Novel Applications for Flexible CIGS-based Photovoltaics for Solar Power Generation, Management and Storage

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ABSTRACT

Converting solar energy into electrical power has been an attractive alternative to fossil fuels for many years, and with the advent of lightweight, flexible, efficient photovoltaic (PV) blankets, many applications have been envisioned where off-grid power generation has become a reality. Ascent Solar's novel flexible, lightweight, monolithically-integrated CIGS on polyimide substrates offers a highly-redundant, robust power generation solution that is available in the consumer market, as well as in development for portable power solutions for today's military, onboard power generation for small unmanned aerial vehicles (sUAV), electric-powered aviation, near-space and space applications. While space vehicles have been using PV from the beginning of its existence, other non-traditional applications are just realizing the potential of on-board power generation. In this presentation, we will illustrate the inherent robust nature of our PV technology, and will be presenting the development of several key product areas using our flexible CIGS PV, including sUAV, electric powered civil aviation, and fully-integrated portable power generation, management, and storage solutions. Challenges for each area will be discussed, and the novel solutions using flexible lightweight CIGS PV will be described, and pertinent data and analyses on performance will be provided.

Keywords: flexible photovoltaics, monolithic integration, maximum peak power tracking, onboard power storage, portable power.

1 INTRODUCTION

From the first observance of the photoelectric effect in 1939 to the first demonstration of a semiconductor-based solar cell in 1904, the conversion of solar energy into electricity had been primarily a scientific endeavor or a novelty use in light-detecting sensors. However, in the mid 1950's, a practical application for solar cells, namely space exploration, pushed the development of solar cells for converting solar energty into useful electrical power. As these early solar cells were based on semiconductor wafer technologies, they were fragile, and in the early stages of solar energy conversion, not very efficient. However, as sunlight above the earth's atmosphere is intense and only shaded occasionally in orbit, photovoltaic power became a primary means for generating electrial power in space applications. Steady improvement of device efficiency has improved the effectiveness of PV in terms of providing the necessary power in this application, but cost has always been prohibitive. Evolution of terrestrial-based applications followed, with many off-grid applications becoming based on PV devices.

However, one common trait remains with regard to these PV technologies, namely, that the PV devices are based on crystalline semiconductor wafers. These devices are inherently fragile and thus require substantial protective packaging to prevent fracturing and otherwise damaging them in normal operation. Furthremore, as the PV devices themselves are discrete and limited in voltage, a number of devices must be interconnected in order to achieve a useful voltage for a given connected circuit.

Ascent Solar Technology, Inc. (AST) was founded to develop a PV technology based on the thin-film copper-indium-gallium-selenium (CIGS) absorber technology, with deposition upon a flexible polyimide substrate. By virtuie of the substrate being a dielectric material, unlike other CIGS manufacturs, AST has been the first to demonstrate monolithically-integrated CIGS PV modules *in production*. By its nature, monolithic integration results in a higher voltage within a smaller area than those associated with discrete cell technologies. Geometrically, monolithically-integrated cells are ideal for higher current PV technologies, such as CIGS, and are well suited for applications where higher-than-normal solar intensity is present, such as high altitude/near-space and space environments. Monolithic integration of flexible CIGS PV also has the distinct advantage over discrete cell technology (either crystalline or thin film flexible) of providing inherent redundancy in cell interconnection. Because the cells are interconnected continuously along their long side, any damage that the module withstands can be mitigated by diverting current paths around the damage (Figure 1). Thus, the monolithically-integrated module that represents a series connection of cells, will continue to operate, albeit at a reduced capacity, but more importantly, the series interconnect is not compromised.

2 MANUFACTUIRNG PROCESS BASED ON MONOLITHIC INTEGRATION

While required for thin-film PV modules on glass substrates, discrete flexible CIGS devices makes up a large portion of the industry. Ascent Solar's unique approach of monolithic integration on a flexible substrate enables larger devices, and thus, small part counts, while enabling higher voltages in smaller footprints. As shown in Figure 2, AST manufacturing process consists of three distinct steps, the first of which is the thin film deposition of all the films, followed by a patterning cell that scribes and interconnects cells in a monolithic integration process. By completely isolating deposition and monolithic integration processes, AST can provide custom modules from a common roll process to customers based their specific voltage/current requirements.

