WHITEPAPER

Lightweight, High-Performance Solar Cells for High Power-to-Weight and Deployable Solar Arrays

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Executive Summary

Thin gallium-arsenide solar cells promise high efficiencies and power to weight ratios, important for satellites of all sizes. Further, such cells can be rolled or folded to achieve high stowed power densities, which is especially important for small satellites, as well as for larger satellites with high power requirements, for example to support electric propulsion. The reduced costs offered by the manufacturing process used for these cells may also be attractive for spacecraft planning to utilize larger electric propulsion systems. Sunnyvale, CA-based Alta Devices holds world records for solar cell efficiency and presents here details of its current lightweight GaAs solar technology as well as highlights of its technology roadmap as applicable to LEO satellites.

Introduction

For over fifty years, space has been dominated by large government or quasi-government players, running expensive programs to build, launch and operate spacecraft. Creating critical public service, defense and communications infrastructure, these programs have rightly been conservative in their technology selection and engineering design.

> The best performing commercial, terrestrial solar cells are made from monocrystalline silicon, which requires a thickness of 100-200 microns for sufficient light absorption

Today there is a new movement in space enterprise being driven by increased participation of small, private players, lower launch costs, and a trend towards achieving system-level robustness through redundancy and replacement, rather than a bulletproof design [1]. In particular, these principles are being applied to design constellations of satellites for various applications including commercial imaging (both still and video) and communication [2, 3]. Relatively large numbers (100 to 1000) of identical satellites are being proposed for these projects; this means that perhaps for the first time, component costs are becoming as or more important than the costs of labor for assembly and test. This is accelerating the adoption of commercial, off-the shelf technologies for use in space as part of the bus systems, and certainly in the payload.

In keeping with this trend, there is interest in using commercial-grade solar cells for powering the spacecraft. However, most terrestrial-type solar cells do not have conversion efficiencies high enough to be of interest, nor do they have sufficient radiation stability. The best performing commercial, terrestrial solar cells are made from monocrystalline silicon, which requires a thickness of 100-200 microns for sufficient light absorption [4]. Therefore these cells must employ crystalline material of very high quality in order to achieve carrier diffusion lengths of this magnitude. Unfortunately, this can make such cells especially susceptible to damage from radiation [5], which can rapidly reduce carrier movement due to the creation of defects in the crystal. This is less of a problem in gallium-arsenide based solar cells, which only require a thin layer (~2 microns) of semiconductor for equivalent light absorption. Therefore, spacecraft designers continue to use specialized gallium-arsenide based solar cells, which provide excellent performance but are thick, heavy, brittle and expensive, because they incorporate the entire wafer.

However, there has been a new development: thin gallium-arsenide solar cells produced via epitaxial lift-off (ELO). Such cells have been developed by Alta Devices for markets that value high efficiency and light weight and cannot support the prices of traditional III-V solar cells, such as solar-powered aircraft and electric cars. As described below, these cells provide good efficiencies and high power to weight ratios, important for satellites of all sizes. Further, such panels made with these cells can be rolled or folded to achieve high stowed power densities.

Another technology that is receiving increasing interest and seeing rapid innovation is electric propulsion, which can offer higher specific impulse, reducing costs and enabling new types of missions [6]. Electric propulsion is power-limited [7]. The greater the amount of available electric power, the greater the efficiency of the electric propulsion system; naturally this means there is a need for larger solar arrays. The reduced costs offered by the manufacturing process used for thin gallium-arsenide cells of the type made by Alta Devices makes them even more attractive for such applications.

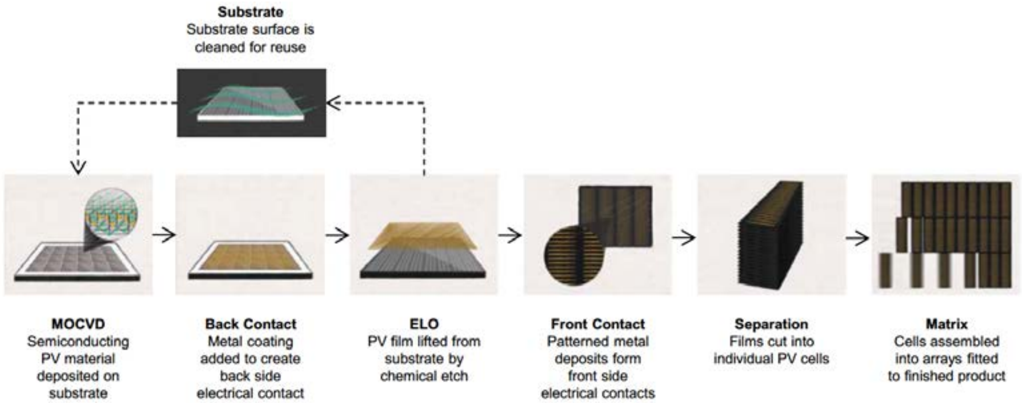

Fig. 1. Manufacturing process flow in the Sunnyvale fab for Alta's thin and lightweight III-V solar cells.

