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Analysis of the GaInP/GaAs/1-eV/Ge Cell and Related Structures for Terrestrial Concentrator Application

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ANALYSIS OF THE GaInP/GaAs/1-eV/Ge CELL AND RELATED STRUCTURES FOR TERRESTRIAL CONCENTRATOR APPLICATION

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ABSTRACT

We analyze the potential of the GaInP/GaAs/1-eV/Ge four-junction solar cell to improve on the efficiency of the state-of-the-art GaInP/GaAs/Ge benchmark. We emphasize three factors: (1) The newly proposed terrestrial concentrator spectrum has a lower ratio of red to blue light than does the old AM1.5 direct standard spectrum. (2) Standard two-layer antireflection coatings do not provide near-zero reflectance over the full spectral range of interest for these devices. (3) GaInNAs junctions used to date for the 1-eV junction have quantum efficiencies less than ~75%. These factors all limit the device current, adversely affecting the four-junction efficiency. We discuss strategies for ameliorating this problem, including going to alternate structures such as a GaInP/GaAs/0.9-eV three-junction device.

OBJECTIVE AND APPROACH

There has been considerable interest in extending the GaInP/GaAs/Ge three-junction cell to higher efficiencies by the addition of a 1-eV junction between the GaAs and Ge junctions [1]. For any of the standard solar spectra, there is enough light between the GaAs and Ge absorption edges that the photocurrent of the three-junction structure is not limited by the photocurrent of the Ge junction in the GaInP/GaAs/Ge structure. However, when an additional 1-eV junction is introduced, the light between the GaAs and Ge absorption edges must now be shared equally between the Ge and 1-eV junctions, reducing the Ge junction photocurrent to half of that in the three-junction structure. As a result, current-limiting by the bottom two junctions in the four-junction structure is significant, with a concomitant adverse effect on the device efficiency. This paper discusses the prospects of the GaInP/GaAs/1-eV/Ge cell for terrestrial concentrator application in light of three factors that act to limit the bottom-junction currents.

(1) Recent developments in the understanding of the spectrum for concentrator operation show that a low aerosol optical depth (AOD) is appropriate for the description of representative spectral conditions [2,3]. The resulting new proposed standard direct spectrum (hereafter the "low-AOD" spectrum) has a ratio of low- to high-energy light that is lower than in the standard ASTM-E891 AM1.5 direct spectrum (hereafter the "AM1.5D" spectrum). The spectra are shown in Fig. 1(a). As discussed below, the limiting of the multijunction current by the third and fourth junctions is much more pronounced with the low-AOD spectrum than with the AM1.5D spectrum.

(2) Standard two-layer antireflection (AR) coatings do not provide near-zero reflectance over the full 300–1800 nm spectral range covered by these multijunction devices. Comparing the device photocurrents assuming a perfect broad-band coat to the photocurrents using a realistic two-layer coat (Fig. 1b), we show below that there is a notable difference in efficiency in going to the realistic AR coat.

(3) Unfortunately, 1-eV junctions made from the leading candidate material, GaInNAs, invariably suffer from poor minority-carrier properties in the material [4-6]. As a result, the best such junctions to date have QEs and voltages

