Research Paths to a Solar Powered World

2011 UC Solar Research Symposium

Sarah Kurtz (and many others)

Dec. 9, 2011
Outline

Phenomenal growth of PV Industry
A mixture of technologies? Or will silicon be king forever?
Research pathways for:
  - CPV (multijunction cells – Defer discussion of optics and light management to the experts)
  - Thin films (CdTe, CIGS)
  - Silicon
The importance and challenge of predicting PV reliability
  - Failure modes
  - Research pathways/results
Summary
News of 2011: PV module prices are low!

Source: Photon International
Growth of PV industry

PV shipments have been doubling every two years

Tons of Si passes microelectronics
Area of Si passes microelectronics
Growth of PV industry

Getting so close to significance will make it harder to grow

In some parts of Germany, on sunny days, PV may supply > 25% of electricity

*www.eia.doe.gov/emeu/international/electricitycapacity.html (4012-2981 GW)/10 yr
Three approaches to PV (and lower cost)

1. Silicon

2. Thin film

3. Concentrator (CPV)

Thin film and CPV: Reduce semiconductor material; CPV uses high-efficiency cells.
PV Technology trends:
New technologies are growing, but have a long way to go to catch up with silicon.
Research Pathways for CPV
Two primary concentrator (CPV) approaches

**High concentration**
- 35% - 40% III-V cells
- 400X – 1500 X

**Low concentration**
- 15% - 25% Silicon cells
- 2X – 100 X
### Why not 100% efficiency?: White

<table>
<thead>
<tr>
<th>Monochromatic light with energy = $E_g$</th>
<th>Temperature</th>
<th>Maximum efficiency</th>
</tr>
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<td></td>
<td>0 K</td>
<td>100%</td>
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White light

- ~22% lost because energy > $E_g$
- ~33% of light is not absorbed

Calculation assumes band gap of 1.4 eV
Why not 100% efficiency?: Temperature

Monochromatic light with energy = $E_g$

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At 300 K, emits thermal radiation

White light

- $\sim 13\%$

- $\sim 22\%$ lost because energy $> E_g$

- $\sim 33\%$ of light is not absorbed

Calculation assumes band gap of 1.4 eV

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<tr>
<th>Temperature</th>
<th>Maximum efficiency</th>
</tr>
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<tr>
<td>0 K</td>
<td>45%</td>
</tr>
<tr>
<td>300 K</td>
<td>32%</td>
</tr>
</tbody>
</table>
Why multijunction?  Power = Current X Voltage

High current, but low voltage
Excess energy lost to heat

High voltage, but low current
Subbandgap light is lost

White light can be converted most efficiently by multiple materials
Choose materials with band gaps that span the solar spectrum

Multiple junctions – currently 3 junctions in champion cells
Champion Solar Cell Efficiencies

Best Research-Cell Efficiencies

Multijunction Concentrators
- Three-junction (2-terminal, monolithic)
- Two-junction (2-terminal, monolithic)

Single-Junction GaAs
- Single crystal
- Concentrator
- Thin film crystal

Crystalline Si Cells
- Single crystal
- Multicrystalline
- Thick Si film
- Silicon Heterostructures (HIT)

Thin-Film Technologies
- Cu(In,Ga)Se₂
- CdTe
- Amorphous Si:H (stabilized)
- Nano-, micro-, poly-Si
- Multijunction polycrystalline

Emerging PV
- Dye-sensitized cells
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells
- Quantum dot cells

Efficiency (%)
Efficiency limits for multijunction cells

Kurtz, Prog. In PV, 2008.

45% may be practical; 50% may be achievable
Success of GaInP/GaAs/Ge cell

Not a laboratory curiosity: records are often set on production hardware
Currently, eight groups claim ≥ 40% cells with six cell architectures

This very successful space cell is currently being engineered into systems for terrestrial use
Multijunction (MJ) solar cells
≥ 40% - multiple designs
These can be assembled in many ways
Lattice-matched 3 junction is commercially available

Lattice matched materials give high crystal quality though they do not provide optimal band gap combination

41.6% @ 364 suns
King 2009; 24th PVSEC Spectrolab

Mars Rover powered by multijunction cells

Lattice matched materials give high crystal quality though they do not provide optimal band gap combination
### Anatomy of a MJ cell – structure

<table>
<thead>
<tr>
<th>1st junction</th>
<th>2nd junction</th>
<th>3rd junction</th>
</tr>
</thead>
</table>
| tunnel junction | tunnel junction | • structure is simplified and not to scale  
• every interface can add defects or series resistance |