Manufacturing Process

Figure 1 shows the overall process flow for the manufacture of the solar cells. We start with 4-inch square wafers of gallium-arsenide and prepare them for epitaxial growth. We then grow the solar cell and release layers by metal-organic chemical vapor deposition (MOCVD), deposit a metal film stack, then laminate a polymer carrier film to the metal layer. This film remains with the solar cell and goes into the finished product, providing mechanical support for the metal and semiconductor films, which are only on the order of 10 microns thick. The wafer attached to the laminated carrier film is then immersed in a series of chemical baths that etches the release layers and separates the films from the wafers. Metal contact fingers and an antireflection coating are then applied to complete the cell structure. Each film is then singulated into multiple smaller cells which can be connected into series or parallel assemblies as needed. This is accomplished in a fully-automated tool.

The wafer itself can be cleaned and reused many times over, leading to a greatly improved cost structure compared to that of traditional gallium-arsenide solar cells. NREL-verified AM1.5 cell efficiencies of 28.8% (single-junction) and 31.6% (dual-junction) have been demonstrated using this process, and an AM1.5 aperture area module efficiency of 24.1% has also been verified by NREL. All three efficiency measures: single junction, dual junction and module level, are current world records.

Description of Product

Alta Devices' current product is a 5cm x 2cm, lightweight, flexible solar cell produced with single-junction GaAs technology and a high-throughput film lift-off and wafer reuse process. Production cell efficiencies are currently reaching 26% (AM1.5). Series/parallel interconnection of cells is performed by fully-automatic equipment capable of producing arrays ("matrices") of roughly 50cm x 50cm size and aperture efficiencies of 25% (AM1.5). The corresponding efficiencies are approximately 22% and 21% under AM0 conditions. The cells themselves weigh about 180 mg per 10 cm^2 cell and the weight of the interconnected matrix is approximately 240 g/m2. This represents a power to weight ratio of about 1000 W/kg (AM1.5, without any cover glass).

Preliminary temperature cycling tests also indicate no degradation of the cell-to-cell and cell-to-ribbon contacts over typical LEO temperature ranges.

Alta has demonstrated the next generation (Gen 4) of its terrestrial solar technology and is transitioning this to production. The Gen 4 technology will offer a weight reduction from 240 g/m^2 to 170 g/m^2, or a power to weight ratio of about 1500 W/kg (AM1.5, without any cover). The thickness of the Gen 4 cell is approximately 55 microns, most of this being the polyester film.

In addition Alta Devices has the ability to produce its dual-junction device technology on the same production platform. This is expected to provide greater efficiency relative to the single junction devices, approximately 24% (AM0).

Considerations for On-Orbit Use

Environmental stresses in low-earth orbit are severe and include frequent temperature cycling, heat, radiation and degradation from atomic oxygen impact. Alta's solar cells have not been extensively characterized with respect to these factors. However, preliminary studies and simulations of device performance with defects of the type expected from 1 MeV radiation indicate high performance retention (>85%) after fluences of at least 1014/ cm^2, suggesting that it may be possible to use these devices for low-earth orbit applications of at least 2-5 years, using conventional cover glass to provide shielding from atomic oxygen, micrometeors and protons. Preliminary temperature cycling tests also indicate no degradation of the cell-to-cell and cell-to-ribbon contacts over typical LEO temperature ranges. Alta Devices plans to conduct additional environmental exposure studies; results will be reported in the near future.

Example Panel Layout

Space solar cells have traditionally been supplied as assemblies with integrated coverglass and bypass diodes (CIC assemblies). This approach could be extended to Alta's solar cells, possibly creating a drop-in replacement for a traditional CIC. This would result in a panel that is thinner and lighter than one made with standard cells, albeit not flexible. A second approach would be to leverage Alta's capability to provide larger series-parallel cell matrices up to about

500mm x 500mm in size in order to reduce array fabrication labor costs and also improving reliability. Large-area, flexible coverglass alternatives could also be used in conjunction with these large matrices. A further advantage of this latter approach is that it enables packing densities exceeding 90%, compensating for the lower efficiencies of single-junction devices at the cell level.

