Projected Performance of Three- and Four-Junction Devices Using GaAs and GaInP

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ABSTRACT

This paper explores the efficiencies expected for three- and four-junction devices for both space and terrestrial applications. For space applications, the effects of temperature and low concentration are investigated. For terrestrial applications, a concentration of 500 suns is assumed and the theoretical efficiencies are calculated as a function of spectral variations including the effects of air mass, turbidity, and water-vapor content.

INTRODUCTION

$Ga_{0.5}In_{0.5}P$/GaAs two-terminal, two-junction solar cells, invented and developed at the National Renewable Energy Laboratory, are in production at both TECSTAR and Spectrolab. The immediate market for these devices is in space; a future (potentially larger) market is terrestrial concentrator systems. The next-generation cells will add additional junction(s) in order to increase the efficiency. Work on a three-junction cell using an active Ge junction under the $Ga_{0.5}In_{0.5}P$/GaAs dual-junction cell has already been reported [1]. However, it would be preferable to add a third junction with a band gap closer to 1 eV. The underlying Ge or other material with band gap of ~0.7 eV could then be used as a fourth junction. Three- or four-junction, series-connected, monolithic III-V cells have the potential to achieve high efficiencies, yet still be manufacturable. Although there are other promising materials for the two upper junctions, in this study we limit ourselves to the well understood $Ga_{0.5}In_{0.5}P$/GaAs material system.

The average efficiencies of solar cells in the field differ from the efficiencies measured under standard conditions because the spectra and temperature vary in the field. Most cells have lower efficiencies at the higher temperatures observed in the sun compared with the temperature used for standard conditions. As the spectrum varies, the photocurrent collected by each junction of a multijunction cell varies. For a series-connected, multijunction cell this can significantly reduce the efficiency. Although we previously calculated the sensitivity of the two-junction, series-connected $Ga_{0.5}In_{0.5}P$/GaAs cell [2, 3] the sensitivities of the three- and four-junction designs have not been reported.

This paper strives to answer three questions: (1) What are the theoretical efficiencies for three- and four-junction devices using $Ga_{0.5}In_{0.5}P$ (hereafter GaInP) and GaAs, and what does this imply about the efficiencies that may be achievable in the near future? (2) Are these three- and four-junction cells practical, or will their performance be severely degraded as the temperature and spectrum vary? and (3) What can we learn about the design of these cells?

APPROACH

The theoretical efficiencies are calculated by generating the individual current-voltage (I-V) curves, then combining them in series (see Fig. 1). To assess the "ideal" efficiencies, we assume that every absorbed photon generates a collected electron-hole pair. The thicknesses of the top layers are adjusted so that each junction produces the same photocurrent, but without letting any of them be more than 3 μm thick except for the Ge, which is fixed at 150 μm. When it is not possible to match the photocurrents (often the GaAs junction cannot generate its share) the thicknesses are adjusted for maximum efficiency. Designs that equalize the short-circuit currents (J_{sc}) give slightly higher efficiencies than designs with equal currents at the maximum-power points. The optimal design algorithm matches the currents somewhere in between J_{sc} and the maximum-power point, but the difference between the optimal design and the design that matches the J_{sc}s is usually less than 0.1%.

The saturation currents are calculated from standard equations, assuming no recombination at the front and back surfaces, and a device design and parameters similar to previous calculations [4]. Parameters for GaInP (1.85 eV), GaAs (1.424 eV), and Ge are used for the first, second, and fourth junctions, respectively (see Table 1).
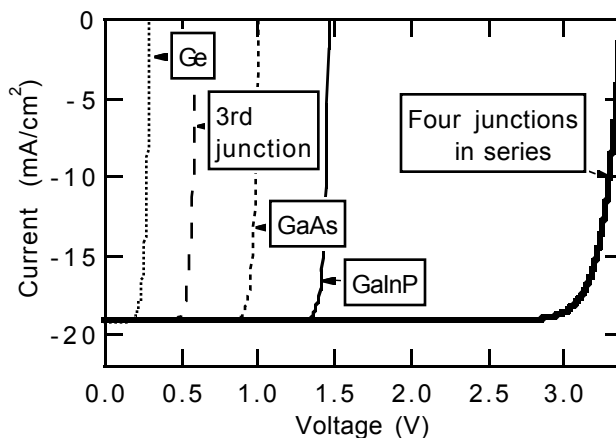

Fig. 1. Example of individual and combined I-V curves after each layer's thickness is adjusted to match the photocurrents.