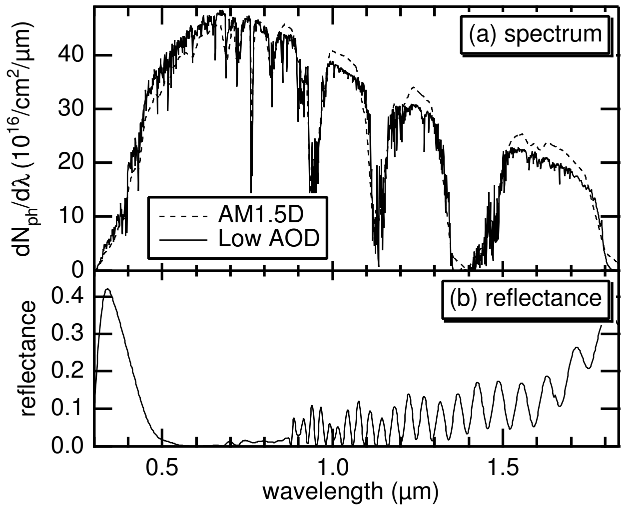

Fig. 1. (a) Low-AOD and AM1.5D direct spectra. Both spectra have been normalized to an integrated intensity of 1000 W/m^2. (b) Model reflectance for a MgF$_2$/ZnS coat on the multijunction structure.

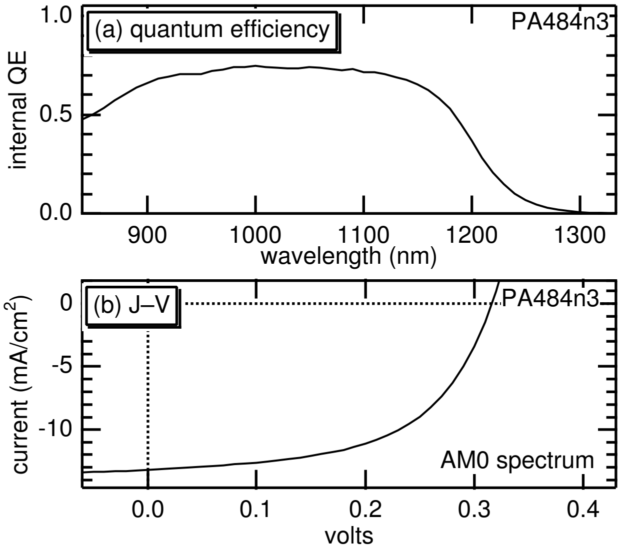

Fig. 2. (a) Internal QE, and (b) J-V curve, for a representative "good" GaInNAs junction.

significantly less than ideal. Fig. 2 shows a typical example: this device has a QE of ~0.7 and a $V_{OC}\approx 0.3$ V, far less than the QE=1 and $V_{OC}=0.6$ V expected for an ideal 1-eV junction. We will calculate the four-junction device efficiency as a function of V_{OC} and J_{SC} for the 1-eV junction, to determine how nearly ideal the junction must be to be useful in a four-junction device.

We compare the resulting four-junction device efficiency with the efficiency of the three-junction device, and find that the potential efficiency gain for the four-junction device is marginal, even with the optimistic assumption that the 1-eV junction can be made virtually ideal. When we extend this analysis to sub-ideal device performance which is characteristic of all actual GaInNAs 1-eV junctions to date, the comparison of four- to three-junction efficiency becomes even less favorable. This result leads to the consideration of alternate device structures that have the potential for improvement on the GaInP/GaAs/Ge structure by avoiding the current-limiting problems of the four-junction structure.

RESULTS AND DISCUSSION

Effect of spectrum

Table 1 compares the photocurrent available to each junction in the three-junction GaInP/GaAs/Ge ("3J#1") structure with the four-junction structure GaInP/GaAs/1-eV/Ge ("4J"), assuming that no optical thinning of the GaAs junction is performed. The table shows that there is more than sufficient light available to the Ge junction in the 3J#1 structure to current-match the top two junctions. However, when the 1-eV junction is introduced, the 1-eV and Ge junctions now have to share the light that in the 3J#1 structure went entirely to the Ge junction. The table illustrates that not only is the 4J structure current-limited by the bottom two junctions but that this current-limiting is more severe for the low-AOD spectrum than for the AM1.5D spectrum.

