Advanced Photovoltaic Development at Air Force Research Laboratory

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ABSTRACT

Photovoltaics continue to be the primary source of electrical power for most near-Sun space missions. The desire to enhance or enable new space missions through higher efficiency, increased specific power (W/kg), increased volumetric power density (W/m^3) and improved radiation resistance, along with decreased costs, continues to push development of novel solar cell and array technologies. To meet present and future space power requirements, gallium arsenide based multijunction solar cells, thin-film solar cells, and more novel technologies such as intermediate bandgap devices are being pursued. These efforts have resulted in a continual advancement in performance, but new paradigms will be required to continue that performance trend. As cell efficiency increases, other cell and power system characteristics may become more important, namely cost and environmental durability as well as power system survivability. Opportunities for high performance photovoltaics continue to expand for both space and terrestrial applications.

Keywords: photovoltaics, spacecraft, power systems

1. INTRODUCTION

Space photovoltaic (PV) development has made continual and remarkable progress, averaging roughly 0.5% per year improvement in absolute efficiency over many decades (figure 1). Early solar cell development activities were driven solely to meet spacecraft performance needs, as PV materials costs were considered to be too high for terrestrial applications. Beginning in the early 1970's, investment in space PV development began to wane as the conventional wisdom of the day asserted that PV generation capability was limited to approximately 1 kW of spacecraft power and beyond that nuclear power systems would be utilized. In addition, financial forecasts indicated that photovoltaics would always be too expensive for terrestrial application. Fortunately, these apparent constraints turned out to be inaccurate, and PV development and applications have flourished for both terrestrial and spacecraft needs.

A wide variety of PV technologies have been investigated and developed in order to attain the continual efficiency improvements demonstrated, with current 1-Sun space solar cells projected to attain >35% efficiency in the near future. History has shown that advancements in cell efficiency, as long as the new technologies have a comparable or better environmental durability than current state of the art, are adopted for widespread use in space for both commercial and government spacecraft. It is interesting to note that a majority of solar cell vendor manufacturing processes have been derived from DOE and DOD investment. Although universities and some private companies continue to conduct potentially disruptive research, many have procured licenses from NREL or obtained government research funds. This robust transition record speaks to the leveraging effect that solar cell efficiency and end-of-life performance have on the overall spacecraft metrics.

This paper focuses on photovoltaic device development efforts within the Space Vehicles Directorate of AFRL specifically, but one should always keep in mind the other parallel development efforts that are required to fully optimize spacecraft power system performance. These efforts include development of appropriate solar cell optical coating technologies, environmental protection technologies (coverglass, etc), electrostatic discharge control technologies at the blanket and array level, high reliability solar cell interconnect technologies and high reliability solar arrays that are mass and stowage volume efficient. In addition to these technologies, a tremendous amount of work is being invested into developing advanced energy storage technologies and power management and distribution technologies. As a solar cell developer, it can be quite distressing to see the fractional percent efficiency improvements one has struggled to obtain being shunted away (treated with reckless disregard by inefficient downstream power management systems) by the power system electronics. High reliability peak power tracking electronics will allow the high efficiency solar cells

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developed to provide their maximum benefit to the spacecraft. Improvements in overall system performance require a holistic approach to component technology and systems development.

