563623
3P

Advanced Thin Film Solar Arrays for Space – the Terrestrial Legacy

Sheila Bailey and Aloysius Hepp
MS 302-1, NASA Lewis Research Center, Cleveland, OH 44135, USA

Ryne Raffaelle
Rochester Institute of Technology

Dennis Flood
NanoDielectrics Corp.

ABSTRACT

As in the case for single crystal solar cells, the first serious thin film solar cells were developed for space applications with the promise of better power to weight ratios and lower cost. Future science, military and commercial space missions are incredibly diverse. Military and commercial missions encompass both hundreds of kilowatt arrays to tens of watt arrays in various earth orbits. While science missions also have small to very large power needs there are additional unique requirements to provide power for near sun missions and planetary exploration including orbiters, landers and rovers both to the inner planets and the outer planets with a major emphasis in the near term on Mars. High power missions are particularly attractive for thin film utilization. These missions are generally those involving solar electric propulsion, surface power systems to sustain an outpost or a permanent colony on the surface of the moon or mars, space based lasers or radar, or large earth orbiting power stations which can serve as central utilities for other orbiting spacecraft, or potentially beaming power to the earth itself. This paper will discuss the current state of the art of thin film solar cells and the synergy with terrestrial thin film photovoltaic evolution. It will also address some of the technology development issues required to make thin film photovoltaics a viable choice for future space power systems.

1. Introduction – the legacy

One of the first thin film cells, Cu_2S/CdS, was developed for space applications. Reliability issues eliminated work on this particular cell type for both space and terrestrial considerations even though AM1.5 efficiencies in excess of 10% were achieved. The major driver in the terrestrial photovoltaic world is dollars per watt. Thin film cells required substantially less material and promised the advantage of large area, low cost manufacturing. However, space cell requirements dictate a more complicated trade space. Until recently the focus in space cells has been on efficiency rather than cost. In a several billion dollar spacecraft the cell cost is relatively small at even a thousand dollars per watt, which is approximately the current array cost. This has primarily been true for spacecraft with power needs from a few hundred watts to tens of kilowatts. However, deployment of a large earth orbiting space power system will require major advances in the photovoltaic array weight, stability in the space environment, efficiency, and ultimately the cost of production and deployment of such arrays. The development of large space power systems, and a host of other proposed space missions, will require the development of viable thin film arrays.[1] Studies have shown that the specific power or power per mass that will be required (i.e., 1 kW/kg) cannot be achieved with single crystal technology.[2] The specific power required is almost 40 times what is presently available in commercial arrays.[3] While high efficiency ultra lightweight arrays are not likely to become commercially available anytime soon, advances in thin film photovoltaics may still impact other space technologies (i.e., thin film integrated power supplies) and thus support a broad range of missions in the next century.[4] Mission examples include micro-air vehicles, ultra-long duration balloons (e.g. Olympus), deep space solar electric propulsion (SEP) "Tug" Array, Mars SEP Array, and Mars surface power outpost (see Figure 1).

Figure 1. Proposed Mars solar electric propulsion vehicle.

Lighter power generation will allow more mass to be allocated to the balance-of-spacecraft (e.g. more payload). In addition, less expensive power generation will allow missions with smaller budgets and/or the allocation funds to the balance-of-spacecraft (e.g. more payload). This is an essential attribute in enabling such missions as the Mars Outpost SEP Tug. Example benefits for the now-cancelled

ST4/Champollion indicate a $50 million launch cost savings and 30% mass margin increase when thin-film PV solar array power generation was combined with advanced electric propulsion. A parametric assessment showed similar advantages for other solar system missions (e.g., main belt asteroid tour, Mars solar electric propulsion vehicle, Jupiter orbiter, Venus orbiter, Lunar surface power system).

Much of the original development of thin film photovoltaic arrays was performed with the terrestrial marketplace in mind. This has been a tremendous benefit to researchers hoping to develop such arrays for space. Features such as cell efficiency, material stability and compatibility, and low cost and scalable manufacturing techniques are important to both environments. However, many key array aspects necessary for space utilization are not important for terrestrial use and thus have not experienced a similar progress. Features such as radiation tolerance, air mass zero (AM0) performance, lightweight flexible substrates, stowed volume and lightweight space deployment mechanisms must be developed before a viable space array can become a reality. Unfortunately, the costs associated with developing these features along with the subsequent space qualification studies mitigate the savings of using a thin film array for space and thus have inhibited the development.

