Current Status of Photovoltaic Development at AFRL

John Merrill
Air Force Research Laboratory, Space Vehicles Directorate
Kirtland Air Force Base, NM 87117
505-853-3427
john.merrill@kirtland.af.mil

Paul E. Hausgen, Donna C. Senft, and Henry H. Yoo
Air Force Research Laboratory, Space Vehicles Directorate
Kirtland Air Force Base, NM 87117

Abstract—Advances\textsuperscript{1,2} in design and manufacturing technology of crystalline multijunction solar cells have continued to push efficiencies higher. Triple junction cells with 28\% efficiency are now available to the user and 30 \% prototype cells have been demonstrated. Development of thin-film solar cell arrays is being aggressively funded for next-generation high power space platforms. Initial modules of thin-film photovoltaics comprised of amorphous silicon and Cu(In,Ga)Se\textsubscript{2} devices have been demonstrated. Space-compatible technologies for thin-film cell integration, contacts, and protective coatings are being developed. Cell-level development efforts aimed at increasing performance are continuing and progress is being made toward a 15\% efficiency goal for cells on lightweight, flexible substrates. High temperature polymer substrates for Cu(In,Ga)Se\textsubscript{2} cells have been demonstrated. Thin-film solar arrays are promising for 3-7 times increase in specific power (W/kg) and stowed volume (W/m\textsuperscript{3}) and a 3-5 times decrease in array cost ($/W) compared to state-of-the-art rigid panel solar arrays.

In the increased capability area, power system needs include increased payload mass budgets, reduced power system and launch costs, increased on-orbit available power, and extended mission lifetime. There are many solar array performance metrics that are indicators of these capabilities including efficiency, specific power (W/kg), and stowage volume (W/m\textsuperscript{3}). To guide development, AFRL has set specific technical objectives for some of these metrics (>35\% for efficiency, 200-450 W/kg) and has established a solar array cost goal of less than $250/W.

Stowage volume is a particularly important parameter because it is an indicator of the maximum power that can be achieved for a given launch vehicle fairing and spacecraft. On-orbit power requirements have been steadily increasing over the years in both the commercial realm (see Figure 1) and for government missions. Therefore, it is important to work toward space power solutions that meet future high power on-orbit requirements.

1. INTRODUCTION

The mission of the AFRL is to lead the discovery, development, and integration of affordable war fighting technologies for our air and space forces. Included in the “air and space” forces are satellites, which require power systems to provide power to operational military payloads. These power systems have needs that fall into two categories: increased capability and decreased cost.

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\textsuperscript{2} IEEEAC paper #1599, Version 2, Updated January 27, 2005

1. INTRODUCTION

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The current investment strategy at AFRL for space power
generation research includes three thrust areas: (1) evolutionary, (2) revolutionary, and (3) quantum leap. The thrust area names indicate the level of space power performance advancement over current state-of-practice technologies. Each thrust area contains innovative technology being developed to meet current and future spacecraft power needs. Near term practical development of technology coupled with visionary “seed” research and development investment are hallmarks of this strategy.

The “evolutionary” thrust area includes crystalline multijunction solar cell development. The term “evolutionary” is used for this thrust area because advancements in this area are expected to be incremental, but steady over time. AFRL has a rich, successful history in this research area. Through AFRL directed efforts, the Air Mass Zero (AM0) efficiency of available crystalline solar cells has increased from ~18% in 1988 to the current value of 29.6% (see Figure 2) [1,2].

Sandwiched between the “evolutionary” and “quantum leap” research thrust areas is the “revolutionary” thrust area. This thrust area is termed “revolutionary” because large gains are expected in space power performance compared to current state-of-practice technology. This is in contrast to the small, steady, and incremental gains in performance provided by technologies in the “evolutionary” thrust. Thin-film solar cells are the constituents of this thrust and they offer great promise for increasing the capability of future spacecraft. While their efficiencies are low compared to state-of-the-art crystalline solar cells, they have other unique attributes that make them very attractive for space use. These attributes include flexibility, low mass, high radiation resistance, and low cost production.

The flexibility and low mass of thin-film solar cells are particularly beneficial because they allow innovative solar array support structures and stowage schemes. With innovative support structures that are currently being developed by multiple aerospace companies, thin-film solar arrays could potentially provide much greater stowed volume (45-60 W/m³ vs. 10-15 W/m³), much greater specific power (250-500 W/kg vs. 70 W/kg), and much lower cost (~$250/W vs. ~$1000/W) than rigid flat panel solar arrays. Stowed volume is of particular interest for increasing on-orbit power availability. On orbit power has typically been limited to ~30 kW due to the inefficiency of packing rigid panels in a launch fairing. Thin-film arrays on flexible substrates could allow > 100 kW to be stowed in a launch fairing.