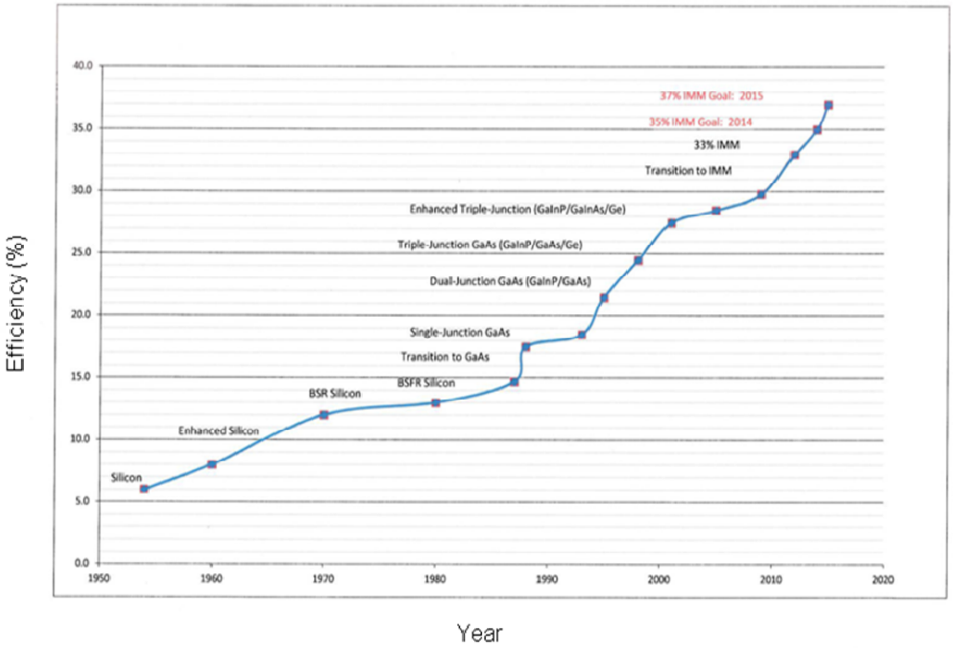


Figure 1. Historical trend of space solar cell efficiency demonstrations over the past 50+ years. The trend shows a ~0.5%/yr increase in efficiency over that period. To maintain that improvement in efficiency, transitions have occurred as older technology reaches full maturation. (from B. Reed, Space Power Workshop 2011).

2. SPACECRAFT POWER NEEDS

The range of electrical power that spacecraft require has expanded over the past decade as new types of spacecraft have been developed (i.e. Cubesats, Nanosats, etc) on the low power end of the spectrum and high power spacecraft applications have expanded. For example large geosynchronous (GEO) communication satellites historically required roughly 15kW of electrical power. This level has recently increased to 25kW and beyond as payload requirements and spacecraft capabilities have grown[1]. For DoD, there is a range of conceptual missions that are enabled through the use of high power solar arrays (>50kW) (table 1). In addition to being mission enabling, very high power solar arrays have the potential to provide significant costs savings, particularly for GEO spacecraft. Studies suggest that fusing electric thruster propulsion to raise the orbit of a spacecraft from Low Earth Orbit (LEO) to GEO can save many millions of dollars through the use of lower cost/performance launch vehicles[2]. Also, the Global Positioning System (GPS) program is assessing the potential to dual launch (two satellites on one launch vehicle) as a means of significant overall program cost savings.

Table 1. High power military missions enabled by very high power solar arrays (from J. Penn, 2010 Space Power Workshop).

Laser Communications
Remote Detection of Chemical Species
Water Vapor Atmospheric Profile
Terrestrial Imaging LIDAR – 450 km

Terrestrial Imaging LIDAR – 1500 km
Airborne Moving Target Indicator
Space Solar Power Demonstrator
GEO Sat on Minotaur IV Class
GEO Sat on EELV Heavy

For high power spacecraft, we are rapidly reaching a limit as to how many solar panels we can fit within the faring of our launch vehicles. Using current solar cells and rigid panel technology, that limit is roughly 30kW. Expanding beyond this level will require higher efficiency solar cells as well as novel solar array mechanical designs that can offer dramatically improved stowed power density.

