FLEXIBLE III-V MULTIJUNCTION SOLAR BLANKET

Kenneth M. Edmondson, D.C. Law, G. Glenn, A Paredes, R.R. King, and N.H. Karam

Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342

ABSTRACT

Thin high-efficiency triple junction GaInP/GaAs/Ge solar cells have been incorporated into prototype flexible blanket coupons with a coupon efficiency of 28% for AM0 (0.1353 W/cm^2). Prototype coupons have a specific power density from 360 – 500 W/kg and may well approach >1000 W/kg with further thin cell and blanket fabrication improvements. Initial LIV results are shown for a thin flexible three-cell and twelve-cell coupon utilizing fully active triple-junction solar cells. This paper will outline the fabrication of prototype three and twelve cell flexible coupons, and initial illuminated I-V (LIV) test results under a large area pulsed solar simulator (LAPSS) at Spectrolab and discusses the advantages and applications of thin flexible GaInP/GaAs/Ge solar blankets. Thin flexible triple-junction solar cells have been demonstrated and incorporated into electrically active prototype blankets with specific power of 500 W/kg.

INTRODUCTION

Solar panel arrays for space applications have relied on either silicon or III-V solar cells for power generation. Multijunction GaInP/GaAs/Ge solar cells have become the cell technology of choice for many satellite developers due to their high conversion efficiency (25-28%), radiation performance, and established space heritage.

The adaptation and application of alternative thin film technologies are of much interest for space use and is the subject of current research [1]. Thin film PV is an attractive alternate to crystalline PV because it can be made on thin flexible substrates yielding a high specific power density and may have lower manufacturing costs. Thin film has the potential of being stowed in small volumes during launch and may result in potentially lower launch costs which are on the order of 10's of thousands of dollars per kilogram depending on the orbit.

Because of the need for increased capability on modern satellites, much effort in both thin film and multijunction solar cells technologies for increasing cell efficiency and performance is in progress.

A new direction in crystalline III-V solar cell improvements has been demonstrated with the production of thin and flexible III-V multijunction solar cells [2].

Thin and flexible III-V crystalline solar cells offer the combined benefits of crystalline multijunction III-V and thin film technologies. Thin and flexible III-V cells combine the high performance of state-of-the art solar cells (achieving 28% AM0 efficiency in production) and the benefit of low mass. This yields high specific power density (W/kg) and high power density (W/m^2) with heritage performance predictability for a range of different operating conditions. We present preliminary results of high efficiency, thin (3 to 4 mils) GaInP/GaAs/Ge solar cell blankets with specific power densities of 360-500 W/kg.

Flexible solar arrays using GaAs/Ge have previously been demonstrated to the level of panel array with specific power density of 130 W/kg [3]. Multijunction flexible solar blankets have the potential for very high specific power density (> 1000 W/kg) enabling significantly lower launch costs. High efficiency multijunction solar cells have an established space heritage and performance capability and flexible multijunction solar blankets would build upon this heritage and performance capability.

THIN CELL DEVELOPMENT

A batch of thin triple junction GaInP/GaAs/Ge solar cells were fabricated with thickness in the range of 75 to 100 μm as described in [4]. Cells from the thin cell process lot were measured on a Spectrolab X-25 solar simulator calibrated to bare cell reference standards (T= 28°C, 0.1353 W/cm^2 AM0). Cell performance was nominal, with an average efficiency of 28.6%.

BLANKET ASSEMBLY

Interconnects were welded onto the cells and the cells were assembled into a three-cell string for the initial prototype blanket assembly (coupon #1). The three interconnected thin electrically active GaInP/GaAs/Ge cells were bonded to 2-mil Kapton sheets with a space-grade adhesive. After curing, a space-grade conformal coating was applied to the coupon and cured. The first fabricated coupon did not have bypass diodes while the second three-cell coupon incorporated bypass diodes on each cell. No cracks or cell breakage occurred during the coupon fabrication.

Initial LIV testing under a Spectrolab XT-10 solar simulator with an uncalibrated spectrum showed no electrical degradation in the coupon performance. The initial coupon LIV showed the cells were performing nominally with no electrical degradiation.

Fig. 1 shows the prototype flexible coupon consisting of three fully active thin GaInP/GaAs/Ge multijunction cells connected in series, wrapped around a cylinder with ~10 cm radius of curvature. The coupon was wrapped around the cylinder for 6 hours. The coupon was measured on a LAPSS before and after flexing and showed no electrical degradation.