2. Thin Film Technology

On-going efforts by NASA and the U.S. Air Force are now addressing these issues associated with the development of thin film arrays for space. NASA is currently supporting joint research efforts in thin film array development with researchers at the Florida Solar Energy Center (FSEC), Daystar, Inc., and Global Solar, Inc. Copper indium diselenide (CIS), cadmium telluride (CdTe), and amorphous silicon (α-Si) thin film materials are three materials that appear to have a good chance of meeting several proposed space power requirements.[5] Reasonably efficient (~ 8 % AM 1.5) large area triple junction blankets using α-Si are already being manufactured.[6] Large area CIS cells are now reaching as high as 10% AM 1.5[7]. Development of other wide bandgap thin film materials that can be used in conjunction with CIS to produce a dual junction device are underway. As has already been demonstrated in III-V cells for space use a substantial increase in the single junction efficiency is possible with a dual junction device.[8] NASA has initiated a dual-junction CIS-based thin film device program with researchers at the University of South Florida. The use of Ga to widen the bangap of CIS and thus improve the efficiency is already well known.[9] The substitution of S for Se also appears to be an attractive top cell material.[10] AM0 cell efficiencies as high as 7% have been measured for $CuIn_{0.7}Ga_{0.3}S_2$ (E_g 1.55 eV) thin film devices on flexible substrates (see Figure 2).

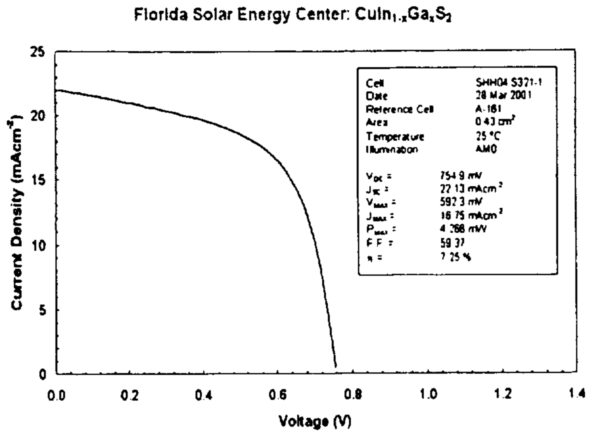

Figure 2. AM0 photoresponse for $CuIn_{0.7}GaS_2$ thin film solar cell deposited on Mo coated stainless steel foil.

Unfortunately most of the high efficiency thin film devices developed thus far have been on heavy substrates such as glass. However, progress is being made in reducing substrate mass through the use of thin metal foils and lightweight flexible polyimide or plastic substrates[11]. A major problem with the use of plastic substrates is the incompatibility with many of the deposition processes. The most efficient thin film cells to date are made by some combination of co-evaporation of the elements and subsequent annealing. The use of such plastic substrates as Upilex or Kapton puts an unacceptable restriction on the processing temperatures. This of course can be obviated by the use of metal foil if one is willing to accept the mass penalty.

Another approach that may allow for the use of plastic substrates is to develop low temperature deposition techniques. Efforts are being made by NASA and others to develop low temperature chemical vapor deposition and electrochemical deposition methods. Low temperature processing techniques (< 400°C) that are compatible with plastic substrates must be developed if the goal of achieving 1000 W/kg (1 kW/kg) cell is to be achieved. Recent use of a single-source precusor for low temperature chemical vapor deposition of $CuInS_2$ and related compounds has demonstrated promise in this regard.[12]

3. Array Specific Power

To achieve an array specific power of 1kW/kg a cell specific power considerably higher than that will be necessary. Similarly, the blanket specific power (i.e., interconnects, diodes and wiring harnesses) must be over 1 kW/kg as well. The Advanced Space Photovoltaic Array (APSA) assessment determined that the mass of the deployment mechanism and structure is essentially equal to the blanket mass for a lightweight system. Therefore, a blanket specific power of approximately 2000 W/kg would be necessary to achieve a 1 kW/kg array.[13] NASA is currently sponsoring an effort by AEC Able Engineering to develop lightweight thin film array deployment systems.

