PRODUCTION AND DEVELOPMENT ACTIVITIES IN MULTIJUNCTION SOLAR CELLS FOR CONCENTRATOR PHOTOVOLTAICS

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ABSTRACT

Multijunction concentrator GaInP/GaAs/Ge cells are now manufactured on a large scale with typical production cell efficiencies of 37% at 500 suns. These cells are enabling concentrator system manufacturers to produce installations of high specific efficiency, competitive with other solar technologies and offering potentials for cost advantage in the future. Relying on years of space manufacturing experience and recognizing the difference between space and terrestrial solar cell manufacturing, Spectrolab is addressing issues of production scale up, developing the necessary manufacturing infrastructure and process control capabilities. Stringent qualification regiment, similar to that of space cells, is applied to assure long term quality. Spectrolab is also continuing the process of increasing the efficiency of concentrator cells beyond recently demonstrated 40.7%. The development activities includes optimization work to further improve three junction devices for near term introduction, as well as longer term research involving bandgap engineered cells with three and more junctions.

1 INTRODUCTION

III-V Semiconductor Compound materials are currently used around the globe to produce space and terrestrial solar cells. While, initially an outgrowth of space development efforts, Terrestrial III-V multijunction concentrator solar cell based concentrator systems are becoming accepted by the photovoltaic industry as a viable technology for large scale generation of power. These systems are unique in their high areal power density. They also offer rapid manufacturing scalability. Very high efficiency multijunction cell enable their success and viability. With typical efficiencies around 37% at 500 suns in production, GaInP/GaAs/Ge concentrator multijunction cells are enabling manufacturers to be in production of systems competitive with other technologies and offering potential cost advantages in the future. The recently demonstrated efficiency of over 40% gives further validity to the expectations from this rapidly growing technology.

2. CELL PRODUCTION

Multijunction cells based on the GaInP/GaAs/Ge material system are now in large scale production at Spectrolab. Relying on years of manufacturing experience, Spectrolab is addressing many issues associated with scaling up the production of concentrator cells, including product automation of the test and interconnection steps. Spectrolab has recognized the differences between space and terrestrial solar cell manufacturing and developing necessary manufacturing infrastructure changes and process control capabilities to be a successful producer of terrestrial cells. Stringent qualification schemes similar to that of space cells, are assuring long term quality.

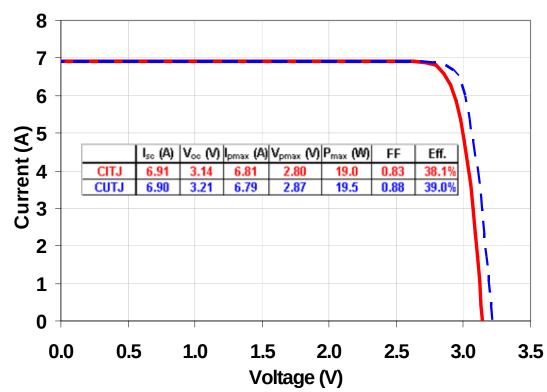

Figure 1: Figure 1: Illuminated I-V curves of peak performance production concentrator cells.

Two types of solar cells are in production at Spectrolab. They are referred to CITJ and CUTJ (similar to the space cell nomenctaure). Peak cell efficiencies of 39% have been observed on 1.00 cm^2 production cells. The IV curves in Figure 1 shows two curves for production cells of higher performance. While CUTJ devices do show some enhanced performance, CITJ cells, with near performance, are more often preferred for their ease of manufacturability.

Figure 2 shows the efficiency distribution of several lots of Spectrolab cells currently in production. They were measured at 50 W/cm^2, for four different configurations of production cells in the concentrator cell qualification program at Spectrolab: CITJ and CUTJ cells for both 1.00 cm^2 and 2.25 cm^2 aperture-area sizes.