- **Ge substrate** (p)
- **GaAs** (n+)
- **AlGaInP** (n+)
- **GaInP** (n+)
- **GaInP** (p)
- **AlGaInP** (p+)
- **AlGaAs** (p++)
- **GaInP** (n++)
- **GaAs** (n+)
- **GaAs** (p)
- **GaInP** (p+)
- **GaAs** (p++)
- **GaAs** (n+)
- **GaAs** or **GaInP** (n+)
- Ge diffused during growth (n+)

- **Metal**
Research opportunities for MJ cells - dopants

Growth of n-type layers at front of cell causes diffusion

When Se dopant is used, the Zn stays put (for these conditions)

Dopants may not end up where you think they should!
Fermi level pinning at growth surface changes equilibrium concentration of point defects: Deppe, APL, 1990.
New World Record: Dilute nitride unique to Solar Junction

1.9 eV
1.4 eV
1.0 eV

3-junction lattice matched (Details estimated because result is not published)

CVD-grown dilute nitride is heavily compensated by H- and C-related defect
Most groups gave up on the dilute nitride a few years ago

Dilute nitride bottom junction with Eg of 0.8 - 1.4 eV

43.5% by Solar Junction
Lattice mismatched growth gives new opportunities

Step grade of composition can confine defects to graded layers
Two-sided triple junction (GaInP/GaAs/GaInAs)

Growth on both sides of wafer gives flexibility.
First explored by Varian in the 1990s.

42.3% @ 406 suns
Spire - 2010

(estimated, since details of the cell have not been published)
Lattice-mismatched triple junction on Ge

Lattice mismatched materials give close to optimal band gap combination, but are more difficult to grow with high yield.

41.1% @ 454 suns
Guter 2009, APL Fraunhofer

Spectrolab now sells mismatched cells

Lattice mismatched materials give close to optimal band gap combination, but are more difficult to grow with high yield
Inverted lattice-mismatched (IMM)

Lattice matched materials are grown first, followed by mismatched – provides pathway to four-junction and higher efficiencies

40.8% @ 326 suns

Geisz
APL
2008
(NREL)

Emcore reported new results at PVSC

Lattice matched materials are grown first, followed by mismatched – provides pathway to four-junction and higher efficiencies
Advantages:
• Path to higher efficiency – 40.8% so far
• Reuse of substrate or use of impure substrate can reduce cost

Invented by Mark Wanlass; 40.8%: Geisz, APL, 2008.
Quantum dot triple junction cells ~40% by Cyrium
## Comparison of six ~40% approaches

<table>
<thead>
<tr>
<th>Design</th>
<th>Efficiency</th>
<th>Efficiency potential</th>
<th>Ease of growth</th>
<th>Thickness</th>
<th>Growth time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice-matched 3-junction</td>
<td>41.6% @ 364 suns</td>
<td>Will be difficult to reach 45%</td>
<td>Lattice matched</td>
<td>No extra layers</td>
<td>Can be grown quickly</td>
</tr>
<tr>
<td>Two-sided 3-junction</td>
<td>42.3% @ 406 suns</td>
<td>Could hit 50% with addition of 4th junction</td>
<td>Only low-E part is affected by mismatch</td>
<td>Extra graded layer on back</td>
<td>Requires 2 steps</td>
</tr>
<tr>
<td>Mismatched 3-junction</td>
<td>41.1% @ 454 suns</td>
<td>Might reach 45%</td>
<td>Requires excellent control over graded layers</td>
<td>Requires one graded layer</td>
<td>Added time of graded layer</td>
</tr>
<tr>
<td>Inverted mismatched 3-junction</td>
<td>40.8% @ 326 suns</td>
<td>Can add more junctions to pass 50%</td>
<td>Requires substrate removal and multiple graded layers</td>
<td>Multiple graded layers</td>
<td>Added time of graded layers</td>
</tr>
<tr>
<td>Quantum-dot in GaAs (3-junction)</td>
<td>~40%</td>
<td>Might reach 45% (QD may be used elsewhere)</td>
<td>QD growth requires special skill</td>
<td>No extra layers</td>
<td>QD nucleation takes extra time</td>
</tr>
<tr>
<td>Dilute nitride – 3 junction</td>
<td>~40%</td>
<td>Could approach 50% with 4th junction</td>
<td>Probably requires MBE growth – might be a benefit</td>
<td>No extra layers</td>
<td>MBE growth is usually slower</td>
</tr>
</tbody>
</table>

Color coding may be controversial; but conclusion is clear: **We don’t have an obvious winner**
Prioritized research pathways

40%-efficient cells are already available

Challenge is to integrate high-efficiency cells with high-efficiency optics to make a high-efficiency system with low cost and high reliability
Research Pathways for Thin Films
Growth of PV industry – Technology Trends

CdTe has been a big success under the leadership of First Solar
Champion Solar Cell Efficiencies

Best Research-Cell Efficiencies

- Multi-junction Concentrators
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  - Inorganic cells
  - Quantum dot cells

Efficiency (%)

Year

(Rev. 9-2011)
Challenges for CdTe

Can the efficiency reach 20%?