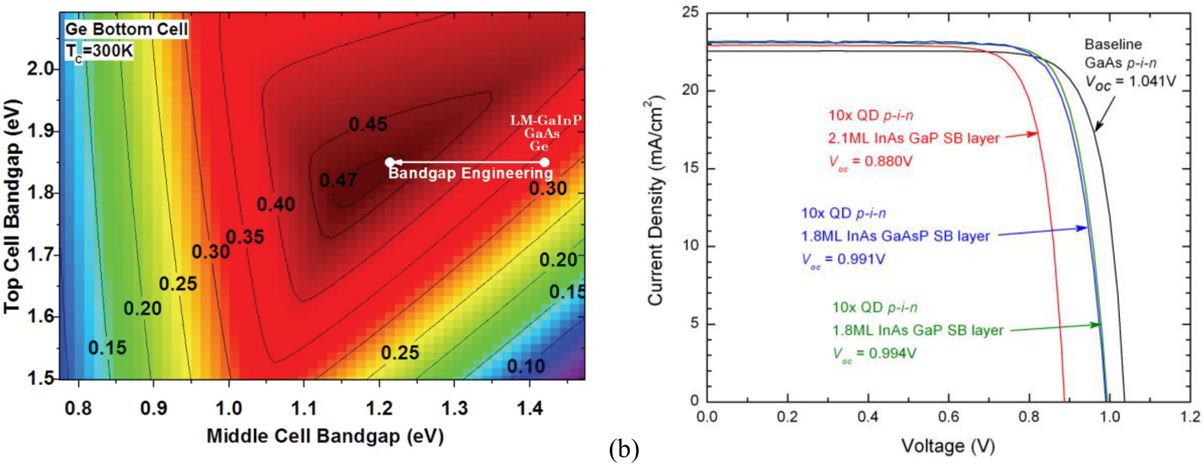
3. MULTIJUNCTION SOLAR CELL DEVELOPMENT

3.1 Germanium Based Multijunctions

Gallium arsenide (GaAs) based multijunction solar cells have been the predominant spacecraft solar cell since the mid 1990's. Prior to that time, it was often said that "GaAs was the solar cell of the future and always would be," based on its significantly higher costs, compared to silicon. In order to supplant silicon solar cells, GaAs technology did not demonstrate a lower cost at the cell level; rather, it was the savings at the array and spacecraft level that justified the significantly higher per cell cost of GaAs. These savings stem from a variety of sources, such as the higher initial performance (~30% higher single junction solar cell efficiency), superior end of life (EOL) performance, reduced labor costs as fewer cells need to be integrated for equivalent EOL power and smaller solar arrays that reduced the drag and attitude control torques imparted to the spacecraft. It is instructive to consider these system level savings and their impact on market acceptance when considering the commercial viability of new solar cell technologies.

GaAs technology quickly progressed from single junction GaAs solar cells on germanium (Ge) to a variety of increasingly advanced dual junction then triple junction solar cells. The path of continual improvement in indium gallium phosphide (InGaP), indium gallium arsenide (InGaAs) on Ge triple junction solar cells appears to be near exhaustion, as evidenced by the series of triple junction solar cell names from Emcore: TJ, ATJ, BTJ and finally ZTJ. These latest space qualified incarnations, by both Spectrolab and Emcore, are roughly 29% efficient at beginning of life (BOL) and have an end of life power remaining factor (P/Po) of ~0.85 (following 1e15/cm^2 1MeV electron fluence). For un-concentrated GaAs family of photovoltaic devices, differences between realized and theoretical efficiencies (Green and others) can't be minimized with current electronic architectures and manufacturing practices.

Work co-funded by AFRL is currently directed at furthering traditional triple junction performance through the inclusion of nano and quantum materials, namely quantum dots (QD) and/or quantum wells. These materials, when added to the (In)GaAs middle junction, have the potential to provide additional current to this current-limiting subcell, with a potentially significant improvement in efficiency (figure 2a). Traditionally, the addition of nano or quantum enhanced materials has resulted in significant decreases in open circuit voltage, while providing limited additional current. Fortunately, remarkable progress has been made in both quantum dot and quantum well enhanced devices. RIT has recently demonstrated quantum dot enhanced GaAs enhanced devices with open circuit voltages approaching 1V, while demonstrating encouraging current enhancement (~0.05mA/cm^2 additional current per QD layer)[3] (figure 2b). In fact, their QD enhanced devices now demonstrate higher performance than their highly efficient non-QD control devices. Emcore and RIT have teamed to transition these encouraging single cell results into full QD enhanced triple junction devices. These nano-enhanced devices also appear to have the potential to enhance the EOL device performance, due to the superior radiation tolerance of the quantum and nano structures[4, 9]. The technology has a low maturity level at this time, (Technology Readiness Level – TRL of ~3) but is likely to progress based on the benefit and the potential for integration into existing production solar cells.



