High-efficiency solar cells for large-scale electricity generation & Design considerations for the related optics

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Optics for Energy
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Outline

• Solar is growing very fast
• Optical concentration
  – Reduces semiconductor material
  – Increases cell efficiency
• The physics of solar cells and high efficiency
  – Why using multiple junctions increases efficiency
  – Success of GaInP/Ga(In)As/Ge cell -- 40.7%
• Optics - design considerations
  – Overview
  – Solar thermal electricity generation
  – PV - high concentration 500X - 1000X (high efficiency)
  – PV - low concentration 2X-4X (Si)
Solar thermal electric

- Parabolic trough is the primary technology today
- Resurgence of interest
- ~ 400 MW installed
- Currently generates ~ 0.01% of US electricity
- Economical for > 100 MW in sunny areas
64 MW Solargenix Parabolic Trough Plant in Nevada - 2007

1-MW Arizona Trough Plant – near Tucson, AZ - 2006
Growth of photovoltaic industry

0.06% of electricity now comes from solar - extrapolates to > 5% in 2020

Competitive with conventional electricity for 0.1% - 1% of market; more in future

Rogol, PHOTON International August 2007, p 112.
Industry growth is currently constrained by Si availability. Reduce semiconductor material by concentrating the light.

Concentration:
1. Reduces semiconductor use
2. Allows use of higher efficiency cell (higher system efficiency)
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  – Thermal
  – PV - high concentration
  – PV - low concentration
Optics in solar cells - getting the light into the active layers

- Broad-band anti-reflection coatings
- Light trapping (textured surface on front or back for Si)
- Many different approaches will be covered in other talks
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

Highest efficiency: Absorb each color of light with a material that has a band gap equal to the photon energy
Multijunction cells use multiple materials to match the solar spectrum
Champion solar-cell efficiencies

Best Research-Cell Efficiencies

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

- Crystalline Si Cells
  - Single crystal
  - Multicrystalline
  - Thick Si Film

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

- Emerging PV
  - Dye cells
  - Organic cells (various technologies)

- NREL National Renewable Energy Laboratory
Success of GaInP/GaAs/Ge cell

This very successful space cell is currently being engineered into systems for terrestrial use.
High-efficiency mismatched cells

Substrate removed after growth

GaAs substrate

GaInP top cell

GaAs middle cell

GaInAs bottom cell

Metal

38.9% @ 80 suns
Geisz, 2007

New research: from 40% to 50%

GaInP top cell

GaInAs middle cell

Grade

Ge bottom cell and substrate

Metal

40.7%  King, 2006

1.8 eV

1.3 eV

0.7 eV
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  – PV - high concentration (low T, uniformity)
  – PV - low concentration (high acceptance angle, reliability)
Key issues for optical design

• Low cost
• High efficiency over broad spectral range
• Large acceptance angle for easy alignment and use of diffuse radiation
• Soiling (maintenance)
Reflective optical designs

Large dish: Stirling engine; PV requires active cooling

Microdishes can be passively cooled

Receiver with homogenizer for PV

Reflective Dish
Reflective optical designs - troughs
Refractive designs for PV - large Fresnel

- Fresnel lens
- Optical secondary
- Concentrator cell
- Heat sink
Refractive optical designs

Fresnel lenses focus light on small cells
Passive cooling

Small lenses and small cells can lead to thin designs and “flat-plate” cooling
What will concentrators look like in the future?

Could we have predicted 100 years ago what airplanes look like today?

Innovation
Optics for solar thermal

• Solar thermal
  – Trough - convenient transport of working fluid
  – Dish or tower - higher temperatures

• Guidelines
  – Hit the target
  – Energy is all that counts
Uses for optics for solar

- **Concentrating PV**
  - High concentration enables use of high-efficiency cells
  - Any concentration reduces use of semiconductor material
- **Guidelines differ for PV**
  - Keep temperature low (lose 0.2-0.4%/°C)
  - Uniformity concerns
  - Chromatic aberrations
  - Don’t care about lowest E light; blue is important
Series connection of cells requires uniformity of light for CPV

100 W can be derived from
1 V @ 100 A
or
100 V @ 1 A

High voltage is always preferred, so connect cells in series

Series-connected cells: current is limited by cell with least light;
Need same light hitting each cell
Uniformity of light is important for CPV, not thermal
Uniformity challenge for CPV

- Dish - need uniform image
- Trough - need clean image (pay attention to shadows for supports and end of image)
- Fresnel - make each cell and lens identical
Low-concentration

Reduce Si usage with low concentration
- Theoretically for non-imaging optics: $C_{\text{max}} = n / \sin \theta$
- For point focus 4 X, limit is acceptance angle $\sim 45^\circ$
- Tracking is now used in many systems
- Efficiency of optics is important
- Use design that is unaffected by soiling
- Small cells may allow for very thin systems with minimal cooling problems
- Historically, low-concentration systems have shown new degradation mechanisms
Summary

- Photovoltaic industry is doubling every two years
- Using concentration may help the solar industry grow even faster
- Multijunction cells provide the path to high efficiency; > 40% and are still increasing
- The optical designs are varied and the requirements differ for solar thermal and PV
Flying high with high efficiency

Cells from Mars rover may soon provide electricity on earth

High efficiency, low cost, ideal for large systems