Photovoltaic Spectral Splitting Approaches for Space Systems

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Brief Introduction

• Early photovoltaic devices for space dominated by the drive to achieve higher efficiency and reduce degradation to space radiation
  – Silicon (Si) cells later transitioned into Gallium Arsenide (GaAs), development noted by extremely modest efficiency gains

• Transition to GaAs cells provided potential for substantial improvements in efficiency through development of multijunction solar cells that utilize solar spectrum more efficiently
  – Early development efforts suffered from the lack of a reliable, efficient tunnel junction to connect monolithically-grown devices

• As a result numerous cell and array designs were investigated
  – Mechanically-stacked solar cells (i.e. GaAs/GaSb @ Boeing)
  – Spectrum-splitting approaches (holographic concentrators, etc.)
  – DoD concentrator efforts focusing on survivability to natural and man-made threats

• Successful development of tunnel junctions has established multijunction GaAs-based cell technology as SOA for space PV
Why use Photovoltaic Concentrators in Space?

Photovoltaic (PV) concentrators offer many advantages similar to those for terrestrial applications. Potential advantages include
- Reduced cost due to reduced cell area
- Reduced mass (dependent upon specific designs)
- Decreased array stowed volume
- Increased radiation hardiness
- Capability of high voltage operation within the space environment
- Inherent protection from natural and man-made threats
- Increased cell performance for outer planetary missions (reduced LILT effects)
- Increases in PV cell yield for designs using smaller cells
- Designs that could enable the first use of new high efficiency, high cost PV devices

But spacecraft designers must also consider
- Sun-pointing requirements
- Higher operating temperatures, thermal design & rejection
- Increased system complexity/decreased reliability
- Loss of mission during operational anomalies (concentrator arrays must be solar pointing to produce power)
- Cost associated with conc. elements, added structure, fabrication, testing, etc.
- Space environmental effects on concentrator & optical materials
- Lack of space flight heritage (different from planar solar array designs)
Space vs. Terrestrial Concentrator Designs

There are some significant differences between space and terrestrial concentrator designs

• Mass is a major performance parameter
• Long-term reliability under thermal, operational, etc. conditions is critical
• Array must stow compactly and deploy reliably
• Environmental conditions are unique & harsh (radiation, UV, AO, vacuum, etc.)
• **Operational sun-pointing requirements lead to lower concentration ratios**

Example using Stretched Lens Array Design

Concentration Ratio Versus Sun-Pointing Tolerance

Relative Array Cost Compared to Planar Array
Spectral Splitting and other Advanced Concentrator Concepts

Multi Band Gap High Efficiency Converter (Rainbow) by JPL

Issues
• complexity
• optical losses
• control & dynamics
• materials
• etc.

Dense PV Array Concepts:
Thin film reflectors redirect sunlight to small PV arrays

20X spectrum splitting approach to achieve system efficiencies > 50%

Lightweight Inflatable Conc. developed by SRS & AFRL
SCARLET: Solar Concentrator Arrays with Refractive Linear Element Technology

- First operational refractive concentrator
  - launched Oct. 1998 on NASA Deep Space 1
  - comet rendezvous mission
  - used as primary power for solar electric propulsion
- Distributed refractive design
  - 7.5X concentration
  - 2.5 kW array
  - used GaInP/GaAs DJ cells

Flight Results
- no deployment or performance problems
- array operated as predicted
Entech Solar Thin Lensfilm (250 microns) Design Using Symmetrical Refraction Approach

Entech Solar Symmetrical-Refraction Lens Offers:

- Minimum Reflection Loss, Maximum Transmittance
- Sharper Focusing
- Shorter F/#
- Exceptional Shape Error Tolerance
  - >200X Better than for Reflective Concentrators
  - >100X Better than for Flat Lenses
Entech Solar Lens Approach to Sun Pointing, Terrestrial Design

Prisms Are Optimized for 20X Concentration and $\pm 0.75$ Degree Sun-Pointing Tolerance

Outdoor Measurements Confirm 90% Net Optical Efficiency at 20X

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NanoStructured Photovoltaic Technology

Quantum Dot Technology Has Potential to Exceed 40% Conversion Efficiency

- Intermediate Band due to QD coupling (IBSC)
- Enhanced photogeneration mechanisms and two-photon effects
- Reduced spectral sensitivity
- No current matching requirement
- Fundamental physics

- Absorption Spectrum Extension
- Low $E_g$ Quantum Dots harvest photons lost due to transmission
- Demonstrated increased current generation
  - Linear increase with number of QD layers
- QD-enhanced GaAs p-i-n solar cell exceeds single junction efficiency (RIT-2010)
- Rich field of study with solid results to date

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Maximum Efficiency</th>
<th>$E_{CI}$</th>
<th>$E_{IV}$</th>
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<td>6000 K Blackbody</td>
<td>46.70%</td>
<td>1.49 eV</td>
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<td>AM0</td>
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<tr>
<td></td>
<td>48.60%</td>
<td>1.36 eV</td>
<td>0.75 eV</td>
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Summary

- Spectral-splitting “solar array” approaches have been overshadowed by the success in monolithic, GaAs-based multijunction cell technology
  - SOA, 3-junction GaAs-based cells (30% AM0 1 sun efficiency; 40+% under terrestrial, high concentration operation demonstrated)
  - Newer high-efficiency devices on the horizon; Inverted Metamorphic Multijunction (IMM) technology has been demonstrated, 5 & 6 junction development efforts underway, use of nanotechnology could further increase potential for higher efficiency at lower cost
  - Space technology rapidly making it’s way into the terrestrial marketplace thru the use of very high concentration systems (500-1000X) that make this relatively expensive cell technology economically competitive with “traditional” terrestrial PV tech.
- Concentrator array designs will still provide an important role in meeting space mission requirements, emphasis on lower concentrations (i.e. 2 – 50X)