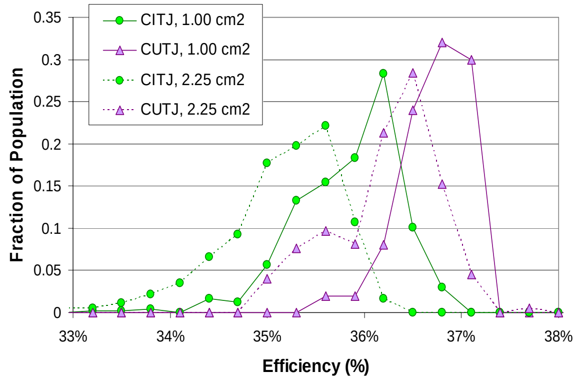

Figure 2 Efficiency distribution at 500 suns (50.0 W/cm^2) from the start of concentrator multijunction solar cell production at Spectrolab, for 1.00 cm^2 area cells.

The efficiency distribution for larger number of production terrestrial concentrator solar cells is shown in Fig. 3. With a mode and average at 37% efficiency, these production cells have a rather mature distribution curve.

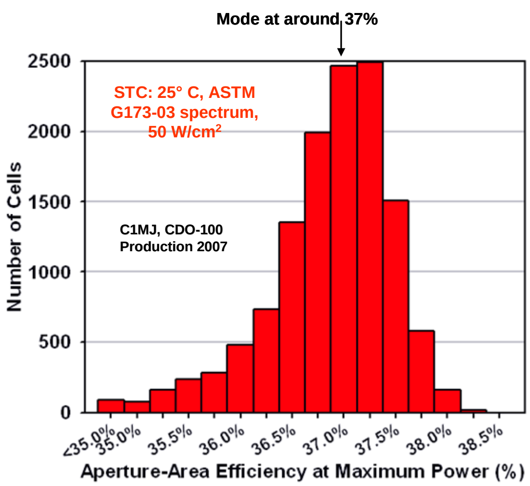

Figure 3: Efficiency distribution for about 13K 1X1cm cells in production at Spectrolab. They produced fairly tight performance with the mode at about 37%.

According to systems builders, solar cells cost is currently as 1/3 to 1/2 of the module cost. Spectrolab is committed to address venues to reduce this number in the future. Spectrolab is continuing to pursue improved manufacturable products for near term introduction that included the latest, high efficiency, device features and manufacturing enhancements. The challenges facing this effort is to select which elements of the cutting edge technology can be robustly manufactured with high production yields needed to meet cost goals. It is also imperative to choose technologies that will offer an assembly tollerant product, with highly stable tunnel junctions and other layers, capable of withstanding qualification testing identified to simulate difficult operating conditions. Spectrolab is also optimizing cells for applications in real system, operating under solar spectrum altered by concentrator optics. Additionally, development work is focusing on the technological aspects that may make the multijunction technology ever less costly to produce with ever higher yields.

Recently, considerable efforts went to establish automated production infrastructure for concentrator cells. While the cells are in the wafer form they run through the semiconductor line, equipped with typical automation and wafer handling. Back end processes, after dicing, requires much improvement. One particularly costly step of cell testing has been addressed by implementing rapid multi-cell testing robot capable of testing multiple cells in one pulse of the low pressure Xenon linear light bulb. The flashing technology has been proven for many years (Specrolab manufactures LAPSS systems since early 1970s) in testing space panels. In case of the terrestrial test, the capability has been augmented by additional filtering designed to generate excellent uniformity and spectral fidelity. The use of very large flash lemps assures unform test conditions accross the test plane. Multiple sizes of cells can be handled with no need for light adjustment. Similarly, an important step of cell interconnection is being address using robotic equipment.