Effect of reflection

Conventional two-layer AR coatings such as MgF_2/ZnS do not provide the desired near-zero reflectivity over the wide spectral range of interest for the three- and four-junction devices under discussion, as shown in Fig.1(b). Table 1 shows the effect of this finite reflectance on the junction currents. For the low-AOD spectrum, the table shows that without reflectance, the 4J device has J_{SC} (after thinning the top cells to achieve current matching) of 14.6 mA/cm^2, which is 92.4% of the J_{SC} for device 3J#1. With the inclusion of the finite reflectance, the J_{SC} for the 4J device decreases to 13.9 mA/cm^2, or 90.8% of the J_{SC} for device 3J#1. Thus, the finite reflectance exacerbates the current-limiting effect in going from the 3J#1 to the 4J device.

Table 1. Photocurrents $J_{SC1,2,3,4}$ (mA/cm^2) available to each junction in various multijunction structures, without any optical thinning of the GaAs junction. The multijunction photocurrent J_{SC} after optical thinning is also shown. Results are shown for both zero and finite reflectance. For the Ge junction, an 80-μm diffusion length typical of these Ge junctions is assumed [7].

Device$^{(a)}$	spectrum	reflect.	J_{SC1}	J_{SC2}	J_{SC3}	J_{SC4}	J_{SC}
3J#1	AM1.5D	none	15.2	15.2	28.4		15.2
		finite	14.7	14.7	26.4		14.7
4J	AM1.5D	none	15.2	15.2	14.2	14.2	14.7
		finite	14.7	14.7	13.2	13.2	14.0
3J#1	low AOD	none	15.8	15.8	26.9		15.8
		finite	15.3	15.3	25.0		15.3
4J	low AOD	none	15.8	15.8	13.4	13.4	14.6
		finite	15.3	15.3	12.5	12.5	13.9
3J#2	low AOD	none	19.1	19.1	21.3		19.1
		finite	18.5	18.5	19.7		18.5
3J#3	low AOD	none	15.8	15.8	21.1		15.8
		finite	15.3	15.3	19.9		15.3

$^{(a)}$Device descriptions:
4J: GaInP/GaAs/GaInNAs/Ge (1.85/1.42/1.0/0.7 eV)
3J#1: GaInP/GaAs/Ge (1.85/1.42/0.7 eV)
3J#2: GaInAsP/GaInNAs/Ge (1.78/1.23/0.7 eV)
3J#3: GaInP/GaAs/GaInNAs (1.85/1.42/0.9 eV)

It is important to emphasize that the values calculated in Table 1 for the third junction in the 4J device assume an *ideal* 1-eV junction with a unity quantum efficiency for absorbed photons. This is a best-case scenario; in actual practice, GaInNAs cells, which are the leading candidates for the 1-eV junction, have to date not shown a QE above ~0.75. Analysis of this case will be given later. First, we consider device efficiencies assuming the best case of an ideal 1-eV junction.

Efficiencies with an ideal 1-eV junction

To know how the three- and four-junction efficiencies compare, we must determine whether adding the 1-eV junction gives a boost in voltage sufficient to more than make up for the loss in photocurrent. A state-of-the-art three-junction benchmark device has a V_{OC} of ~2.5 V at one-sun standard measurement conditions. Adding an *ideal* 1-eV junction would add about 0.6 V to this V_{OC} for a ~20% boost. We saw above that adding this junction would also lower the multijunction photocurrent by ~10%, assuming the low-AOD spectrum and taking reflection into account. Therefore we can conclude that adding an *ideal* fourth junction will give an efficiency on the order of 10% higher than the three-junction structure.

To make this estimate more precise, we calculate device efficiencies by computing the J-V curves for the three- and four-junction structures. We use a semiempirical model [8] that extrapolates the performance of the GaInP, GaAs, and Ge junctions from the measured performance of state-of-the-art three-junction devices [9,10], while treating the GaInNAs junction by taking V_{OC} and J_{SC} as empirical inputs to the ideal-diode equation. (Series resistance and

