SOLAR CELLS FOR NASA RAINBOW CONCENTRATOR*

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ABSTRACT

The RAINBOW concentrator system is based on a concept of splitting the solar spectrum and focussing each portion on a solar cell having a bandgap matching the input spectral portion. Efficiencies over 40% are predicted for systems using a four-bandgap cell assembly under 20X concentration. Reported here are the results of materials growth, processing, and testing of four different solar cells designed to populate the RAINBOW testbed, under development at JPL. The cells are 0.74-eV InGaAs on lattice-matched InP, 1.1-eV InGaAs on lattice-mismatched GaAs, 1.43-eV GaAs on GaAs, and 1.85-eV InGaP on lattice-matched GaAs. Quantum efficiencies between 0.8 and 1.0 have been realized for the spectral region from 0.5 to ~1.5 μm.

INTRODUCTION

Solar photovoltaic arrays based on III-V semiconductors have been employed most widely for powering spacecraft. Some of the highest-quality III-V cells, such as GaAs, can attain efficiencies of ~18%, under one-sun illumination. One highly pursued approach to the improvement of III-V solar cell systems has been the development of multi-junction devices. Even state-of-the-art single-junction solar cells can utilize only a portion of the solar spectrum. Incident light energy must be greater than the bandgap of the cell to generate current; photons of longer wavelength are wasted. To utilize more of the solar spectrum, cells have been developed in which two or more dissimilar bandgap materials are grown atop one another, with the higher (or highest) bandgap material being on the top. This multi-junction device is, in effect, a vertically stacked array. Commercial versions of double- and triple-junction devices are currently performing with AM0 efficiencies of ~25%; the goal in efficiency for which device makers are striving is >30%.

An alternative approach to the stacked cell array approach is to split the solar spectrum and focus the spectral portions onto cells of different bandgaps. The bandgaps can be selected to make the best matches with corresponding spectral regions in order to obtain maximum efficiency. An efficient optical system is required to disperse the solar spectrum across the array of cells, which can be mounted on a flat or even slightly curved surface. This multi-bandgap assembly is, essentially, horizontal in layout.

The idea of splitting the solar spectrum and then focussing spectral regions onto cells with tailored bandgaps was first proposed by Alvi et al. [1]; they proposed using a set of selective mirrors to divide the solar spectrum. Development of this concept was done by Blocker [2], and an array based on the concept was studied and reported on by Bekey and Blocker [3]. The general results at the time indicated that very high efficiencies were attainable, and that the reduced thermal loads produced further beneficial effects. A significant deficiency in the approach, however, was the large loss in optical throughput of the components used to attain the spectral separation.

The solar-splitter concept was re-examined and modeled by Lewis et al. [4] in 1997. Their approach, termed RAINBOW, proposed the use of a concentrator and dichroic filters for beamsplitting, with a predicted overall system efficiency of 40% at 20X concentration.

The approach of the JPL team for this study has been to employ a parabolic Fresnel lens/concentrator to effect the solar splitting. In early testing of this system, an overall efficiency of 35% at 10X concentration has been achieved with only three types of commercially available cells. Modification of the optical system will be made to get concentrations greater than 20X. The illuminated testbed for the concentrator will then be populated with strings of four types of solar cells, with bandgaps ranging from 0.74 eV to 1.85 eV. The fabrication and testing of these cells are reported here.

EXPERIMENTAL

The four cell types which were grown and processed for this project were 0.74-eV InGaAs on lattice-matched

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InP, 1.1-eV InGaAs on lattice-mismatched GaAs, 1.43-eV GaAs on GaAs, and 1.85-eV InGaP on lattice-matched GaAs. The structures for these cells are shown in Fig. 1-4. These structures have yielded efficient cells at AM0, one-sun conditions; although they have not been tested under concentration, the cells are expected to perform well at 20X, based on results from other studies by our group.

p++	$In_{0.53}Ga_{0.47}As$	0.1 μm
p+	InP	0.1 μm
p+	$In_{0.53}Ga_{0.47}As$	0.3 μm
n	$In_{0.53}Ga_{0.47}As$	2.0 μm
n+	$In_{0.53}Ga_{0.47}As$	0.1 μm
n+	InP (100)	500 μm

Fig. 1. Epi-layer structure of the 0.74 eV InGaAs cell.

n	$In_{0.2}Ga_{0.8}As$	0.1 μm
n	$In_{0.68}Ga_{0.32}P$	0.05 μm
n	$In_{0.2}Ga_{0.8}As$	0.5 μm
p	$In_{0.2}Ga_{0.8}As$	3.0 μm
p+	$In_{0.68}Ga_{0.32}P$	0.05 μm
p+	$In_{0.2}Ga_{0.8}As$	1.0 μm
p	$In_{0.14}Ga_{0.86}As$	0.5 μm
p	GaAs	0.2 μm
p	GaAs (100) 2° off toward (110)	350 μm

Fig. 2. Epi-layer structure of the 1.1 eV InGaAs cell.

p++	GaAs	0.1 μm
p+	$In_{0.48}Ga_{0.52}P$	0.05 μm
p+	GaAs	0.5 μm
n	GaAs	3.0 μm
n+	$In_{0.48}Ga_{0.52}P$	0.1 μm
n+	GaAs	0.5 μm
n+	GaAs (100)	350 μm

Fig. 3. Epi-layer structure of the 1.43 eV GaAs cell.

n+	GaAs	0.1 μm
n++	$In_{0.48}Ga_{0.52}P$	0.01 μm
n+	$In_{0.48}Ga_{0.52}P$	0.05 μm
p	$In_{0.48}Ga_{0.52}P$	1.5 μm
p+	$In_{0.48}Ga_{0.52}P$	0.1 μm
p+	GaAs	0.2 μm
p	GaAs (100) 15° off toward (111) B	350 μm

Fig. 4. Epi-layer structure of the 1.85 eV InGaP cell.