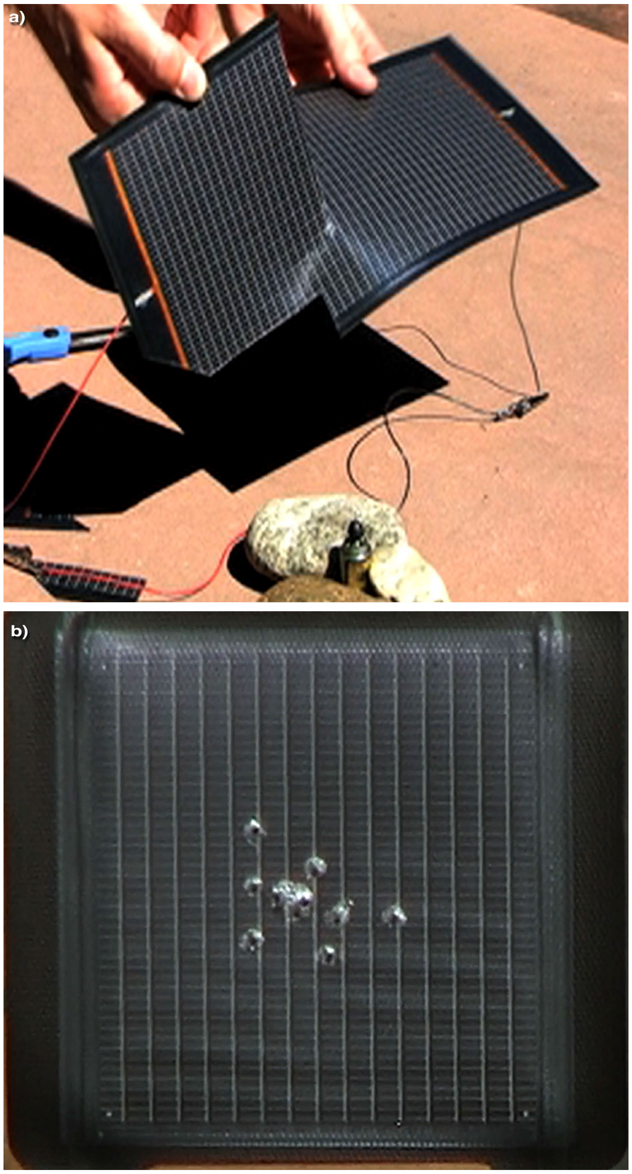

Figure 1: Demonstrated Robust Design of Flexible CIGS Module with Respect to a) Cutting or b) Penetrations.

Because monolithic integration results in narrow cells in series that are the width of the module, the distance current needs to travel to be collected per cell is much smaller than discrete cells (either crystalline or flexible thin film) and current generation per cell is thus lower than what is practical for discrete cells. Discrete cells cut this narrow would be extremely difficult to integrate into strings, while the monolithic integration process ensures that these cells are interconnected during processing. Figure 3 shows a 15cm x 15cm module that consists of sixteen (16) cells in series, producing 9VDC Voc (7.4V Vmax) at nominally 2W output. This module was designed specifically for this voltage output to power our USB charging circuitry. As a result, the inherently high current density of CIGS device chemistry can be somewhat mitigated by monolithic integration by economically integrating small area cells in series with reduced current path, and applications where the device operates under high sun intensity (e.g. solar concentration, high-altitude and space applications), monolithic integration can result in a significant reduction in module losses compared to other technologies (Figure 4).