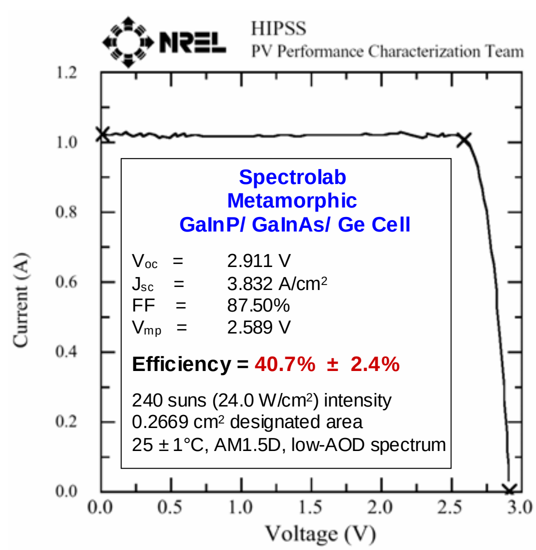

Figure 4: Illuminated I-V curve for the record 40.7% metamorphic 3-junction cell, independently certified at NREL.

4. RESEARCH EFFORTS

In the area of research of higher effieincy products, Spectrolab is continuing the process of increasing the efficiency of concentrator cell. The multijunction solar cells made by Spectrolab reached fficiency of 40.7% for metamarpic (IV curve shown in Figure 4) and 40.1% for pseudomrphic types. These advanced cells serve as technological targets, optimized and engineered for efficiency gains. Many of the high-efficiency features developed in the course of the experimental work leading to the 40.7% MM and 40.1% LM record cells are implemented in production solar cells at Spectrolab, increasing the performance of production cells and reducing $/watt price.

Our research activities to further improve cell efficiency include not only incremental improvement of three junction cells, but more advanced technological steps. Metamorphic configurations still offer the highest possible efficiency gains, but we are addressing possible enhancements not only to metamorphic cells, but more advanced pseudomorpic configurations. While laboratory lattice matched cells of around 40% are produced in small quantities, laboratory metamorphic, or lattice-mismatched, GaInP/ GaInAs/ Ge 3-junction cells have reached 40.7% efficiency, under the standard reporting spectrum for terrestrial concentrator cells (AM1.5D, low-AOD, 240 suns, 25°C), passing the 40% efficiency milestone for the first time [2]. Research groups around the world are studying the ability of metamorphic materials in band gap selection to the photovoltaic (PV) cell [1-9]. For the next generations of experimental and production III-V multijunction cells, we considering the terrestrial concentrator cells with 4 or more junctions with variety of subcell band gaps, accessible with lattice-matched (LM) and metamorphic (MM) III-V materials.

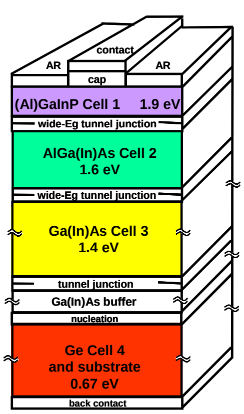

Figure 5: Schematic cross-sections of a 4-junction (Al)GaInP/ AlGa(In)As/ Ga(In)As/ Ge terrestrial concentrator solar cell.

New multijunction cell architectures have the theoretical potentials to reach 45 to 50% efficiency levels. Terrestrial concentrator solar cells with 4, 5, 6 or more junctions trade lower current for higher voltage [12]. A 4-junction concentrator solar cell is shown in cross-section in Fig. 5. As a result of their low current densities, cells with 4 or more junctions can have substentially lower resistance power losses. The potetial challenge is to assure current matching among all the

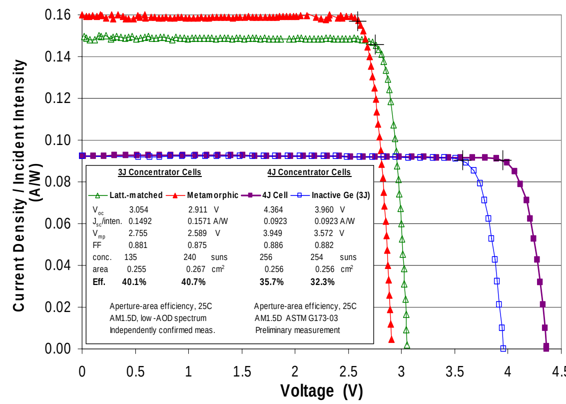

Figure 6: Measured light I-V characteristics for 4-junction GaInP/ AlGaInAs/ GaInAs/ Ge terrestrial concentrator solar cells, with and without an active Ge subcell 4 (bottom subcell).

subcells under the different terrestrial spectrum. Modeling exercises do show that the problem is not as serious as originally feared [12]. Prototype terrestrial concentrator cells have been built and tested as shown in Fig. 6, with preliminary efficiencies measured at 35.7% [12].