Gains in specific power can addressed through an increase in the operating voltage. Higher array operating voltages can be used to reduce the conductor mass, especially at the high power levels that may be encountered. The APSA was designed for 28 volt operation at several kilowatts output, and the resulting wiring harness comprised about 10% of the total array mass, giving it a specific mass of about 0.7 kg/kW. Designing the array for operation at 300 V could easily allow a reduction of the harness specific mass by 50% or more, with a concurrent increase in the APSA specific power of 5% or more without any other modification. In any event, it is clear that future thin film, light weight solar arrays must be capable of high voltage operation in the space plasma environment, and it is likely that the required voltages will approach 1000v to 1500v to be compatible with direct drive electric propulsion spacecraft (i.e., no voltage step up is required to operate the thrusters). Such a requirement is completely compatible with the demand for high specific power. NASA has bench marked a thin film stand-alone array specific power that is 15 times the state-of-the-art (SOA) III-V arrays; area power density that is 1.5 times that of the SOA III-V arrays, and specific costs that are 15 times lower than the SOA III-V arrays.[14]

4. Space Qualification

The cells, blankets, and deployment mechanisms must all be able to withstand the rigors of space utilization. This will require that they are stable with respect to thermal cycling, vibration and mechanical stresses, and exposure to radiation (specifically high energy protons and electrons) and atomic oxygen. This poses tremendous challenges for substrate and cell stability and module electrical and physical interconnects. A benefit to the use of thin film CIS in this regard is its radiation tolerance. CIS has been shown to retain much more of its beginning of life (BOL) power than a comparable III-V cell.[15] In fact, little or no degradation has been measured for $CuInGaSe_2$ thin film cells due to 1 MeV electron irradition at a fluence of 10^{16} (see Figure 3).

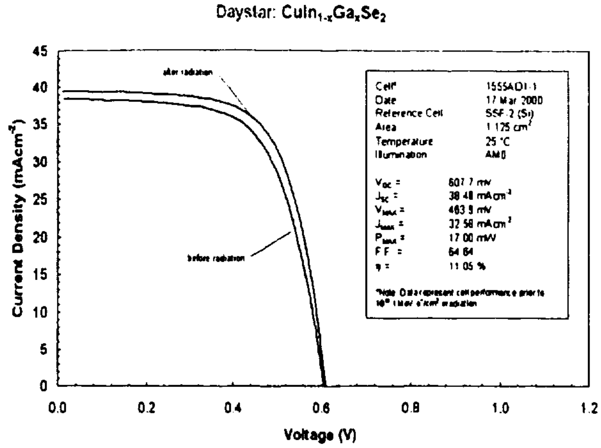

Figure 3. AM0 photoresponse of $CuInGaSe_2$ thin film cells on Mo coated Ti foil before and after electron irradiation.

5. Integrated Thin Film Power Systems

NASA has also been working to develop a lightweight, integrated space power system on a flexible substrates (see Figure 4)[16]. The system will consist of a high efficiency thin film solar cell, a high energy density solid state Li ion battery, and the associated control electronics in a single monolithic package. This requires the development of suitable materials and low temperature chemical processing methods necessary to produce battery components that are compatible with thin film solar cells and other microelectronic components.

Thin film Li ion batteries have recently been directly integrated with monolithically interconnected photovoltaic modules and other electronic components for monolithic energy conversion and storage devices and distributed power nanosatellites.[17] These systems have the ability to produce constant power output throughout a varying or intermittent illumination schedule as would be experienced by a rotating satellite or "spinner" and by satellites in a low earth orbit (LEO).

An integrated thin film power system has the potential to provide a low mass and cost alternative to the current SOA systems for small spacecraft. Integrated thin film power supplies simplify spacecraft bus design and reduce losses incurred through energy transfer to and from conversion and storage devices. It is hoped that this simplification will also result in improved reliability. NASA is looking for a 5-fold improvement in specific power over SOA for earth-orbiting systems.[14]

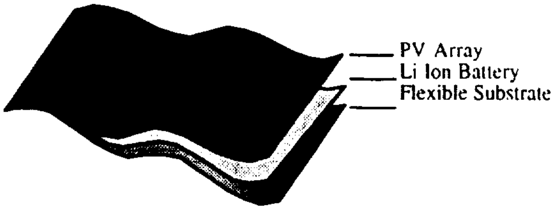

Figure 4. Thin film integrated power supply.

6. Summary

NASA has identified several areas in which large area thin film photovoltaic arrays can be of tremendous benefit for space exploration and development. Space qualified blankets (i.e., large area arrays on lightweight flexible substrates) with efficiencies as low as 12% (AMO) will serve as an enabling technology for a host of proposed missions. NASA plans to utilize the demonstrated radiation tolerance and possible efficiencies offered by materials such as $CuInSe_2$ by developing a low temperature deposition process that is compatible with plastic substrates. It is also hoped that this process may help to enable a dual junction CIS-based thin film device. Finally, it is anticipated that large area thin film arrays can be combined with other thin film devices (i.e., Li ion batteries) to produce completely autonomous and lightweight power supplies.