Table 1. Parameters used for the calculations, including the temperature coefficient of the band gap (E_g), the intrinsic carrier concentration at 300 K, the electron and hole mobilities, and the base minority-carrier lifetime.

Model	E_g T Coeff. (mV/K)	n_i at 300K (1/cm^3)	elec. mob. (cm^2/Vs)	hole mob. (cm^2/Vs)	base elec. τ (μs)
GaInP	-0.66	1.0e3	4000	200	0.013
GaAs	-0.46	2.1e6	8900	400	0.013
Ge	-0.37	2.3e13	3800	1820	22

The third junction is modeled after GaAs, but using lower band gaps. Losses from grid shadowing, series resistance, and shunt resistance are neglected. Dark current with a diode quality factor of 2 is also neglected. The modeling of Ge is different from the direct III-V materials because of the indirect (0.67 eV) gap below the direct (0.8 eV) gap. The Ge absorption coefficient in (1/μm) is calculated from

$$\text{Ge abs.}(E) = 0.5 \times (E-0.8)^{0.5} + 5 \times (E-0.67)^2$$

where E is the photon energy in eV. The 22 μs minority-carrier lifetime [5] in the Ge yields a high V_{oc} of 0.27 V (under 1-sun AM0 illumination in a four-junction structure). This is significantly higher than has typically been obtained for a Ge junction under the GaInP/GaAs cell, but suggests what could ideally be achieved.

The reference AM1.5 Spectrum (ASTM E-891) is defined as the result of the BRITE Monte Carlo model using AM 1.5, turbidity at 500 nm (i.e., aerosol optical depth) of 0.27 and precipitable water (also referred to as "total column water vapor") of 1.42 cm. Here, SPCTRAL2, a much simpler and easier to implement model for clear-sky spectral distributions, is used to compute various direct-normal spectral distributions [6]. Although the reference spectra are representative of the continental United States, they were derived from measurements in Florida and are not representative of the sunny locations that are anticipated for concentrator systems (see appendix). Only the direct beam is calculated here.
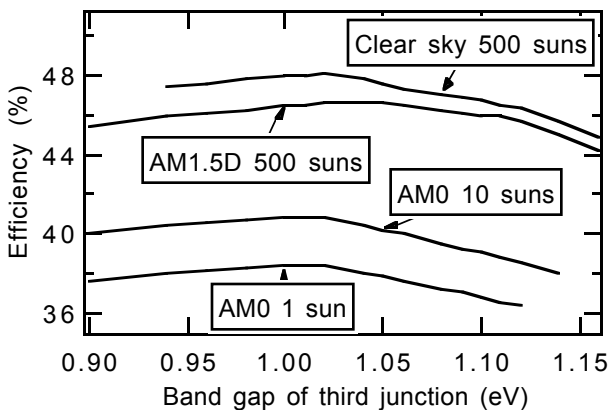