(a) (b)

Figure 2. (a) Modeled AM0 efficiency benefit of reducing middle cell bandgap for conventional TJ device. (from S. Hubbard, 35th IEEE PVSC 2010) and (b) experimental current-voltage data for QD enhanced GaAs solar cells (from C. Bailey, 37th IEEE PVSC 2011).

3.2 Inverted Metamorphic Multijunction (IMM)

In order to break the performance barrier of conventional germanium based multijunction solar cells, Mark Wanlass and his co-workers at NREL developed a novel lattice mismatched device structure, eventually named IMM[5]. This device structure maintains the high efficiency of the high power producing conventional triple junction subcells (namely the InGaP and InGaAs subcells), while substituting a current-matched and lattice-mismatched metamorphic bottom InGaAs cell (~1eV) for the Ge subcell. This change increases the overall device voltage while maintaining a high current density. Emcore and Spectrolab have adopted this IMM technology, with Emcore maturing it into a >34% 4- junction device and >36% 6-junction device[6]. (figure 3a).

Counterbalancing the significant improvements in absolute efficiency, IMM devices face challenges in environmental stability. The addition of new subcells and the tight current matching between subcells means that reductions in current of any particular junction, either from radiation degradation or changes in spectral transmissivity, are amplified and potentially significant. Figure 3b shows the external quantum efficiency (EQE) for a non-optimized 4-junction IMM device, both as fabricated and following 1 MeV electron bombardment at two different fluences. Unexpectedly, the subcell showing the largest degradation in current generation is the 1eV InGaAs device. The exact reasons for this are still being investigated, but using this data, Emcore predicts EOL optimized 4-junction IMM cells to attain a power remaining factor of >0.82 with a BOL efficiency of ~34%.

The very nature of the IMM design requires that the active solar cell be removed from the growth substrate, with the final IMM configuration being a thin (< 20 micron) III-V epitaxial layer with very high performance (>600W/kg). Unfortunately, IMM devices are extremely fragile, having essentially no tensile strength. Microcracks have been shown to occur due to handling issues, interconnect stresses and thermal cycle induced stresses when integrated into higher order assemblies (coupons and blankets). These defects are deleterious and AFRL has invested significant resources into developing appropriate IMM integration technologies to reduce or eliminate these effects. Recently, IMM integrated coupons have withstood numerous GEO thermal cycles (1000 cycles from -175°C to +130°C) with minimal degradation, suggesting that engineering solutions can offer a robust IMM package suitable for spaceflight.

The maturation of IMM integration continues with the recently announced AFRL ManTech effort, a ~$13M, multi-year effort to develop the manufacturing process for fabricating IMM devices. At the completion of the MANTECH program, a qualification program following the AIAA S-111 and S-112 solar cell qualification protocols, is scheduled to begin. Given the radically different physical nature of the IMM device, a new paradigm is being developed within the aerospace industry, wherein the IMM devices could be delivered from the solar cell manufacturer to the customer as a pre-integrated string, rather than as individual devices, as is commonly done today. Much work is required to fully develop this new process as well as coordinate this packaging and integration change with industry.