Acknowledgements

The authors wish to thank John Tuttle of Daystar Technologies, Inc. and Neelkanth Dhere of the Florida Solar Energy Center for their contributions to this work. We would also like to acknowledge the NASA Cooperative Agreements NCC3-710 and NCC3-563 with the Rochester Institute of Technology.

References

[1] G. Landis and A.F. Hepp, "Applications of Thin Film PV for Space," 26th IECEC, 2, 256 (1991).

[2] D.J. Hoffman, T.W. Kerslake, A.F. Hepp, M.K. Jacobs, and D. Ponnusamy, "Thin film Photovoltaic Array Parametric Assessment," 35th *IECEC*, 1, 670 (2000).

[3] D. Flood, "Thin Film Photovoltaics: Apllications to Space Power," 34th *National Heat Transfer Conference*, Pittsburg, PA, August 20-22, (2000).

[4] R.P. Raffaelle, J. Underwood, D. Scheiman, J. Cowen, P. Jenkins, A.F. Hepp, J.D. Harris, and D.M. Wilt, "Integrated Solar Power Systems," *28th IEEE PVSC*, Anchorage, AK September 17-22 (2000).

[5] J. Tringe, J. Merrill, and K. Reinhardt, "Developments in Thin-Film Photovoltaics for Space," *28th IEEE PVSC*, Anchorage, AK September 17-22 (2000).

[6] W. Fuhs and R. Klenk, "Thin-Film Solar Cells Overview," *2nd World Conf. On Solar Energy Conversion*, Vienna, Austria (1998).

[7] R.W. Birkmire, "Compound Polycrystalline Solar Cells: Recent Progress and Y2K Perspective," *Photovoltaics Science and Engineering Conf.*, Sapporo, Japan (1999).

[8] K. Barnham and G. Duggan, *J. Appl. Phys.* **67**, 3490 (1990).

[9] M. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, F. Hasoon, and R. Noufi, "Progress Toward 20% Efficiency $Cu(In,Ga)Se_2$ Polycrystalline Thin-Film Solar Cell," *Progress in Photovolt.*, 7, 311 (1999).

[10] C. Dzionk, H. Metzner, S. Hessler, and H.E. Mahnke, *Thin Solid Films* **299**, 38 (1997).

[11] K. Tabuchi, S. Fujikake, H. Sato, S. Sito, A. Takano, T. Wada, T. Yoshida, Y. Ichikawa, H. Sakai, and F. natsume, "Improvements of Large-Area SCAF Structure a-Si Solar Cells with Plastic Thin Film Substrate," *26th IEEE PVSC*, Anaheim, CA (1997).

[12] J.D. Harris, D.G. Hehemann, J. Cowen, A.F. Hepp, R.P. Raffaelle, and J.A. Hollingsworth "Using Single Source Precursors and Spray Chemical Vapor Deposition to Grown Thin Film $CuInS_2$," *28th IEEE PVSC*, Anchorage, AK September 17-22 (2000).

[13] P. Stella and R.M. Kurland, *The Advanced Photovoltaic Solar Array (APSA) Technology Status and Performance*, 10th Space Photovoltaic Research and Technology Conference, NASA CP-3107, 421-432, (1986).

[14] A.F. Hepp, NASA GRC Thin Films Technology Product Agreeement (2000).

[15] H.W. Schock and K. Bogus, "Development of CIS Solar Cells for Space Applications," *2nd World Conf. On Solar Energy Conversion*, Vienna, Austria (1998).

[16] D.J. Hoffman, G.A. Landis, R.P. Raffaelle, and A.F. Hepp, "Mission Applicability and Benefits of Thin-Film Integrated Power Generation and Energy Storage," *36th IECEC*, Savannah, GA, July 29-Aug. 2 (2001).

[17] R.P. Raffaelle, J. Underwood, J. Maranchi, P. Kumta, O.P. Khan, J.D. Harris, C.R. Clark, D. Scheiman, P. Jenkins, M.A. Smith, D.M. Wilt, R.M. Button, and A.F. Hepp, "Integrated Microelectronic Power Supply (IMPS)," *36th IECEC*, Savannah, GA, July 29-Aug. 2 (2001).