Fig. 2. Ideal efficiencies of three-junction cells as a function of the third-junction band gap using GaInP and GaAs for the top cells. The clear-sky conditions used air mass 1.5, water vapor of 1 cm, and a turbidity of 0.1. The top-cell thicknesses were reoptimized for each data point.
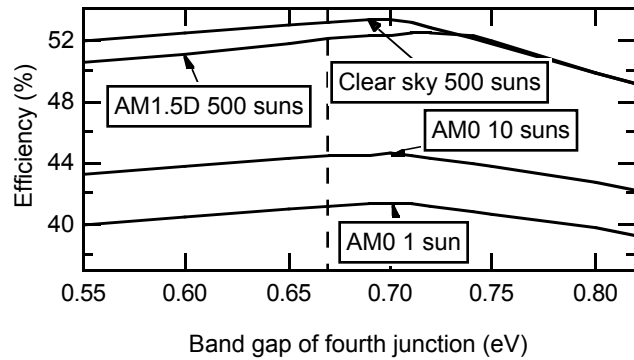

Fig. 3. Ideal efficiencies of four-junction cells as a function of the band gap of the fourth junction, using the data of Fig. 2. The third-junction band gaps were 1, 1.05, and 1.03 eV for the AM0, AM1.5D, and clear-sky conditions, respectively. The vertical dashed line marks the band gap of Ge. The GaAs-like model was used for the fourth junction.

RESULTS

The effect of the third-junction band gap on the three-junction cell efficiency is shown in Fig. 2. The optimal band gap depends only slightly on the spectrum, i.e., 1.0 eV for AM0 and 1.05 eV for the AM1.5D spectrum. Values in the range of 0.95 to 1.05 eV for AM0 and 0.95 to 1.10 eV for terrestrial concentrator cells are close to optimum. The "clear-sky" conditions represent those expected for an optimal location for concentrator systems.

The efficiencies shown in Fig. 2 can be increased by adding a fourth junction underneath of the three-junction stack. Fig. 3 shows that four-junction cells have an ideal efficiency of over 40% for AM0 (1-sun) conditions and over 50% for terrestrial concentrator conditions. Although Fig. 3 uses a GaAs-like model for the fourth junction, use of the Ge model gives similar results.

Table 2 compares the theoretical and achieved efficiencies of GaInP/GaAs two-junction cells. These can be used to predict practical efficiencies from the "ideal" efficiencies presented here. However, these overestimate what can be achieved if it is not as possible to approach the theoretical efficiencies for four-junction cells (compared with two-junction cells) because of difficulty in creating a broad-band anti-reflection coating, because of degradation of lower junctions during the growth of subsequent junctions, and because growing an "ideal" Ge junction is qualitatively different from growing "perfect" III-V

Table 2. Comparison of theoretical efficiencies with achieved efficiencies for two-junction GaInP/GaAs cells. The production numbers are based on only one year of experience.

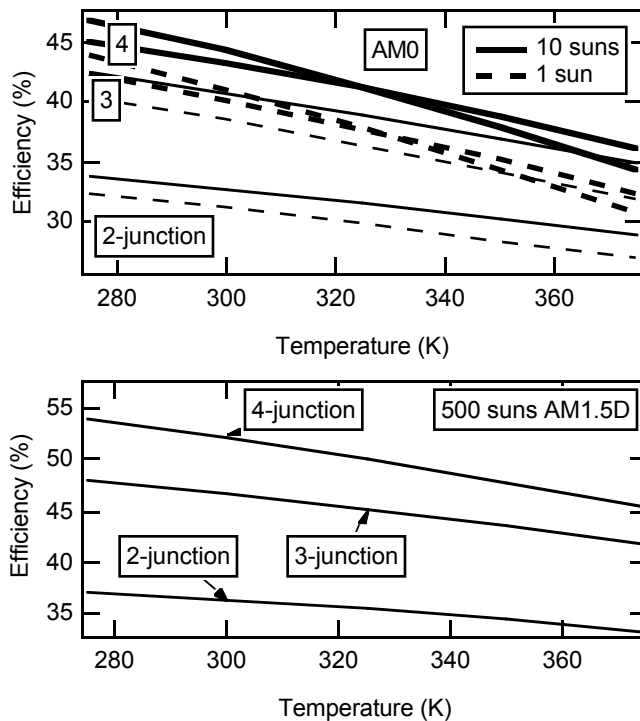| Conditions	Theory	Achieved	Ratio
AM1.5Global [7]	34.0%	29.5%	87%
AM1.5Global [8]	34.0%	30.3%	89%
AM0 [7]	31.1%	25.7%	83%
AM0 (production best) [9]	31.1%	23.6%	76%
AM0 (production aver) [9]	31.1%	22%	71%
AM1.5Direct (150X) [10]	35.5%	30.2%	85%