Why is the Voc so low?

Will a shortage of Te be a problem?
Growth of PV industry – Technology Trends

CIGS has achieved higher efficiencies – why is it behind CdTe? Why no “First Solar” for CIGS? What about Solar Frontier?
Challenges for CIGS

What does it take to reach large-area uniformity consistently?

Can high efficiencies be achieved in large area?

Is it useful to develop an indium-free version?

Can it be successfully deployed in flexible formats?

Will Solar Frontier be the next “First Solar”? 
Research Pathways for Silicon
Si dominates the PV industry – Will it always dominate?
PV module prices are coming down

Si module prices have dropped more than a factor of two in last 3 years!
Where will silicon lead to?

Silicon has already achieved what many said it would never achieve. Where will it go next?

Opportunities for more cost reduction:
- Low purified Si prices
- Economies of scale
- Many improvements and tweaks
- Radically new approaches as you’ll hear later today

Biggest opportunities now may be with other aspects:
- Soft costs (Recent DOE opportunity)
- Reliability
Research Pathways related to PV Reliability
Examples of Field Failures

- Broken Interconnects
- Ground Fault
- Broken Cells
- Delamination
- Corrosion

John Wohlgemuth

Figure 2. Solar-Cell Electrochemical Corrosion
Additional Field Failures

 Electro-Chemical Corrosion of TF Module

 Broken Glass Leading to Corrosion

 John Wohlgemuth
Reliability questions – tough to answer

Engineer: How do I decide what warranty to put on my product?

PV customer: How do I know which PV will last the longest?

Investor: How do I convince my board that a $1B PV investment is low risk?

Insurance agent: How do I set the rates for insuring PV projects?
The PV QA Task Force was formed last July and consists of six Task Groups;

**Task Group 1**: PV QA Guideline for Manufacturing Consistency  
(leader Ivan Sinicco)  
~200 volunteers

**Task Group 2**: PV QA Testing for Thermal and mechanical fatigue including vibration (leader Chris Flueckiger)

**Task Group 3**: PV QA Testing for Humidity, temperature, and voltage  
(leaders John Wohlgemuth and Neelkanth Dhere)

**Task Group 4**: PV QA Testing for Diodes, shading and reverse bias  
(leaders Vivek Gade and Paul Robusto)

**Task Group 5**: PV QA Testing for UV, temperature and humidity  
(leader Michael Köhl)

**Task Group 6**: Communication of PV QA ratings to the community  
(leader David Williams)

http://www.nrel.gov/ce/ipvmqa_forum/index.cfm
Survey of degradation rates – assess risk

Historical Degradation Rates from Literature

Literature data shows statistical distribution of degradation rates. These can be used to calculate risk. A web-based database will assemble and quantify these as a function of location.

Dirk Jordan
Objective: Quantify relationship between weather-induced damage and accelerated thermal cycling test.

Damage is non linear with temperature change; how do we characterize weather data?
Rainflow algorithm provides method
Need to validate the accuracy of assumptions

Partly cloudy day causes more damage than clear day

Nick Bosco & Tim Silverman
Separate reversible from irreversible changes

After exposure, thin-film modules show reversible and irreversible changes

One module showed 30% increase
When is concentrated UV a problem for CPV?

Does concentrated sunlight at cell contain damaging UV dose?

Acrylic lenses don’t transmit much UV, but some reflective designs do.

David Miller
Summary of Research Pathways

- **CPV**
  - System Integration of High-efficiency cells & optics

- **CdTe**
  - Why is the Voc low?

- **CIGS**
  - How to make it consistently uniform in large area with high efficiency

- **Si**
  - Incremental improvement or radical new approach?

- **All**
  - Reliability studies for all technologies

- A variety of opportunities

- What about Alta?
Vision of a planet powered by renewable energy
By year 2100 or before?

Thank you to:
Jerry Olson
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Aaron Ptak
Jeff Carapella
Waldo Olavarria
Myles Steiner
Ryan France

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Nick Bosco
Dirk Jordan
Ryan Smith
Matt Muller
Bill Marion
Bill Sekulic
Dave Miller
Mike Kempe
Peter Hacke
Kent Terwiliger
Many others…

Thank you for your attention!