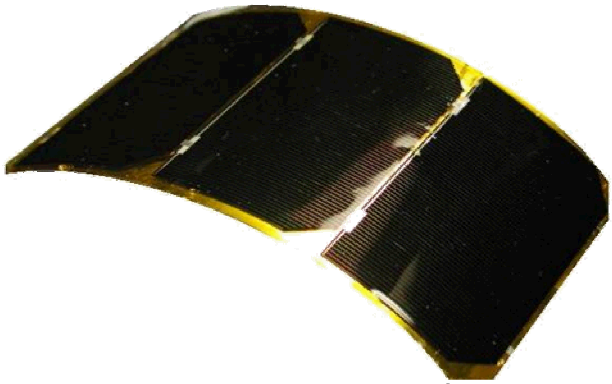

Fig. 1 Flexible multijunction prototype flexible coupon wrapped around a ~10 cm radius of curvature. There was no electrical degradation in LIV test after coupon flex test.

LARGE AREA PULSED SOLAR SIMULATOR (LAPSS) TEST RESULTS

Fig. 2 shows the test results of the initial three-cell prototype coupon measured on a Large Area Pulsed Solar Simulator (LAPSS) at Spectrolab. The LAPSS was calibrated to balloon flight reference standards. The LAPSS LIV curves for pre- and post-flexing (wrapping) of the coupon around a radius of 10 cm radius is shown in Fig. 2. No electrical cell performance degradation was observed, as the variation in maximum power was <1%. Accuracy is ±1%.

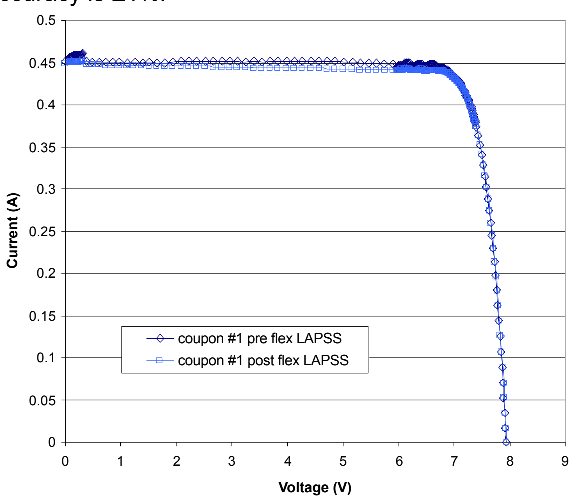

Fig. 2 LIV curves measured on LAPSS of three-cell GaInP/GaAs/Ge prototype coupon #1 showing no loss in performance.

Slight cracks have appeared in the coupon from strain induced by the leads connected to the coupon. However, the cracks don't appear to affect the LAPSS performance of coupon #1. Coupon #2 is similar to coupon #1 except incorporates bypass diodes on each cell and has a thinner optical coating. Initial LAPSS data gave a maximum power of 3.1 W, although subsequent handling and flexing have degraded the maximum power by 6%. The small cracks in the coupon may have contributed to a small shunt in the LIV curve. The cracks are possibly due to the strain induced by the leads.

Based on the initial LAPSS results, the prototype coupons reached 500 W/kg specific power density. This is the highest power density for a flexible multijunction blanket coupon. Further improvements in the thin cell process and blanket assembly as well as solar cell improvements could push the specific power to over 1000 W/kg.

Next, a larger thin-cell flexible coupon was fabricated. Fig. 3 shows a photograph of a twelve-cell flexible coupon. The construction is similar to that of coupon #1, with the addition of a superstrate material. The coupon consists of six cells in series and two strings in parallel for a nominal 12.1 W coupon.

Fig. 3 Thin twelve-cell flexible solar blanket. with an initial specific power density of 360 W/kg.

The initial LAPSS LIV data for the twelve cell flexible coupon is shown in Fig. 4. The coupon delivered the expected performance with a maximum coupon power of 12.4 W. Including the entire mass of the coupon in the specific power density results in specific power density of 360 W/kg. The reason the power density is lower than in the three-cell coupon is because the twelve-cell coupon had the addition of a bonded superstrate and the coupon busbars and all the wire leads were included in the mass measurement.

THIN CRYSTALLINE III-V CHALLENGES

Processing and fabrication of very thin triple-junction solar cells (<100 μm) present new challenges. Blanket assembly of thin flexible cells is a key area of focus. While some techniques of traditional panel assembly are directly transferable to thin cells, such as welding, others such as bonding to flexible substrates present new challenges. Typically cells are bonded with interconnects and coverglass and then arrayed into strings. Thin flexible cells do not necessarily have coverglass and the flexible blanket substrate may consist of different materials.