The “quantum leap” thrust area includes technologies that are high-risk investments, but offer the promise of huge leaps over current state-of-practice space power technology. Technologies of interest in this thrust are nanocomposite solar cells, dye-sensitized solar cells, large-grain crystalline solar cells, and In₁₋ₓGaₓN-based solar cells. The return on investment from these technologies is much more long term than those in the “evolutionary” thrust area.

### 3. MULTIJUNCTION SOLAR CELL RESEARCH

AFRL’s crystalline multijunction solar cell research has taken GaAs-based crystalline technology from single-junction 18% solar cells to triple-junction solar cells nearing 30% efficiency. Triple junction cells with 28% efficiency are now available to the user and 29.9 % prototype cells have been demonstrated. Advanced 3-junction solar cells
with an efficiency range between 29 and 30% are expected to be available for space power generation within a year.

The next goal for this high-efficiency technology is a 4, 5 or 6-junction solar cell with an efficiency of ≥ 35% and increased radiation resistance, increasing on-orbit power capability or reducing power system cost. Multijunction solar cell programs are continuing under Dual Use Science and Technology (DUS&T) programs. These two multi-year programs with Spectrolab, Inc. and Emcore Photovoltaics involve 50-50% cost sharing between industry and government to develop 35% solar cells. Improvement of solar cell performance will be achieved by better utilization of incoming solar spectrum; some of the approaches include 1) incorporation of new low bandgap materials for solar cell junctions 2) development of lattice mismatch multijunction solar cells, 3) increasing the number of junctions to 4, 5, and 6-junction solar cells, and 4) combinations of approaches 1, 2, and 3. A summary of the multijunction cell development programs for Emcore and Spectrolab is shown in Table 1.

Spectrolab’s approach involves 4, 5, and 6-junction lattice-matched cells using diluted nitride, GaInNAs and highly lattice-mismatched solar cells utilizing high In content GaInAs. Emcore is targeting lattice mismatched 4, 5, and 6-junction solar cells including use of a new low bandgap material, GaInSb. These two DUS&T programs with different approaches to reaching the 35% efficiency goal offer risk-reduction to the overall program.

### 4. THIN-FILM SOLAR CELL RESEARCH

AFRL’s thin-film solar cell research is focused on two technologies: a-Si and CIGS. The goals of this research are: 1) increase conversion efficiency for both a-Si and CIGS to 15% by 2010; 2) increase cell level specific power (350–500 W/kg) by supporting research on lightweight substrates such as thin metal foils and polyimides; 3) establish space survivability through ground testing and flight experiments; and 4) develop monolithic integration to further reduce production cost. Each goal is a means toward either increasing on-orbit power capability or reducing power system cost.

AFRL-funded cell development programs are intended to make changes in cell technology geared to space application by increasing cell specific power via tilting performance/cost tradeoffs toward higher efficiencies and supporting the development of cell production processes with lightweight substrates such as metal foils and polyimide. A summary of the cell development programs for the two most promising thin-film technologies, a-Si and CIGS, is listed in Table 2.

AFRL has a strong history of successfully transitioning novel solar cell technology into operational space use, with thin-film technologies next on the list. Successful technology transition requires demonstrating solar cell capability in ground testing and on orbit. To this effect, AFRL is investing in two flight experiments and the most comprehensive ground test program for thin-film solar cells to date. The thin-film solar cell flight experiment on the AFRL Roadrunner Mission will consist of a-Si and CIGS, each producing roughly 60 W of power. The flight is planned for mid-2005 and will be in LEO. This will be the first flight in which thin-film solar cells supply power to the spacecraft bus. The AFRL Deployable Structures Experiment (DSX) will host a significantly larger thin-film solar cell experiment (4.5 kW) and it will fly in MEO expected in 2010. The goals of these experiments are to demonstrate and characterize on-orbit thin-film solar cell performance and create on-orbit performance models essential for successful transition to operational use.

### 5. CONCLUSION

AFRL has a visionary research strategy that has created significant advancements in space solar cell technology to meet future space power needs at low cost. A central tenant in this research strategy is thin-film solar cells. Given the beneficial attributes of thin-film solar cells, namely flexibility, high radiation resistance, low mass, and low cost production, the present AFRL program is expected to result in their future, operational use in space.
REFERENCES


BIOGRAPHY

Mr. John Merrill is Deputy Program Manager for the Advanced Power Generation Group in the Space Vehicles Directorate, Air Force Research Laboratory. His responsibilities are a mix of program management and research projects primarily in the development of photovoltaics for space. Mr. Merrill previously was involved in development of next generation thermal-to-electric conversion technologies and has also investigated embrittlement behavior in Ni-based single crystal superalloys. He holds a B.S. and M.S. in Materials Science.