Fig. 4. The efficiencies of two-, three-, and four-junction cells as a function of temperature. In the AM0 figure, the four-junction lines are in bold, with the two lines representing cells designed for optimal efficiency at 300 K and 375 K.

junctions. The achievement of these efficiencies depends very strongly on identification of an appropriate material for the third junction.

The efficiencies of two-(GaInP/GaAs), three-, and four-junction devices are presented for AM0 (1 and 10 suns) and AM1.5 Direct (500 suns) as a function of temperature in Fig. 4. The thicknesses of the top junctions were chosen to optimize the efficiency at 300 K, then held constant for the calculations at other temperatures, except when two lines are shown to compare the effect of optimizing the cell at 375 K. The utility of including the Ge junction increases with concentration. For 1-sun, AM0, the three- and four-junction efficiency curves cross at 350-380 K, depending on the design of the cell. At 500 suns, the advantage of adding the Ge junction is significant even when the cell is operated at a high temperature. The advantage of the four-junction over the three-junction cell would be less for a practical cell, but the "ideal" Ge junction has a V_{oc} close to 115 mV at 375 K under 1 sun, implying that a significant part of the temperature coefficient observed in Fig. 4 is a result of mismatched photocurrents. (The photocurrent of the Ge subcell decreases with increasing temperature.) For a more detailed discussion of the effect of temperature on multijunction cell performance see reference [11].

Fig. 5 shows the effects of air mass, turbidity, and water vapor on the efficiencies of the terrestrial multijunction cells. The effects of water vapor and turbidity are very different. High turbidity primarily removes blue photons, especially for high air-mass values, causing the photocur
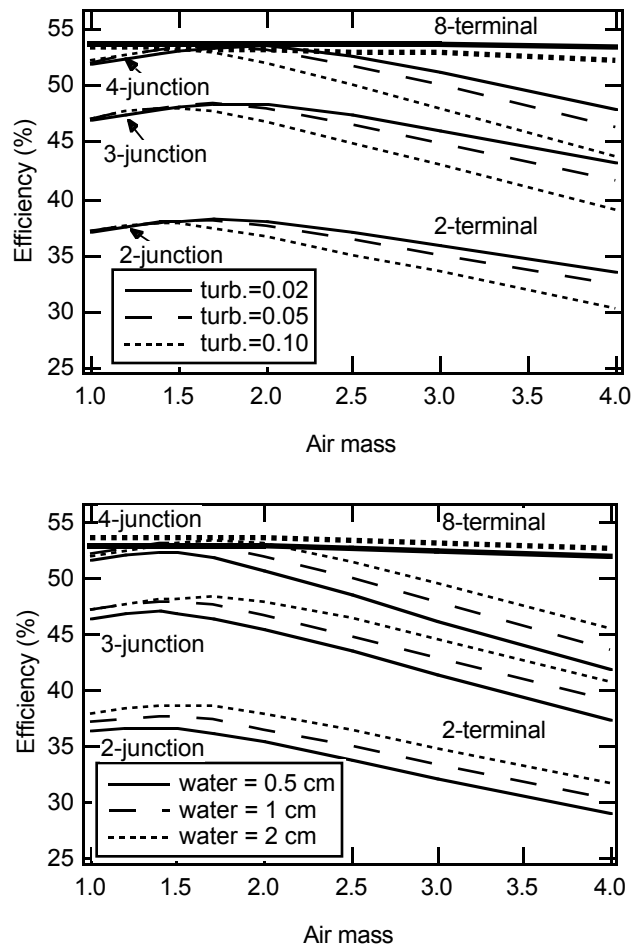
Fig. 5. Effect of air mass, turbidity, and water vapor on the efficiencies of terrestrial concentrator (500 suns) cells at 300 K. The cell thicknesses are optimized for water vapor of 1, turbidity of 0.1, and air mass of 1.5, with the third junction's band gap of 1.03 eV. The bold lines represent an eight-terminal configuration, whereas the rest use series-connection with two-terminals. Unless otherwise specified, the water vapor and turbidity were set to 1 and 0.1, respectively.