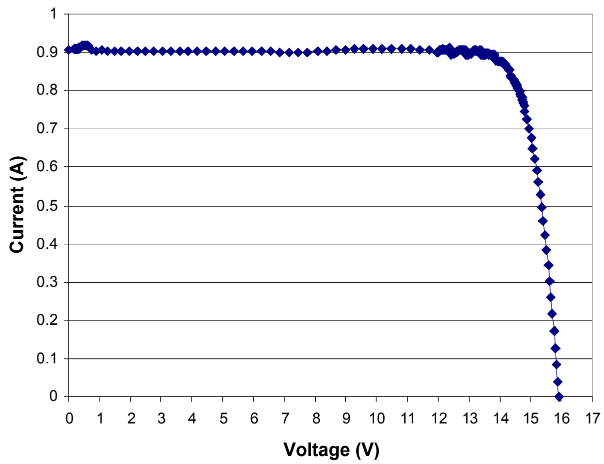

Fig. 4 LAPSS LIV curve on twelve-cell flexible coupon with specific power density of 360 W/kg.

One improvement will be to alleviate the potential high-stress points of the interconnects under blanket flexing or twisting. The cell is most prone to breakage at these points.

Electrical characterization of thin cells indicates no new problems should be anticipated. LIV and SR measurements can be performed on thin cells with more careful handling of cells during test. Large area panels and arrays are routinely measured with LAPSS. There is no issue with LAPSS testing of flexible coupons at this time other than to develop new calibration standards with similar optical coatings as the cells under test.

NEXT STEPS

Thin III-V multijunction cell blanket technology is currently in its infancy. We are developing and evaluating various optical coatings, interconnect schemes, substrate materials, etc.

Characterization of the cell performance with various combinations of substrates and superstrates will need to undergo the typical tests and characterizations representative of the expected operating environment. Assessment of compatibility with flexible deployment mechanisms will be an essential task for directing future blanket development.

Environmental, stiffness, and acoustic evaluations are required to be performed on the blanket technology, once larger blankets are designed and fabricated. Close collaboration with satellite array deployment manufacturers will be necessary to insure successful design, integration, and deployment of flexible solar blankets.

ADVANTAGES OF THIN FLEXIBLE III-V MULTIJUNCTION SOLAR BLANKETS

Satellite designers are constrained by a number of factors such as cost, mass, stowage volume, and power needs. In order to increase satellite capability, higher power solar arrays are needed. The best approach is to develop higher efficiency solar cells without a large increase in cost to increase the available power to a satellite buss. Other cost-reducing options are available as well, with much interest in applying potentially low cost thin film solar cells for space use.

Thin film solar cells have an established maturity in terrestrial applications and are promising for space PV applications. Thin film solar cells has two benefits over traditional III-V solar cells; lower manufacturing cost and higher radiation resistance [5]. However, the efficiency of thin film solar cells is much lower than commercially available crystalline III-V solar cells which are currently 28% and fast approaching 30% under AM0 conditions.

The drawback of thin film solar cells is that while very flexible, they would require very large solar arrays to be deployed in space to provide large amounts of power. The increased size and potential complexity of having such large arrays in space has been in explored in studies funded by the Air Force Research Laboratory (AFRL) and NASA. One study concluded that "although thin-films themselves can have a very high W/kg metric, the large area increase dramatically reduces the mass advantage at the system level while other key metrics, such as W/m^3 and MOI become less favorable" and "indications are that fabrication and test costs for the larger thin-film array may more than offset the projected cell cost gains" [5].

The development of thin and flexible solar arrays utilizing III-V GaInP/GaAs/Ge solar cells would be of great benefit to the aerospace industry. By reducing the array mass and traditional hard panel arrays, thin flexible multijunction solar cells address the need for lower mass, reduced stowage volume, and most critically higher power with excellent radiation performance and established space heritage. Once the technology is fully developed and mature, insertion into a lean manufacturing environment could greatly reduce the cost. Additionally, the development of thin flexible solar cells leverages the development of higher efficiency solar cell technology currently in progress at Spectrolab.

Table 1 lists the target specific power and power density of thin, flexible solar blankets using different Spectrolab multijunction solar cell technology. In addition, flexible solar array could also enable modular array designs that have lower stowage mass and volume. This can have a profound impact on mission capabilities, overall satellite weight, and cost.

Table 1 Ultra-high specific power density solar blanket target.

	ITJ cells	UTJ cells	XTJ cells	NJ cells
Efficiency (%)	26.5	28.3	30	33
Power density (W/m^2)	339	357	378	420
Specific power (W/kg)	**948**	**1013**	**1074**	**1181**

APPLICATIONS

Thin flexible III-V solar blankets has applications for space, near-space, and terrestrial uses.

The commercial and government aerospace industry would benefit by the production and use of flexible high efficiency solar arrays. Solar arrays with 100 kW of power are possible. Such high power arrays are capable of meeting the increasing need for power on modern satellites. The benefit is in the reduced mass, reduced stowage volume, higher power generation, and potentially lower launch costs. Flexible solar blankets could be made to be compatible with deployment mechanisms for flexible solar arrays with power targets of 100 kW of on orbit power. A fully deployed flexible solar array is shown conceptually in Fig. 5.