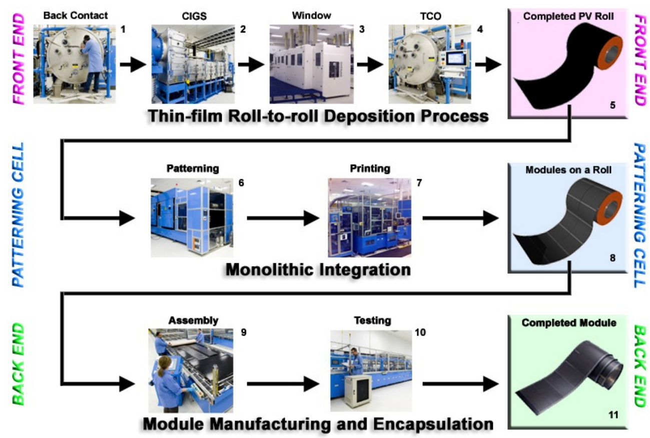

Figure 2: Schematic Representation of the AST Manufacturing Process.

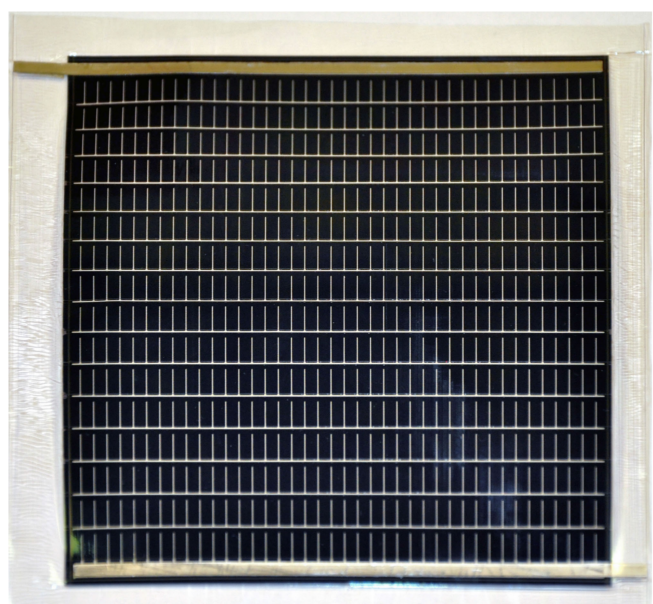

Figure 3: Photograph of AST's 15x15cm 'USB' module with Sixteen (16) Cells in Series (top to bottom)

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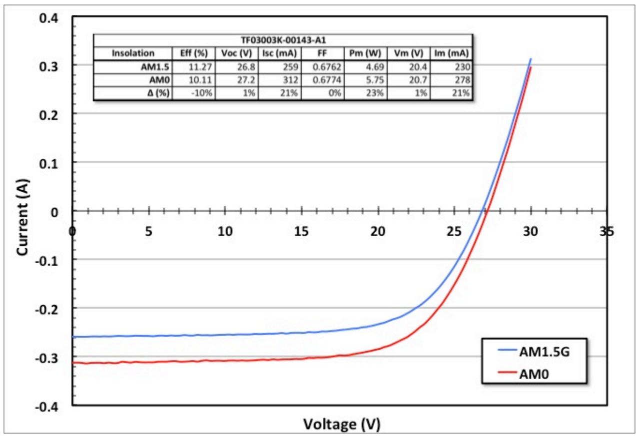

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Insolation	Eff (%)	Voc (V)	Isc (mA)	FF	Pm (W)	Vm (V)	Im (mA)
AM1.5	11.27	26.8	259	0.6762	4.69	20.4	230
AM0	10.11	27.2	312	0.6774	5.75	20.7	278
Δ (%)	-10%	1%	21%	0%	23%	1%	21%

Figure 4: I-V Characteristics of a 15x30cm Module under Terrestrial (AM1.5G) and Space (AM0) Test Conditions.

3 NOVEL APPLICATIONS OF FLEXIBLE MONOLITHICALLY INTEGRATED CIGS

Because of the unique combination of lightweight flexible polymeric substrate, thin-film deposition processes, novel manufacturing process, and monolithic integration, AST's CIGS technology can be applied to a wide range of applications. Its inherent robustness makes it ideal for rugged military and off-grid portable power markets. Furthermore, its thinness and aesthetically-pleasing uniform black appearance is also ideal for consumer products; AST established EnerPlex™ as its commercial brand for portable power solutions for modern consumer electronics (Figure 5).

