAs release layer.

3. MOVPE of GaAs contact layer.

4. MOVPE of AlInGaP window layer.

5. MOVPE of GaAs emitter layer.

6. MOVPE of GaAs base layer.

7. MOVPE of InGaP BSF.

8. MOVPE of AlGaAs contact / buffer layer.

9. Deposition of back contact metals and bonding of cell to flexible handle (PET).

10. Dissolution of AlAs release layer and release of cell from epi-wafer.

11. Lithography and etching of contact layer.

12. Frontside metalization.

13. Deposit AR coating.

14: Edge isolation.

15: J-V testing and sorting.

133 cm² single junction GaAs solar cell on flexible handle.

Ongoing NREL Analysis
9/13/2013
Step 1: Unpack and Clean GaAs Parent Epi-Substrate—3
(The Reference Case Scenario in the Bar Chart Assumes 50 Reuses and 70% Yields)

The Costs for the Epi Substrate as a Function of Reuse Number
Reference Case Repolishing Cost ($8 per repolish per 133 cm² wafer) and Cell Efficiency (25%)

Please see the annotated notes below this slide for more details.
Cost Summary, by Step, for the Reference Case.
(20 substrate reusages, precursor utilizations of 30% for the III- source and 20% for the V- source, 15 μm/hr GaAs, 70% effective cell yield )

Calculated Device Processing Costs for Single-Junction III-V's
500 MW$_{P(DC)}$ U.S. Facility, 25% Cell Efficiency, 70% Yield, 5 yrs Equipment Depreciation

Please see the annotated notes below this slide for more details.
Technology Roadmap Simulations for Single-Junction III-V’s (GaAs Base)

Cost Model Results for Single-Junction (SJ) GaAs Solar Cells by ELO

$150 for 133 cm² Substrates, 0.25 Laborers per Reactor, U.S. Manufacturing

All stated efficiencies are AM 1.5G and 1000 W/m²

$0.00 $1.00 $2.00 $3.00 $4.00 $5.00 $6.00 $7.00 $8.00 $9.00 $10.00 $11.00 $12.00 $13.00

Current US $/ W

$13.60/ W

Improvements in Epi-Substrate Utilization
Increase Parent Epi-Substrate Reuses:
From 20 reuses to 500 reuses
Replace Chemical-Mechanical Repolishing with Wet Bench Surface Preparation
Lower WACC:
From 9% to 7%

$13.00

Improvements in Cell Processing
Increase Material Utilization:
From 30% to 50% for TMG, TMI, and TMA
From 20% to 30% for AsH₃ and PH₃
Reduce GaAs Base Thickness:
From 2.5 µm to 1.5 µm
Increase GaAs Deposition Rate:
From 15 µm/hr to 20 µm/hr
Secure Lower TMG Costs:
From $2.50/g to $2.00/g
Eliminate Au, Pt and/or Pd from metallizations
Improve the Effective Cell Yield:
From 70% to 95%
Lower WACC:
From 7% to 6%

$12.00

Novel Manufacturing Process*
*Publicly Available Demonstrations Currently Unknown
Reduce Device Materials Costs by 80% from the Long-Term Case for MOVPE (e.g., different precursors and higher utilizations)
Reduce Cell Labor & Depreciation Expenses by 80% from the Long-Term Case for MOVPE (e.g., higher dep. rates and larger batch sizes)

$11.00

$10.00

$9.00

$8.00

$7.00

$6.00

$5.00

$4.00

$3.00

$2.00

$1.00

$0.00

Reference Case (η=25%)
Mid-Term (η=27%)
Long-Term MOVPE (η=29%)
Long-Term SJ GaAs (η=29%)

NREL Cost Analysis 9/23/2013

$4.60/ W

$2.40/ W

$1.00/ W

$0.50/ W

(SunShot Adjusted Cell Price Goal)

Required margin to meet minimum sustainable cell price
Depreciation (Capital Equipment and Building)
Electricity
Labor & Maintenance
Materials Costs for Device Layers
Parent epi-substrate and Chemical-Mechanical Polishing

Epi-Substrate
CMP
Sample Products

Integrated 7-in Tablet
Power: 4.3W
Area: 17.35 x 10 cm

Smartphone Case
Power: 1.3W
Area: 5 x 10.5 cm

Tablet and Smartphone Cases
What can be done to bring the costs down?