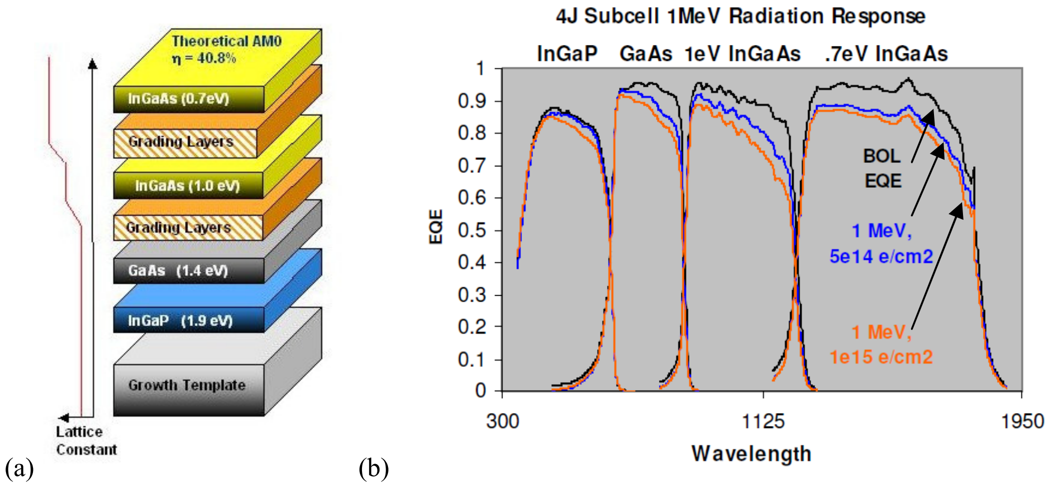


Figure 3. (a) IMM 4-junction device design and (b) measured external quantum efficiency (EQE) for the 4-junction IMM as a function of radiation fluence (from P. Patel, 37th IEEE PVSC 2011).

3.3 Mechanically Stacked Multijunction Technology

AFRL has teamed with Spectrolab and another government agency to investigate mechanically stacked multijunction solar cells based on a semiconductor bonded technology (SBT) as an alternate approach to >30% efficiency[7]. This approach addresses the desires for an optimum combination of solar cell bandgaps through a mechanical integration of lattice matched subcells rather than addressing lattice mismatch in a monolithic growth process, as in the IMM approach. Figure 4 shows a recent result of that effort for a 4-junction SBT cell composed of a GaAs based high bandgap tandem and an indium phosphide (InP) based low bandgap tandem. The data shows that good electrical conductivity and optical transmissivity has been obtained at the semiconductor bonded interface. The challenges being addressed in this effort are forming reliable, survivable, large area wafer bonds as well as approaches to permit the reuse of both the GaAs and the InP substrates.

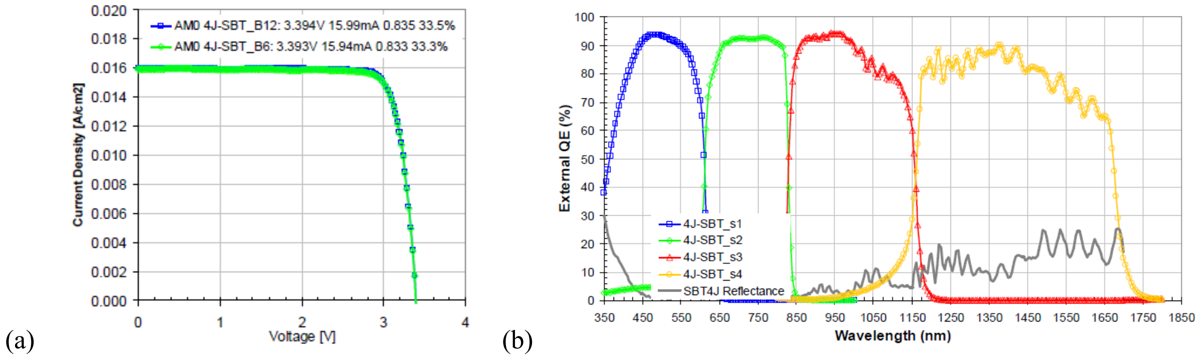


Figure 4. (a) AM0 I-V curve of 1 cm^2 mechanically stacked 4-junction solar cell and (b) external quantum efficiency of the same technology (from J. Boisvert, 37th IEEE PVSC 2011).

4. THIN FILM SOLAR CELL DEVELOPMENT

The Space Vehicles Directorate at AFRL has historically had a strong program investigating thin film technologies, primarily amorphous silicon (a-Si) and copper indium gallium diselenide (CIGS). These materials have the promise of reasonable efficiency (15% to 20%), low cost, flexibility, radiation stability and high mass specific power

(W/kg). The high efficiency and low mass of IMM technology (section 3.2) has replaced thin films in terms of applications reliant upon solar arrays with high mass specific power. Fortunately, the terrestrial market for thin film cells has blossomed, allowing AFRL to leverage the significant terrestrial investment for potential space and aerospace applications. This leveraging opportunity has benefited from the previous AFRL investment, as many thin film technology companies are now investigating thin, low mass substrates for their products rather than producing all of their cells on rigid glass substrates, superstrates or heavy metal foils. This low-mass packaging format is not only beneficial for spacecraft applications, but enables simplified terrestrial integration of their technology. Figure 5 shows several recent program successes where a-Si cells on low mass Kapton substrates from United Solar Ovonics have been integrated into high profile military aerospace applications.