Figure 5: Photograph of EnerPlex™ Porable Power Systems that Support the Active Urban and Outdoor Lifestyles.

3.1 Portable Power Applications

On January 5th, AST announced a fully-integrated portable PV system folding PV-based power system (patent pending) at the 2015 Consumer Electronics Show (CES) that provides power generation, power management, power storage, and power distribution. Referred to as the MilPak™ family of portable PV products (Figure 6), the system contains sixteen (16) 15cmx30cm module that nominally generate 60 watts. As each module is designed to operate at the requisite peak power voltage and current, all sixteen modules are connected in PARALLEL, thus reducing the chance that damage to any module would result in a loss of the entire system. In order to facilitate maximum power conversion under a wide range of conditions (sun angle, temperature, solar intensity), a maximum peak power tracker (MPPT) maintains the output of the PV blanket by monitoring the power output and adjusting the voltage and current operating point of the PV to maintain maximum power. As solar power can vary during the day with clouds, artificial shading, etc., a lithium-ion battery pack is used as the power 'buffer' and its charge state is maintained by the MPPT as well. An internal DC power bus operates various output options, including high-current USB power charging interfaces, as well as a high-power output that ranges from 19VDC to 28VDC, depending upon the customers needs. All connectors are, at a minimum, IP-67 rated and some variants of the MilPak™ utilize military-grade connectors and switchgear throughout. MilPak™ represents a lightweight (3.7 kg) fully-integrated foldable power system (Figure 7). Specifications for this system are shown in Table 1.

Figure 6: Photograph of the MilPak™ E System.

Figure 7: Photographs of the Deployment Sequence of MilPak™ E .

Table 1: Specifications for MilPak™ E

Name:	MilPak™ E
Solar PV:	Monolithic Flexible CIGS with Maximum Peak Power Tracking
- Vmax	18.5VDC
- Imax	3.2A
- Pmax	60W
- Pnominal	52W
Storage:	• 86.5 Whr Lithium Ion with Battery Management System Protection
Output:	• Circuit Breaker Protected • 2 x 5VDC, 2.1A USB (regulated) • Either 19, 24 or 28V DC (regulated, custom voltages available) • 55W maximum (chainable)
Physical:	
- Stowed	80 x 410 x 220 mm
- Deployed	75 x 1990 x 725 mm
- Mass	3.7 kg (8.2 lbs)

3.2 Aerospace Applications

The low current/high voltage nature of AST's CIGS makes it ideal for space applications where the higher solar intensity above the ground equates to higher current per cell. By the nature of the cells in a monolithically integrated module, these devices handle higher solar intensities better than other technologies. AST has developed a lightweight flexible package that protects the PV from moisture and ultraviolet (UV) light while maintaining an overall areal density of 350-400 g/m^2. Combined with the afore-mentioned properties, the 'SuperLight' package can be used in any weight-sensitive application such as bonding onto fixed-wing surfaces to larger airship applications. Figure 8 shows the Silent Falcon™ small unmanned aerial system (sUAS) that uses AST's SuperLight construction for extending flight time. Unlike other sUAS concepts or prototypes, Silent Falcon™ is ***in production***, as are the AST flexible PV modules mounted to the wing surfaces. Flight time of Silent Falcon is designed to exceed 8 hours with contributions from the AST flexible PV blanket.

Figure 8: Silent Falcon™ sUAS Staged for Lauch with Ascent Solar Technologies SuperLight PV Integrated into the Wings for Extended Flight Time. Flight time of Silent Falcon is designed to exceed 8 hours with contributions from the AST flexible PV panels

4 SUMMARY

AST's flexible, monolithically-integrated PV product is inherently robust and is ideal for a wide range of applications where weight is a challenge, or where the PV must conform to a curved surface, such as a wing surface. Monolithic integration is also ideal for genrating a usable voltage in a small area and can be tailored to produce a specific output as required by the attached load requirements. Such an approach enables the rugged 60W military blanket with fully-integrated power storage, management, storage and distribution functions. Furthermore, the inherently small cell area makes this construction for high-intensity solar applications, such as high altitude and space applications.