Consider a lightweight panel design constructed with a polyimide backing, cell assemblies and conventional coverglass. Table 1 compares the power and weight metrics of a hypothetical folding panel assembly design, using cells of the type made by Alta versus the more common wafer-based solar cells. The length of the panel has been adjusted slightly in each case to provide a maximum packing for both cell types. The overall sizes of the panels, shown in Fig. 2, are 83 mm x 425 mm (Alta Devices' cells) and 83 mm x 405 mm (conventional cells). The width of the panel sections has been chosen to be 83mm, which can accommodate the 80mm width of the conventional solar cells. The cell-to-cell overlap of Alta's cells can be adjusted to optimize packing. In this example, we use an overlap that results in the same 80mm dimension as the conventional cells. We assume that the AM0 cell efficiencies are 30% for the conventional cells, 21% for Alta's single junction cells and 24% for Alta's dual-junction cells. The thickness of the polyimide is assumed to be 200 microns (0.008 inch). We believe this thickness is realistic, can accommodate adhesives and thermal control layers, provide sufficient mechanical strength and shield the back of the solar cells.

Space solar cells have traditionally been supplied as assemblies with integrated coverglass and bypass diodes (CIC assemblies).

The conventional triple-junction solar cell has a footprint of 80 mm x 40 mm, aperture area of 30.2 cm^2, and mass 2.6 grams. With 75 microns of coverglass (and neglecting adhesive), the mass of the conventional assembly is 3.2 grams, and the power output is 1.2 watts. Alta's assembly has a footprint of 80 mm x 50 mm, aperture area of 37.5 cm^2, and mass of only 0.7 grams, using Gen 4 cells. Power output per assembly is 1.05 watts with single junction devices and 1.2 watts with dual junction devices. As shown in Table 1, the thin-GaAs 5x1 assemblies can provide a ~40% improvement in power to weight ratio. The reduction in per-panel power output does mean that additional panel area or extra panel sections would be needed to reach the same amount of total power.

Table 1. Weight and power comparison of panels populated with conventional solar cells and Alta Devices' solar assemblies.

Case	Area (cm^2)	Mass (g)	Mass of 75µm cover glass (g)	Total mass of assembly (g)	Footprint	Qty	Area of backing (cm^2)	Mass of backing	Total mass	Watts per assembly	Total watts	W/kg	W/m^2
Conventional 3J Cell	30.2	2.6	0.6	3.2	40x80 mm	9	336	9.4	37.9	1.20	10.8	285	321
Alta 5x1 1J	40.0	0.7	0.8	1.5	50x80 mm	8	353	9.9	21.5	1.05	8.4	391	238
Alta 5x1 2J	40.0	0.7	0.8	1.5	50x80 mm	8	353	9.9	21.5	1.20	9.6	447	272

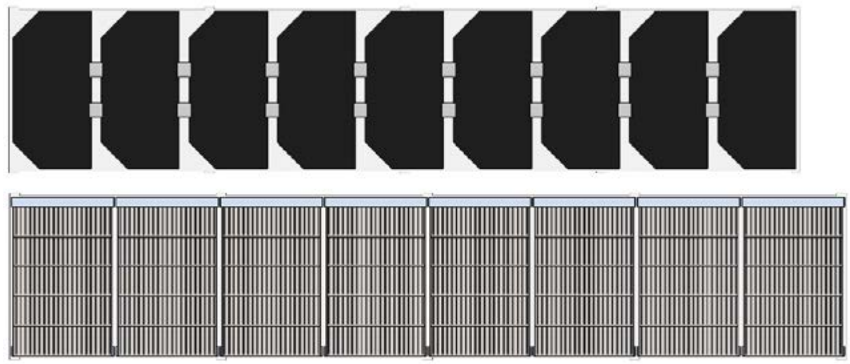

Fig 2 : Layouts with conventional solar cells and Alta Devices' solar assemblies. Higher packing factors are possible with the latter.

Conclusion

Thin gallium-arsenide solar cells have the potential to provide a good balance of conversion efficiency, reduced array weight, elimination of cell breakage and a significant reduction in costs relative to conventional space solar cells. While much work remains to be done to determine the suitability of such cells for on-orbit use, the technology has the potential to be a scalable source of electric power for the emerging space economy.

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ABOUT ALTA DEVICES

Alta Devices **(www.altadevices.com)** holds the world record for single-junction solar cell efficiency (28.8%). It manufactures ultra-lightweight gallium-arsenide based solar cells in its Sunnyvale, California factory and provides application engineering support to OEM customers worldwide. Alta Devices can be contacted at info@altadevices.com.