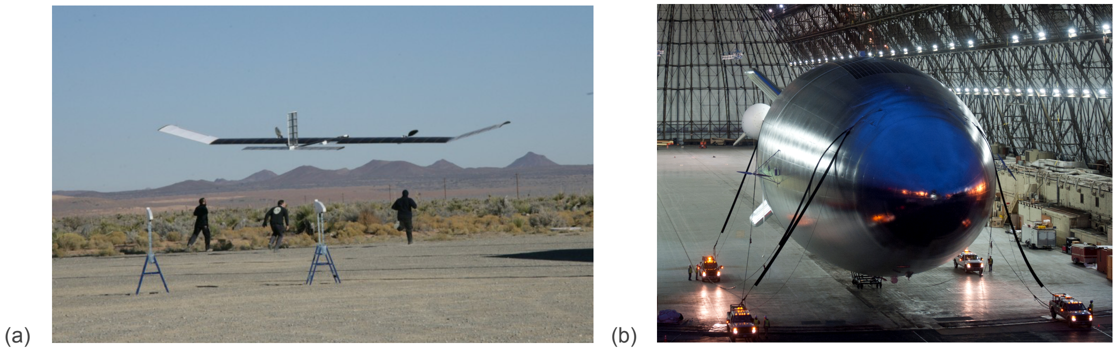


Figure 5. (a) QinetiQ Zephyr solar powered unmanned aerial vehicle being launched in Arizona. The Zephyr few for 14 days continuously, being powered by United Solar a-Si solar cells developed under AFRL funding. (courtesy of QinetiQ). (b) Lockheed Martin HALE-D airship powered by United Solar a-Si solar cells being readied for launch. a-Si panels are visible on the top of the airship (courtesy of Lockheed Martin)

While thin-film developers have made excellent progress in improving device efficiency for terrestrial applications, the device performance is not yet sufficient to warrant their use in traditional spacecraft applications. AFRL has some small programs to investigate novel approaches for dramatically improving device efficiency. These programs are primarily focused on developing materials and processes to support the fabrication of a CIGS based multijunction solar cell. Single junction CIGS has demonstrated >20% AM1.5 in a rigid format and >17% AM1.5 in a flexible configuration. It is a natural, albeit technically challenging, extension to move this high potential technology into a multijunction configuration. Recent advances in developing silver (Ag) alloyed with CIGS materials offers encouraging prospects for developing a high bandgap partner for a CIS bottom cell.

5. PATHWAYS TO ULTRA-HIGH EFFICIENCY POWER SYSTEMS

Development of high efficiency solar cells has progressed through a combination of materials improvements, development of new materials and the use of ever increasing number of subcells in a multijunction configuration (figure 1). As is commonly understood, the optimum efficiency for a single junction device (~30% AM1.5) is achieved by balancing two loss mechanisms: non-absorption of photons and over-excitation or thermalization losses from photons with energies in excess of the cell bandgap energy. To overcome these limitations, multijunction approaches have been developed, essentially acting as photon sieves, thereby reducing both loss mechanisms simultaneously. Following this path, the ~20% efficient GaAs single junction solar cell has progressed to the >33% efficient 4-junction IMM device. One may question how far we can or should follow this pathway to ever higher efficiency devices. Figure 6 begins to address that question by predicting the practically achievable efficiency for multijunction solar cells as a function of the number of subcells. One may debate the absolute value of device efficiency in this calculation, however the general trend is likely to be much less controversial. The data clearly indicates that there are diminishing returns as subcells are added. The question becomes whether the additional device efficiency gained is worth the cost, complexity and potentially reduced environmental stability incurred by adding an additional junction? At a recent space PV workshop, the question of where multijunction cell development will conclude was posed. The group consensus was that going beyond 6 junctions would be unlikely. So the question is, if we are interested in achieving efficiencies in excess of ~40% AM0 and we do not believe that we can get there through multijunction approaches, what technical path do we follow?