Table 2. Calculated efficiencies of the GaInP/GaAs/Ge three-junction structure 3J#1 under various operating conditions, and the efficiencies of the corresponding four-junction device structure 4J obtained by adding an *ideal* 1-eV junction to the three-junction structure. Efficiencies for alternative three-junction structures 3J#2 and 3J#3 (as defined in Table 1) are also shown for selected operating conditions. Details of the calculation are given in Ref. [8].

spectrum	suns	T(K)	reflect.	efficiency (%)			
				3J#1	4J	3J#2	3J#3
AM1.5D	1	300	none	31.8	36.4		
			finite	30.9	34.7		
AM1.5D	500	300	none	38.2	44.6		
			finite	37.2	42.5		
AM1.5D	500	350	none	35.5	40.6		
			finite	34.5	38.5		
low-AOD	1	300	none	33.1	36.3	36.3	37.7
			finite	32.1	34.5	35.0	36.6
low-AOD	500	300	none	39.8	44.4	44.4	44.5
			finite	38.7	42.3	42.8	43.1
low-AOD	500	350	none	37.0	40.4	39.0	41.6
			finite	35.8	38.3	37.4	40.2

grid shadow losses are neglected here, so that the efficiencies calculated for the high-concentration operating conditions should be considered upper bounds on what is likely to be achievable in practice [8].) The results are shown in Table 2 for various concentrations and temperatures, for both the AM1.5D and low-AOD direct spectra. Raising the concentration and lowering the temperature both improve the four-junction efficiency relative to the three-junction efficiency, because the additional voltage contributed by the 1-eV junction in the four-junction structure increases with increasing concentration and decreasing temperature.

The conditions in Table 2 that are most relevant to application in terrestrial concentrator systems are the high-concentration, elevated-temperature conditions of 500 suns and 350K. The table shows that using the AM1.5D spectrum and neglecting reflectance, the four-junction structure efficiency would be 5.1 efficiency points higher than the three-junction device. However, when we account for the low-AOD spectrum and the finite reflectance, the four-junction efficiency is now only 2.5 efficiency points higher than the three-junction benchmark structure.

Efficiencies with a non-ideal 1-eV junction

The estimate of 2.5 efficiency points to be gained by adding the 1-eV junction to the three-junction structure (low AOD, 500 suns, 350K) is a best-case estimate, which assumes that the 1-eV junction can be made essentially ideal. Unfortunately, the leading-candidate 1-eV junctions made of GaInNAs show markedly sub-ideal voltage and current. Figure 3 shows the efficiency of the four-junction structure as a function of the J_{SC} and V_{OC} of the third junction for 500 suns at T=350K. The low-AOD spectrum is used, and reflection is accounted for. The contour representing the 35.8% efficiency of the three-junction device (see Table 2), which the four-junction device must exceed to have any potential usefulness, is indicated in bold. The gray region illustrates (very roughly) the combinations of V_{OC} and J_{SC} that are generally attained by the best 1-eV GaInNAs junctions. We see from the figure that these GaInNAs junctions would yield four-junction efficiencies several points below breakeven with the three-junction structure. Both J_{SC} and V_{OC} of the 1-eV junction must be increased significantly merely to break even; indeed, even if these parameters could be further increased to their ideal values, the four-junction structure would still exceed the three-junction breakeven by only about three efficiency points.