rent from the entire cell to be limited by the GaInP junction. High turbidity values cause significant decrease in efficiency for large air-mass conditions. In contrast, high water-vapor levels cause loss of infrared photons some of which are not useful to the cell. Higher water-vapor levels cause the efficiency to increase because, although the generated power decreases slightly, the power incident on the cell decreases faster, resulting in an overall increase in the ratio of the two.

The effect of the water vapor is most easily seen by comparing the two- and eight-terminal data. The eight-terminal data show that the potential efficiency from the cell changes very little with water vapor. The two-terminal data change more with water vapor, demonstrating that there will be measurable loss associated with different photocurrents generated in the four junctions as the spectrum changes.

The cell can be optimized to perform best for any set of conditions by changing the thicknesses of the top cells. However, once a design has been chosen, changing the turbidity, water vapor, or air mass will result in a mismatch between the photocurrents. It is important to note that at 40° latitude, about 2/3 of the annual irradiance is delivered with air-mass values between 1 and 2 [3], implying that some decrease in performance for high air masses will be tolerable because the high air-mass conditions represent a small fraction of the delivered power. We conclude that, although variations in atmospheric conditions will affect the generated power in a measurable way, this effect is less than the increase in power obtained by increasing the number of junctions for well designed cells.

SUMMARY

The theoretical efficiencies for four-junction cells using GaInP and GaAs are shown to exceed 40% and 50% for the AM0 and 500X, AM1.5D conditions, respectively. Past experience and extrapolation of past experience imply that we might achieve 32% and 40% for the same sets of conditions, respectively, provided that we can identify an appropriate material for the third junction and simultaneously achieve high quality for all four junctions. The sensitivity of the multijunction designs to variations in spectrum and temperature are significant, but smaller than the advantage gained by using more junctions. Adjusting the thicknesses to optimize the efficiency usually results in very thin GaInP layers and GaAs layers that are close to 3 μm thick. The third-junction band gap is close to optimal design when in the ranges of 0.95 to 1.05 eV for AM0 and 0.95 to 1.10 eV for terrestrial concentrator cells.

APPENDIX

Spectral variations result both from the predictable variation in air mass and the less predictable fluctuations in atmospheric conditions. Using the SPCTRAL2 model, complex variations in spectra can be calculated from the air mass, the precipitable water vapor, and the turbidity at 0.5 μm. The latter have been modeled and averaged for 30 years in many sites in the United States. A few of these averages are tabulated in Table 3. The values typically fluctuate around these mean values by a factor of about 2. The values are closely correlated because humid air causes swelling of aerosols.

Table 3. 30-year averages (from National Solar Radiation Data Base) for water vapor (w.v.) and turbidity at 0.5 μm. Jan. and July were chosen to represent the extremes in observed average values.

Location	Jan. w.v.	July w.v.	Jan. turbid.	July turbid.
Ely, NV	0.51	1.37	0.02	0.07
Las Vegas, NV	0.69	1.70	0.05	0.11
Daggett, CA	0.82	1.52	0.04	0.10
Phoenix, AZ	0.97	2.15	0.07	0.15
Salt Lake City, UT	0.65	1.72	0.06	0.10
Albuquerque, NM	0.54	2.10	0.04	0.10
Boise, ID	0.81	1.57	0.04	0.08
Alamosa, CO	0.47	1.80	0.03	0.04

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