The growth of nearly defect-free lattice-mismatched materials was achieved through the use of proprietary buffer layers that confine the misfit dislocations at the buffer-substrate boundary. All cell structures were grown at NASA Glenn Research Center, using two metal organic vapor phase epitaxy (MOVPE) reactors. The alloy structures were grown using the organometallic precursors of trimethyl indium, trimethyl gallium, diethyl zinc (for p doping), and the hydride precursors of phosphine, arsine, and silane (for n-doping). Crystalline quality and composition were determined using high resolution x-ray diffraction, while Hall effect measurement and electro-chemical C-V profiling were used for doping calibrations.

Device processing included vacuum deposition of layered contacts appropriate to the semiconductor type for each cell; contacts consisted of thin layers of Ge, Cr or Zn, covered by much thicker layers (~1 μm) of Au. Anneals at 350-400 °C for 5 minutes in nitrogen were usually needed to ensure low-resistivity Ohmic contacts to the cells with larger bandgaps. All cells were processed with the same mask set, yielding devices with mesa areas of 1 cm^2 and with a grid coverage of 4.6%.

Following an initial round of characterization of the cells for electrical performance, the cells were covered with anti-reflective coatings (ARCs). The ARCs were composed of a layer of MgF_2 on a layer of ZnS. For each cell type, the thickness of each dielectric layer was fixed to give a minimum reflectivity for the range of wavelength response for the cell. The ARCs typically improved the short-circuit currents and efficiencies of the cells by 33-40%; the effectiveness of the ARC for the 0.74-eV cell was not so high, improving efficiencies by only ~25%.

At least 30 cells of each bandgap have been fabricated. Ultimately, strings of each type, up to eight or nine cells long, all current-matched, will be assembled. The strings will be placed as compactly together as possible to cover the rectangular testbed area of 4–5 cm by 8-10 cm (some flexibility is built into the optics). Results reported here are for single cells only.

CELL PERFORMANCE

Electrical performance of the cells was measured at 25°C with a Spectrolab X-25 solar simulator under AM0, one-sun illumination, and with a filter-based spectral response apparatus. All measurements were performed at the NASA Glenn Research Center. Results of the current-vs-voltage measurements for the cells are summarized in Table 1. All data are for cells with ARCs, with areas of 1.0 cm^2.

BANDGAP(eV)	MATERIAL	I_{sc} (mA)	V_{oc}(V)	FF	EFF(%)
0.74	InGaAs	60.3	0.402	69	12.18
1.10	InGaAs	39.3	0.730	79	16.61
1.43	GaAs	31.1	1.056	85	20.42
1.85	InGaP	12.2	1.375	81	9.95

Table 1. Cell performance at AM0, one sun conditions.

Whereas performance of most of the cells is quite good, the performance of the 1.85-eV InGaP cells is clearly not optimized. As shown in Fig. 4, that cell structure does not have a window. Efforts to grow satisfactory windows are underway, but have not yet been successful. The deficiency of the InGaP cells is shown most clearly in Fig. 5, a plot of the external quantum yield for the set of cells. The yields for the lower-bandgap cells are quite good, with efficiencies greater than 0.8 for appreciable extents of their ranges of sensitivity. The external quantum yield for the InGaP cell falls well short of the yields of the other cells in the range of its intended application, i.e., 0.3-0.7 μm.

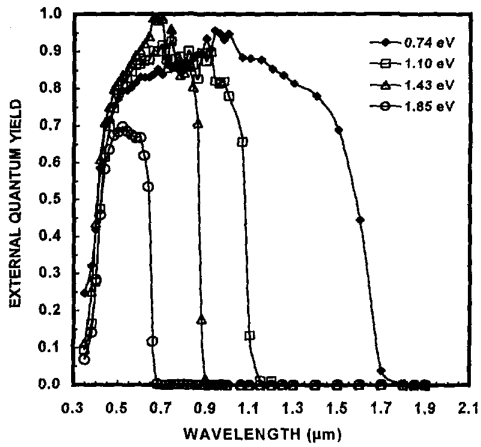

Fig. 5. External Quantum Yield for the RAINBOW cells.

The aim of further work on the InGaP cell structure would be improvement of the yield to greater than 0.9, most likely through the development of a less lossy window. The first candidate material for a window was $Al_{0.53}In_{0.47}P$. Although this material has not been analyzed for impurities, secondary ion mass spectrometry of a different stoichiometry, $Al_{0.33}In_{0.67}P$, grown as a window for other cells under development, has detected an oxygen impurity level of 1.0×10^{18} cm^{-2}. Presence of oxygen in this layer provides recombination centers, resulting in loss of minority carriers. Work to reduce oxygen and to improve the material is underway. An alternative material for use as a window is AlGaAs. Failure to improve the 1.85-eV cell is mitigated somewhat by the good blue response of the other cells.

SUMMARY

Four types of solar cells have been fabricated to provide coverage of the RAINBOW Concentrator testbed area and to match up solar spectral regions with cells of matching wavelength sensitivity. The structures grown are 0.74-eV InGaAs on lattice-matched InP, 1.1-eV InGaAs on lattice-mismatched GaAs, 1.43-eV GaAs on GaAs, and 1.85-eV InGaP on lattice-matched GaAs. Testing of these cells shows appreciably high quantum yields for devices with ARCs, i.e., yields of 0.8 to 1.0, for three of the cell types. Further improvement of the 1.85-eV cell structure remains, although its presence in the testbed might not be required unless its quantum efficiency can be improved to greater than 0.9. Assembly of the cells into strings is currently underway, and results of the testing of the overall system efficiency will be reported elsewhere.

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