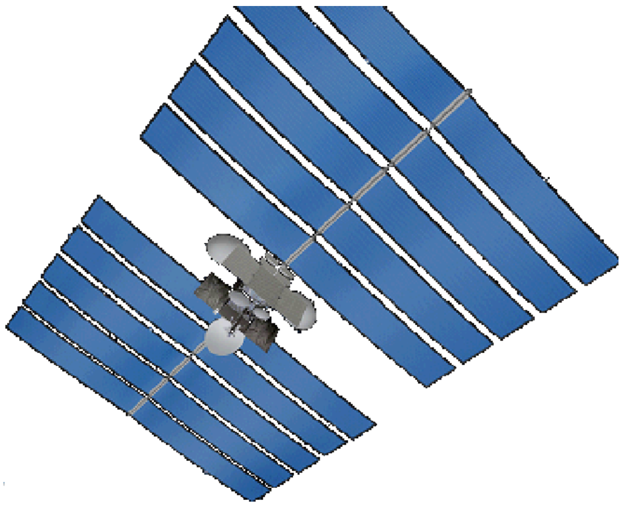

Fig. 5 Conceptual design of deployed 100 kW solar arrays on a satellite.

Additionally, flexible solar arrays could be of interest for NASA related missions. NASA has stated their vision for space exploration [6]. This would require high power generation on the surface of Mars and the Moon. Such applications could entail large deployable and modular solar arrays for powering autonomous rovers and bases on the surface of the Moon or Mars and perhaps interplanetary missions utilizing large arrays which are low mass at launch.

Near-space applications consisting of high altitude unmanned airships are an exciting potential new application for flexible solar blankets as the high power generated and reduced mass of the solar cells result in very high power densities >1000 W/kg and multijunction cells could be optimized for the operating environment.

Terrestrial applications are also possible. While the terrestrial market is dominated by the Si and thin film PV technologies, specialized applications could be met by thin flexible solar blankets such as portable power for temporary or emergency applications.

SUMMARY

A thin flexible solar blanket has been demonstrated with multijunction GaInP/GaAs/Ge solar cells less than 100 μm thick. The prototype three- and twelve-cell coupons have been characterized by LAPSS testing and show the expected power for the AM0 spectrum. Initial LIV performance is nominal with all the coupons delivering the expected power output. Coupon #2 incorporated by-pass diodes. The initial results of a flexibility test show no electrical degradation in performance for coupon #1 and 6% degradation in coupon #2 from cracks possibly induced by the strain of the leads.

Specific power density of the three-cell coupons is 500 W/kg at the coupon level and 360 W/kg for the twelve-cell coupon. Space-grade materials have been used to assemble these first large-area cell coupons prototypes.

Performance of the thin large area flexible blanket coupons is encouraging in that much larger prototypes can be fabricated, handled, and subjected to additional characterizations representative of the space environment.

The benefits of flexible III-V solar blankets are many, with reduced launch costs, high specific power, high power density, excellent radiation performance, and established space heritage. Expected applications of flexible solar blankets include the aerospace market utilizing deployable flexible solar blanket arrays generating 100 kW of power, near space applications, and portable terrestrial power.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the National Aeronautics and Space Administration (NASA) for this work performed under the Exploration System Research and Technology (ESR&T) program. Fig. 5 provided courtesy of Ray Stribling at the Boeing Satellite Design Center (SDC).

REFERENCES

1] P.E. Hausgen, J.E. Granata, P. Tlomak, J. Jones, S. Enger, B. Zuckermandel, *Proc. 31st IEEE Photovoltaic Spec. Conf.*, 2005, p 614.

[2] T. Takamoto, T. Agui, H. Washio, N. Takahashi, K. Nakamura, O. Anzawa, M. Kaneiwa, K. Kamimura, K Okamoto, *Proc. 31st IEEE Photovoltaic Spec. Conf.*, p 614, 2005, p. 556 – 558.

[3] P. M. Stella, R. M. Kurland, H. G. Mesch, *Proc. 23st IEEE Photovoltaic Spec. Conf.*, p .21, 1993.

[4] D. Law, et al., *To be presented at the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4) May 7-12, 2006, Waikoloa, Hawaii*

[5] D.M. Murphy, M.I. Eskenazi, S.F. White, and B.R. Spence, *Proc. 29st IEEE Photovoltaic Spec. Conf.*, 2002, p. 782.

[6] http://www.nasa.gov/home/hqnews/2006/jan/HQ_06027_Griffin_vision_statement.html