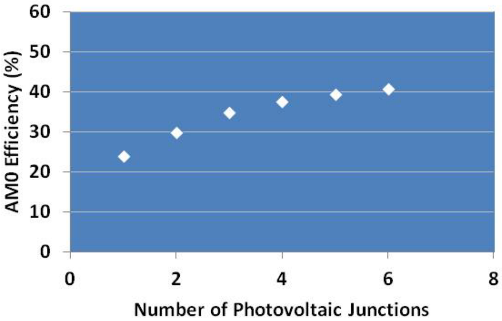


Figure 6. Theoretical estimation of solar cell device efficiency as a function of the number of subcells (data from P. Sharps, 33rd IEEE PVSC, 2008)

To address that question, AFRL has been investing in two approaches that have the potential to demonstrate >40% efficiency, namely concentrator solar array technologies and new solar cell technologies, such as intermediate band solar cells (IBSC), hot carrier solar cells, etc. Space concentrator solar arrays have an interesting space heritage, ranging from highly successful missions (e.g. SCARLET and Deep Space 1) to very expensive power system losses (e.g. Boeing 702). Fortunately, the space power community has learned by both the successes and the failures and there is a resurgence in government interest in space concentrating solar array technology[8]. Concentrator solar arrays offer many advantages for spacecraft applications, namely:

- Improved efficiency of conventional solar cells, due to optical concentration
- Improved environmental shielding, leading to higher end of life performance particularly for high radiation orbits
- Simplified ability to operate array at high voltage, particularly important for high power arrays (>30kW)
- Inherently robust from certain man-made threats
- Enabling for new device concepts that require high photon flux (e.g. IBSC)
- Potential for significant cost savings from reduced photovoltaic device area requirement

Concentrator arrays are not without their challenges, principally low volumetric specific power (W/m^3) when stowed for launch, concerns of optical efficiency losses due to contamination, array pointing requirements levied onto the spacecraft attitude control system as well as survival power needs should the spacecraft lose attitude control and begin to tumble. These latter two points have become less of a barrier recently as attitude control reliability has improved. New array designs are currently being investigated to address these challenges in programs that have recently been started.

There have been many encouraging theoretical projections regarding the efficiency potential of IBSC solar cells (>60%), being roughly equivalent to a >50 junction solar cell. AFRL funded programs have primarily focused on the fundamental development of QD materials and processes, with a near term objective of improving triple junction devices as described previously[9]. That work has clearly demonstrated technical progress in improving device efficiency but has also demonstrated a significant challenge in effectively coupling the incident photon flux into the quantum structures in order to appropriately utilize the full solar spectrum. Novel materials and structures are being investigated to integrate the high performance QD materials developed with new cell designs to maximize the interaction of photons with quantum materials, including nipi superlattice structures, plasmonics, etc.[10] The IBSC and other ultra high efficiency approaches are viewed as long term opportunities, whereas concentrators could provide >40% efficient arrays in the relative near term.

6. BEYOND EFFICIENCY

The quest for ever higher efficiency has defined the overarching motivation for AFRL's PV research programs for the past decade. History has demonstrated that improvements in solar cell device efficiency eventually become space qualified technologies, particularly given the leveraging effect higher efficiency devices have on the spacecraft balance of system (mass, volume, deployed area/drag, etc). It is worth considering where or if this value proposition of efficiency will change in the future. For example, a 1% absolute improvement in efficiency for a 10% solar cell is obviously more significant, in a relative sense, than it would be for a 40% efficient device. Improvements in cell efficiency have sometimes come with an associated increase in cell cost ($/W) and increased sensitivity to environmental challenges (e.g. changes in spectral transmissivity of optical components, differential radiation degradation rates, etc). One could argue that at some point, a reduction in the cost/benefit of higher efficiency cell technologies will begin to limit the motivation to develop ever higher efficiencies.