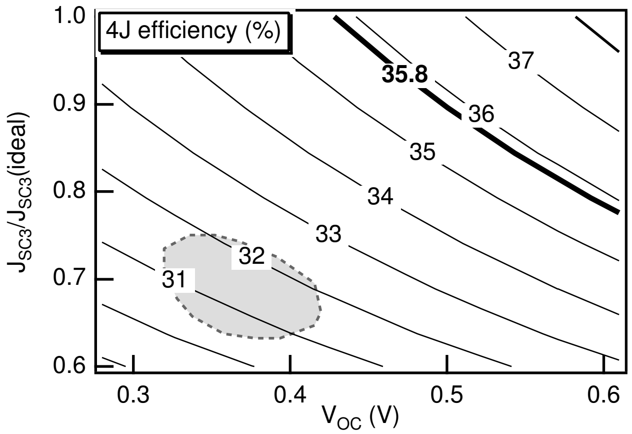

Fig. 3. Efficiency (%) of the four-junction device as a function of the V_{OC} and J_{SC} for the 1-eV junction. The low-AOD spectrum is assumed, and reflectance is included. Operating conditions are 500 suns, T=350K. J_{SC} is indicated as a fraction of the J_{SC} that would be obtained for an ideal junction that collected all absorbed photons. The grey region illustrates roughly the combinations of V_{OC} and J_{SC} that are generally attained by the best 1-eV GaInNAs junctions.

ADDITIONAL AND ALTERNATIVE APPROACHES

The results above show that, even if it proves possible to develop a nearly-ideal 1-eV device, only a few efficiency points will be gained over the three-junction benchmark device under terrestrial concentrator operating conditions. Additional improvements are desirable.

Ge junction collection length

Figure 4 shows the combined photocurrent available to the GaInP and GaAs junctions, as well as the current available to the 1-eV and Ge junctions, calculated for the 4J structure as a function of the collection length in the Ge junction. One possibility for further improvement, suggested by Fig. 4, would be to improve the carrier collection length in the Ge junction. Increasing this length from 80 µm to 300 µm would boost the combined current of the bottom two junctions by 8%, raising the efficiency by about 1.5 points. Increasing the collection in the Ge might be accomplished, at least in part, by designing reflector layers into the device to obtain multiple passes of light through the Ge junction. Note that the bottom two junctions (3 and 4) will always current-limit the multijunction J_{SC} no matter how much the Ge junction collection length is increased.

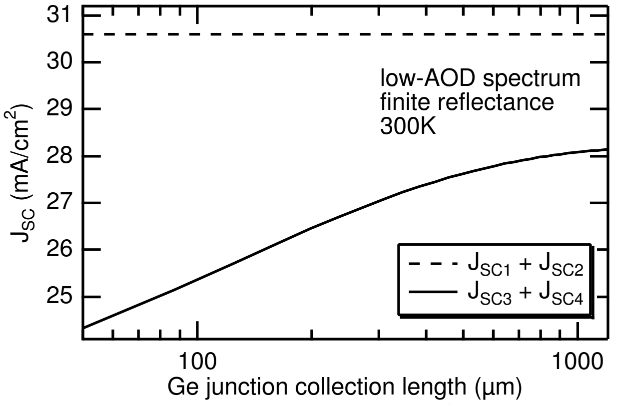

Fig. 4. Ideal junction photocurrents for the top two junctions ($J_{SC1}+J_{SC2}$) and the bottom two junctions ($J_{SC3}+J_{SC4}$) in the four-junction structure, as a function of the effective collection length in the Ge junction.

AR coat

Table 2 shows that four-junction device efficiencies could also be improved by as much as two efficiency points if a more sophisticated AR coat with a wider bandpass region than a conventional two-layer coat were used. This would probably necessitate the use of three- or four-layer designs for the AR coat.

Alternative three-junction structures

Finally, alternate *three*-junction designs may be considered that do not suffer from current-limiting by the third junction. One such approach would be a 1.75-eV/1.25-eV/Ge three-junction device. Lattice-mismatched and lattice-matched approaches to such a structure have been given by Dimroth [11] and by Li [12], respectively. This device structure is denoted 3J#2 in Tables 1 and 2. Its projected efficiency, for ideal junctions, is shown in Table 2 to be very close to that of the 4J structure.