- Huge breakthrough in reducing materials deposition cost.
- Use concentrators. With epitaxial liftoff, 500 X concentrators might not be necessary. Trackers for 10 X concentrators are relatively cheap.
Cadmium Telluride Solar Cells

- Direct bandgap, $E_g = 1.45 \text{eV}$
- High module production speed
- Very inexpensive
- 20.4 % efficiency

Image from Rommel Noufi
Schematic from Bulent Basol
CdTe: Industrial Status

First Solar is the leader. It takes them 2.5 hours to make a 13.4% module.

The energy payback time is 0.8 years.

Average Manufacturing Cost
- 2006: $1.40/watt
- 2007: $1.23/watt
- 2008: $1.08/watt
- 2009: $0.87/watt
- 2010: $0.77/watt
- 2011: $0.74/watt
- 2012: $0.64/watt
- 2013: $0.53/watt
Efficiency limits

Sources of energy loss

- Thermalization of excess energy
- Below band gap photons not absorbed

CB (Conduction Band)
VB (Valence Band)

Increasing $V_{OC}$ and decreasing $J_{SC}$
There are lots of 3\textsuperscript{rd} Generation ideas to beat the Shockley-Quiesser limit, but only one that works.
Higher-efficiency MJ cells require new materials that divide the solar spectrum equally to provide current match.

Ge provides lattice match but the bandgap is too small.

**Example Structures**
- **Conventional MJ Cell**
  - Ge: 0.7 eV
  - GaAs: 1.4 eV

**New Solar Junction MJ Cell**
- GaInNAs: 1.0 eV
- GaInP: 1.8 eV
- GaAs: 1.4 eV
4-junction cell with 44.7% efficiency at 297 suns

World record solar cell with 44.7% efficiency, made up of four solar subcells based on III-V compound semiconductors for use in concentrator photovoltaics. ©Fraunhofer ISE
Multijunction Cells are Very Expensive

- These complex structures are grown very slowly under high vacuum.

- 37% cells can be purchased for $50,000/m²

- Concentrating the light is essential.
Concentrating Light

It is possible to track the sun and concentrate the light by 500X

Dish Shape

Sol Focus
Hybrid Tandems Are Intended to be a High-Performance Low-Cost Option

**Efficiency**

- **Organic**
  - 12% efficient
  - $30/m²

- **Hybrid**
  - 30% efficient
  - $100/m²

- **Epitaxial Crystalline**
  - 45% efficient
  - $40,000/m²

**Cost**

- **Organic**
  - $30/m²

- **Hybrid**
  - $100/m²

- **Epitaxial Crystalline**
  - $40,000/m²

**Low Cost Defect-Tolerant Technology:**
- Perovskite, Organic, Nanowires or II-VI
  - $E_g \approx 1.9 \, eV$

**Established Technology:**
- Silicon or CIGS
  - $E_g \approx 1.1 \, eV$
InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by Exceeding the Ray Optics Limit

Jesper Wallentin, 1 Nicklas Anttu, 1 Damir Asoli, 2 Maria Huffman, 2 Ingvar Åberg, 2 Martin H. Magnusson, 2 Gerald Siefer, 3 Peter Fuss-Kailuweit, 3 Frank Dimroth, 3 Bernd Witzigmann, 4 H. Q. Xu, 1, 5 Lars Samuelson, 1 Knut Deppert, 1 Magnus T. Borgström 1*

Surface recombination velocity = 170 cm/s

Stion, Khosla-Funded PV Startup, Hits 23.2% Efficiency With Tandem CIGS

Greentech Media
February 24, 2014
‘Perovskite’ Describes a Crystal Structure Class