Table 2. Thin-Film Cell Development and Module/Array Development Efforts Funded by the AFRL as part of the Space Thin-Film Solar Cell Development Program

<table>
<thead>
<tr>
<th>Company or Program Name</th>
<th>Program</th>
<th>Technology</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing Satellite Systems</td>
<td>Thin-film Solar Cell Module Development</td>
<td>a-Si and CIGS</td>
<td>Metal foils</td>
</tr>
<tr>
<td>Lockheed Martin Space Systems</td>
<td>Thin-film Solar Cell Module Development</td>
<td>a-Si and CIGS</td>
<td>Metal foils</td>
</tr>
<tr>
<td>United Solar Ovonic</td>
<td>Performance enhancements &amp; monolithic integration on polyimide</td>
<td>a-Si</td>
<td>Stainless steel and polyimide</td>
</tr>
<tr>
<td>Iowa Thin Film Technologies (ITFT)</td>
<td>Monolithic integration and efficiency improvements</td>
<td>a-Si</td>
<td>Polyimide</td>
</tr>
<tr>
<td>International Solar Electric Technologies (ISET)</td>
<td>Non-vacuum painted-on process &amp; lightweight substrates</td>
<td>CIGS</td>
<td>Polymer</td>
</tr>
<tr>
<td>Foster-Miller</td>
<td>High temperature polymer substrates</td>
<td>CIGS</td>
<td>Polymers</td>
</tr>
<tr>
<td>ITN Energy Systems</td>
<td>Dielectric coatings to enable monolithic integration</td>
<td>CIGS</td>
<td>Metal foils</td>
</tr>
<tr>
<td>Triton Sommer Materials</td>
<td>Tandum CIGS cells</td>
<td>CIGS</td>
<td>Metal foil</td>
</tr>
<tr>
<td>JDS Uniphase (OCLI)</td>
<td>Multi-functional protective coating development</td>
<td>a-Si and CIGS</td>
<td>Metal foils and polymers</td>
</tr>
<tr>
<td>Ion Beam Optics</td>
<td>Study effect of grain boundary size and orientation</td>
<td>CIGS</td>
<td>Metal foils</td>
</tr>
<tr>
<td>Radiation Testing</td>
<td>Measure and model effects of radiation on thin-film cells</td>
<td>a-Si and CIGS</td>
<td>Metal foils</td>
</tr>
<tr>
<td>ITN Energy Systems Interphases</td>
<td>Increasing efficiency of large area CIGS solar cells</td>
<td>CIGS</td>
<td>Metal or polymer</td>
</tr>
<tr>
<td>MicroSat Systems</td>
<td>Lightweight solar array support structures</td>
<td>a-Si and CIGS</td>
<td>Metal or polymer</td>
</tr>
</tbody>
</table>
Dr. Paul Hausgen is a key member of the Advanced Space Power Generation group at AFRL. He is responsible for the development of lightweight thin-film solar arrays for the Roadrunner and DSX (Deployable Structures Experiment) flight experiments. Dr. Hausgen also directs lightweight solar module development programs with Lockheed Martin Astronautics and Boeing Satellite Systems. In addition, he directs lightweight solar array support structure efforts with Boeing Satellite Systems (in cooperation with NASA Glenn) and Microsat Systems. In addition, he directed efforts in the improvement of thin-film solar cell efficiency. Dr. Hausgen received his Ph.D. from Georgia Institute of Technology in Mechanical Engineering in 2000. He has previously conducted research in thermal to electric conversion systems and the application of nano-molecular structures for solar spectrum alteration. Dr. Hausgen holds one U.S. patent.

Dr. Donna Senft is Chief of the Advanced Space Power Generation group at the Air Force Research Laboratory Space Vehicles Directorate at Kirtland AFB, New Mexico. She is responsible for the development of space solar cell and array technology for the Air Force and oversees a broad portfolio of efforts ranging from the development of multijunction solar cells to thin-film photovoltaics to long-range studies on the impact of nanotechnology on power generation. Dr. Senft received her Ph.D. in Materials Science and Engineering from the University of Illinois at Urbana-Champaign in 1994 and also holds degrees in Physics and Engineering Science. Dr. Senft has previously been employed by Sandia National Laboratories and has participated in a small start-up business venture. She is the holder of 3 US patents and has published a number of papers in photovoltaics and the fundamentals of the nucleation and growth of device materials.

Dr. Henry Yoo, a Research Electrical Engineer, has over 25 years of professional experience in photovoltaics in a wide range of practical R&D and manufacturing for both terrestrial and space applications including thin film solar cells, polycrystalline and single crystalline Si solar cells, and high efficiency III-V compound solar cells. Dr. Yoo currently oversees AFRL efforts on the development of advanced crystalline multijunction solar cells. He also supervises efforts in improving the radiation hardness of crystalline solar cells and nitride materials for crystalline multijunction photovoltaics. Dr. Yoo received his Ph.D. in Electrical Engineering from Southern Methodist University in 1976 and has previously been employed by Emcore Photovoltaics, Tecstar/Applied Solar, and Arco Solar. Dr. Yoo has published over 25 technical papers on the topic of photovoltaics.