Another alternative three-junction design is a GaInP/GaAs/0.9-eV three-junction structure (denoted 3J#3 in Tables 1 and 2) in which the Ge junction is deactivated and an 0.9-eV junction is put in its place. With a 0.9-eV junction with a near-ideal voltage of 0.5 eV, this approach would improve the device voltage by about 0.3 V over the GaInP/GaAs/Ge benchmark device, without limiting the current. For the operating conditions of 500 suns, low-AOD spectrum, and 350K, this structure has a projected efficiency at least two efficiency points greater than any of the other device structures discussed here, and more than four points greater than the efficiency of the benchmark 3J#1 structure. In fact, even higher efficiencies would be projected if the bottom-cell band gap were chosen to be 1.0 eV instead of 0.9 eV. What makes the 3J#3 structure with its 0.9 eV bottom cell band gap especially interesting is the large excess of photocurrent available to the bottom junction compared to the photocurrent available to the top two junctions, making this device structure tolerant of the non-ideal photocurrent collection efficiencies that plague GaInNAs junctions.

Table 1 shows that under the low-AOD spectrum with finite reflectance considered, there is 19.9/15.3=1.3 times as much light available to the bottom junction as to the top two. Thus, the bottom junction need collect only 1/1.3=77% of the light available to it to avoid current-limiting the top two junctions. Such a collection efficiency may be within reach for GaInNAs junctions. Figure 5 shows contours of efficiency as a function of the third junction V_{OC} and J_{SC} as for Fig. 3, but for this new alternative three-junction structure 3J#3. It is hard to predict what V_{OC} and J_{SC} could actually be achieved for a 0.9-eV GaInNAs junction, as there is a scarcity of experimental results for such a device at present. The grey region in Fig. 5 represents a (perhaps optimistic) guess generated by assuming that 0.9 eV and 1.0 eV GaInNAs junction performances would be similar except that the lower-band-gap junction would have V_{OC}s correspondingly lower by 0.1 V. In the context of this assumption, a comparison of Figs. 3 and 5 indicates that we are closer to breakeven for the 3J#3 structure than for the 4J structure, due to the better tolerance of poor third-junction photocurrent collection for the 3J#3 structure.

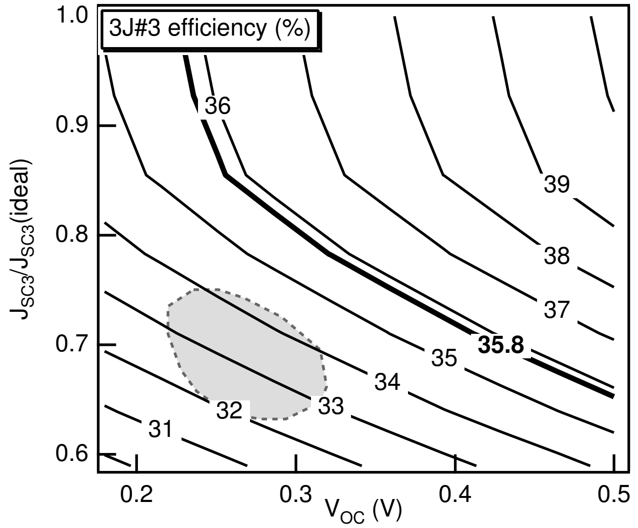

Fig. 5. Efficiency (%) of the 3J#3 device as a function of the V_{OC} and J_{SC} for the 0.9-eV third junction. Operating conditions are the same as for Fig. 3. The gray region illustrates a guess at the combinations of V_{OC} and J_{SC} that might be achievable by 0.9-eV GaInNAs junctions (see text).

CONCLUSIONS

The 4J GaInP/GaAs/1-eV/Ge structure is projected to be 2.5% (absolute) more efficient than the GaInP/GaAs/Ge (3J#1) benchmark for terrestrial concentrator operating conditions, assuming that a near-ideal 1-eV junction could be fabricated. To date, 1-eV junctions have not demonstrated performance adequate for exceeding breakeven. Under terrestrial concentrator operating conditions, the GaInP/GaAs/0.9-eV structure (3J#3) is projected to have a higher efficiency than the 4J structure, and to be more tolerant of poor photocurrent collection in the 0.9 eV junction.

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