Generic formula: $ABX_3$

$\text{CH}_3\text{NH}_3^+ \quad \text{Pb}^{2+} \quad \text{I}^-$

$\text{CH}_3\text{NH}_3\text{PbI}_3$

*Methylammonium-lead-iodide*
Perovskite Solar Cells are Soaring

Snaith et al., *En. Env Sci.* Jan 2014
Snaith et al., *Nature* Sep 2013
Grätzel et al., *Nature* Jul 2013
Perovskite Solar Cells Evolved From the Dye-Sensitized Solar Cell

![Perovskite Solar Cell Diagram](image)

- **Current density (mA cm⁻²):**
  - $P_{in}$: 96.4 mW cm⁻²
  - $J_{sc}$: 20.0 mA cm⁻²
  - $V_{oc}$: 993 mV
  - FF: 0.73
  - PCE: 15.0%

- **Diagram shows the layers:**
  - Au
  - HTM
  - TiO₂/CH₃NH₃PbI₃
  - FTO
  - Glass

![Simple Scanning Electron Microscopy (SEM) Image](image)
Perovskites AreCompatible With A Planar P-I-N Architecture

$J_{sc} = 21.5 \text{ mA/cm}^2$
$V_{oc} = 1.07 \text{ V}$
$FF = 0.68$
$\eta = 15.4\%$
### Low Bandgap – $q \cdot V_{oc}$ Loss in Perovskite Solar Cells

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap (eV)</th>
<th>$q \cdot V_{oc}$ (eV)</th>
<th>Energy loss (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>1.43</td>
<td>1.12</td>
<td>0.31</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.12</td>
<td>0.75</td>
<td>0.37</td>
</tr>
<tr>
<td>CIGS</td>
<td>~1.15</td>
<td>0.74</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Perovskite</strong></td>
<td><strong>1.55</strong></td>
<td><strong>1.07</strong></td>
<td><strong>0.48</strong></td>
</tr>
<tr>
<td>$(\text{CH}_3\text{NH}_3\text{PbI}_3)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>1.49</td>
<td>0.90</td>
<td>0.59</td>
</tr>
<tr>
<td>a-Silicon</td>
<td>1.55</td>
<td>0.89</td>
<td>0.66</td>
</tr>
</tbody>
</table>

M. Green et al. Solar cell efficiency tables (version 42) July 2013
The traps are shallow

The Perovskite is a Strongly-Absorbing Direct Band Gap Semiconductor
The Perovskite Bandgap can be tuned by Chemical Substitution

The band gap can be tuned from 1.57 eV to 2.23 eV by substituting bromine for iodine in CH$_3$NH$_3$Pb(Br$_x$I$_{1-x}$)$_3$

For hybrid tandem with CIGS

data by McGehee group and Noh et al., Nano Lett. 2013
Hybrid Tandem Architectures

4 Terminal
- Easier prototyping
- No current matching required
- No tunnel junction or recombination layer required

2 Terminal
- Fewer layers that parasitically absorb
- Module fabrication easier
Our Semitransparent Perovskite Cells

Colin Bailie, Grey Christoforo

\[ \eta_{\text{semi-transparent}} = 10.4\% \]
\[ \eta_{\text{opaque}} = 12.3\% \]
### Preliminary Cost Estimates

<table>
<thead>
<tr>
<th></th>
<th>Today’s Silicon</th>
<th>Silicon-Perovskite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>19.4 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Cost/Area</td>
<td>$153/m²</td>
<td>$167/m²</td>
</tr>
<tr>
<td>Cost/Watt</td>
<td>$0.79/W</td>
<td>$0.67/W</td>
</tr>
</tbody>
</table>

Expected improvements in silicon technology will take the cost below $0.5/W!
Conclusions

• Conventional silicon leads the solar cell race, but will not take us where we need to go.

• Several technologies could take over in the next 10 years.

• We are still discovering new materials with substantially better properties.

• I think multijunction solar cells will be thin, light, cheap and > 30 % efficient.
Final thoughts

• We have to solve the energy problem.

• Any technology that has good potential to cut carbon emissions by > 10 % needs to be explored aggressively.

• Researchers should not be deterred by the struggles some companies are having.

• Someone needs to invest in scaling up promising solar cell technologies.