Should that point be reached, it is likely that research on photovoltaics will not cease, rather it will broaden, with certain missions, still reliant upon obtaining the highest solar cell efficiency possible, driving high efficiency cell research, while other objectives (e.g. lower cost, survivability, environmental durability, packaging efficiency, etc) rising in importance. As an example of the latter, the DoD terrestrial market for high efficiency solar cells appears to be expanding. Recent joint DoD/DOE programs have begun to investigate concentrator PV (CPV) as a power option for military forward operating base power. In addition, several DoD research and development efforts are investigating the ability to transfer high efficiency space photovoltaics to deployed soldier power applications. In both of these instances, the cost/benefit trade of PV is compared to either extremely expensive conventional fuels, expensive both in terms of lives lost in transit (>1000 lives lost in Iraq and Afghanistan in attacks on supply vehicles) and actual dollars (estimated $400 per gallon), or to batteries that have a very problematic logistics trail (shipping, disposal, etc) and impact on deployed soldier capability. In a recent report, a former Pentagon official estimated that the US military spends approximately $20.2 billion annually for air conditioning in Iraq and Afganistan[11]. Obviously PV generated power is well positioned to offset a significant amount of this power, with a tremendous potential for savings, both in terms of lives saved, dollars saved and reduced environmental footprint. This expansion of space heritage solar cell technology applications is likely to translate into increased production capacity and potentially lower costs for spacecraft solar cells.

7. CONCLUSIONS

The path of spacecraft photovoltaic development has demonstrated a remarkable history of ever improving device performance and consistent transition from laboratory discovery to qualified spacecraft component. Current efforts are focused on multiple paths to continue the progress in device efficiency, with ~37% efficient laboratory devices expected in the near future. As efficiency improves, we expect our research efforts to broaden to encompass other device attributes of value to the spacecraft community. A tremendous leveraging opportunity has opened up for transition of high efficiency space solar cells to be repurposed for terrestrial base and soldier power.

REFERENCES

[1] Hoang, B. and Lyon, R., "Space Systems Loral 25-kW Power Systems for CY2010 Class-A Satellites and Challenges Ahead for Higher Electrical Power Subsystems," Proc. 2010 Space Power Workshop (2010).

[2] Penn, J., Richardson, G., Brown, N., Ranieri, C. and Henning, G., "Spacecraft Applications Enabled by High Powered Solar Array Technology," Proc. 2010 Space Power Workshop (2010).

[3] Bailey, C., Forbes, D., Raffaelle, R., Hubbard, S., "Near 1 V Open Circuit Voltage InAs/GaAs Quantum Dot Solar Cells," APL, Vol98, Issue 16, page(s): 163105 - 163105-3 (2011).

[4] Fedoseyew, A.I.. Turowski, M., Raman, A., Taylor, E.W., Hubbard, S., Polly, S., Balandin, A.A., "Investigation and Modeling of Space Radiation Effects in Quantum Dot Solar Cells, Proc. 35th IEEE Photovoltaic Specialists Conference, pages 2633-2536, (2010)

[5] Wanlass, M., et al, " Monolithic, Ultra-Thin GaInP/GaAs/GaInAs Tandem Solar Cells," Proc. 33rd IEEE Photovoltaic Specialist Conference, pages 729-732 (2006)
[6] Patel, P., et al, "Experimental Results from Performance Improvement and Radiation Hardening of Inverted Metamorphic Multi-Junction Solar Cells," Proc. 37th IEEE Photovoltaic Specialist Conference (2011)
[7] Bosivert, J., et al, "Development of Space Solar Cells at Spectrolab," Proc. 37th IEEE Photovoltaic Specialist Conference (2011)
[8] Kurt, K., et al, "Multiple NEO Rendezvous, Reconnaissance and In-Situ Exploration," Proceedings AIAA SPACE 2011 Conference, AIAA2011-7218 (2011).
[9] Hubbard, S., et al, "Investigation of Quantum Dot Enhanced Triple Junction Solar Cells," Proc. 37th IEEE Photovoltaic Specialist Conference (2011)
[10] Solcum, M.A., et al, "Demonstration of an nipi Photovoltaic Device," Proc. 37th IEEE Photovoltaic Specialist Conference (2011)
[11] http://www.npr.org/2011/06/25/137414737/among-the-costs-of-war-20b-in-air-conditioning

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