Through the use of metamorphic materials in cells with 4 or more junctions bandgaps can be selected for right matching.Theoretical efficiency of an ideal 4-junction cell is nearly 60% under the AM1.5D terrestrial spectrum at 500 suns.

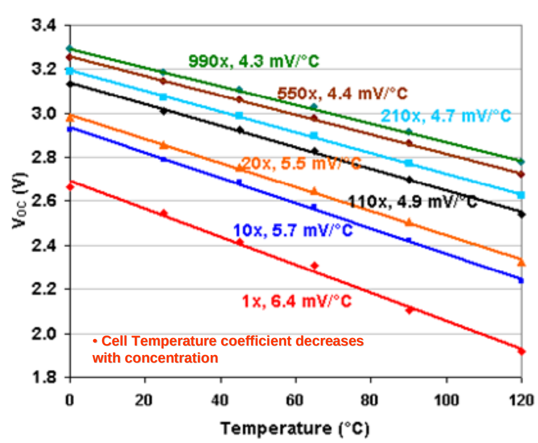

Figure 7. Temperature coefficients at concentration are lower than at one sun, helping with the real operating performnce (typically 60 to 100ºC)

4. OPERATIONAL PERFORMANCE MEASUREMENTS

Spectrolab is also pursuing studies of operational aspects of concentrator cells. As an example, our quantifiable measurements show that there is a favorable lowering of the temperature coefficient with increased concentration. These challenging measurements, conducted at multiple light levels and temperatures, do confirm the preducted beneficial changes in temperature coefficients as a function of the light concentration.

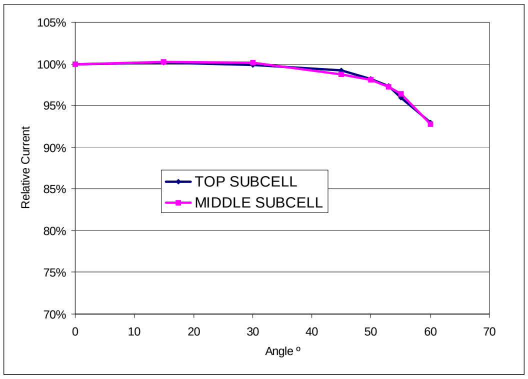

Figure 8 Concentrator cells show robust performance even for rays incident at angles as high as 60ºC off normal.

Additional studies (Figure 8) have been conducted to look at the spectral, angular dependence of concentrator cell performance. This work shows that there is a high degree of tolerance to the incoming rays at rather shallow angles. Concentrator cells can be expected to perform at above 90% of the normal incidence performance even for rays incoming at angles of 60º. Additional light IV measurements show even higher level of angular tollerance. With this type of angular performance, shallow focal length concentrators can be considered even without the use of secondary optics.

5 SUMMARY

Current vintage production GaInP/ GaInAs/ Ge cells are manufactured with over 37% efficiency, enabling near term deployment of systems. Laboratory multijunction solar cells have reached 40.7% efficiency for metamorphic semiconductor technology, and 40.1% for lattice-matched cells. These highest efficiency monolithic device create a foundation stone for further improvements in production cells. Technologies based on metamorpic semiconductors offer possible bandgap selection that may permit future realization of even higher-efficiency III-V multijunction cells. New multijunction, metamorphic cell configurations with 4, 5, and 6 junctions havepotentials to increase cell efficiencies to 45% and beyond.

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