Improvement of Solar Cell Efficiency

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***Abstract*—**One way of improving the efficiency of solar cells is to subdivide the broad solar spectrum into smaller energy ranges and to convert each range with a cell of appropriately matched bandgap. The most common approach to implementing this idea has been to use a monolithic or mechanical stack of cells arranged in order of increasing bandgap, with the highest bandgap cell uppermost. This provides automatic filtering of incident sunlight so that each cell absorbs and converts the optimal spectral range. The potential of an earlier experimental approach based on steering light in different wavelength bands to non-stacked cells recently has been re-explored with good results. The present work extends this previous work by putting measurements on a more rigorous basis and by improving the 'composite' experimental efficiency of selected cells to beyond 43%, the highest reported to date for any combination of photovoltaic devices.

***Keywords*— high efficiency; concentrator cells**

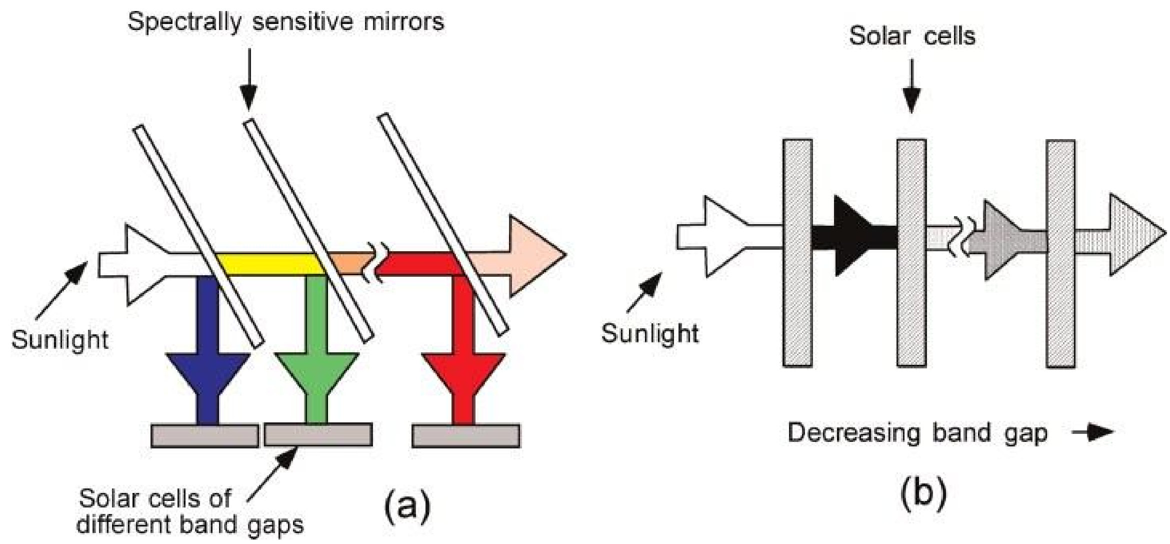
I. INTRODUCTION

The idea of splitting the solar energy spectrum into smaller energy bands and converting each of these bands by a cell of appropriate bandgap (Figure 1) seems to have been first suggested in 1955 by Jackson. However, it was not until 1978 that this idea was first demonstrated experimentally by Moon et al. , with an efficiency of 28.5% measured in outdoor sunlight using a 17-layer dichroic reflector stack to steer the light of energy above 1.65eV onto an AlGaAs cell and below 1.65eV onto a silicon cell. Subsequent interest has been in monolithic stacks of cells as in Figure 1(b) for thin-film, space cell and concentrator cell use. However, the greater flexibility in cell choice made possible with the spectrum splitting approach, combined with the low losses associated with dichroic reflectors, makes it likely that higher efficiency will always be possible than with the monolithic approach, at the expense of greater system complexity. This potential has recently been demonstrated with a composite cell efficiency of 42.7% for split-spectrum cell combinations involving a total of five cells of different bandgap. This work is extended by increasing composite efficiency to beyond 43% and by putting measurements on a more rigorous footing. The recently published split-spectrum results corresponding to an efficiency of 42.72.5% are summarized in Table I. All cell measurements were

Made by the National Renewable Energy Laboratory (NREL) at a cell temperature of 258C under the global ASTM G173-03 spectrum. The short-circuit current density shown is an indicator of the utilization of available photons in each spectral range. For the two series connected cells, the value shown is the actual current multiplied by 2, since each cell generates approximately the same current. Before discussing reasonable criteria for such split spectrum measurements, it is worth reviewing the conditions under which normal concentrator cells are measured. Efficiency, such as for recent 40% efficient monolithic tandem cells , is measured relative to the intensity of light striking a cell, ignoring any losses in the optics that would be required to concentrate the sunlight (as well as any diffused component of sunlight incident on the system aperture). Measurements are also made with the light as uniformly distributed over the cell as possible whereas, in any experimental system, light would need to be concentrated in regions away from the cell extremity to avoid excessive optical loss, increasing cell resistive loss. The cell temperature is also controlled during measurement. These sensible but favorable measurement conditions result in a substantial boost in the efficiencies of cells reported under concentrated sunlight compared to those reported under non-concentrated sunlight, due to the much larger losses likely in any system attempting to utilize concentrator cells. For example, the authors' group provided cells for the most efficient non-concentrating (one sun) and concentrating silicon modules, with the former giving a much higher efficiency of 22.9% compared to 20.5%, despite using lower efficiency cells, at least as determined by the different measurement conventions. Moreover, the concentrator module responds only to direct sunlight. What additional boosts occur in reporting split spectrum results? If losses in concentrating optics are ignored, as in normal concentrator cell measurements, the only additional losses in the scheme of Figure 1(a) arise from any non-ideal performance of the dichroic reflectors. The dichroic reflectors involve dielectric stacks that are essentially lossless at visible and near infrared wavelengths. In the work of Moon et al., the dielectrics ZnS and Na_3AlF_6 were used. The main non-ideality involved is not absorption

Fig1:. Multi-junction cell concepts:

(a) Spectrum splitting; (b) cell stacking



2.5% relative performance loss attributable to the non-ideal properties of the dichroic reflectors in this case. One would imagine that additional effort in improving filter design would further reduce this loss This loss is small compared to other unavoidable losses involved in using concentrator cells, including the lens, light uniformity and thermal losses previously mentioned. It is also small compared to the normal 6% measurement uncertainty in measuring the

Cell	Supplier	Spectral range (nm)	Cell area (cm^2)	Irradiance (kW/m^2)	'Aperture' (cm^2)	Current density[a] (mA/cm^2)	Efficiency[b] (%)
GaInP/GaAs	Emcore	280–890	0.1245	24.2	3.0	27.6	31.7
(two terminal stack)							
Si	U Delaware	871–1200	0.158	8.67	1.4	11.7	5.4
GaInAsP/GaInAs	NREL	1100–4000	N/A N/A	—	—	—	5.6
(three terminal stack)		1100–1350	N/A	40.1	N/A	7.8	3.7
GaInAsP GaInAs		1350–1800		41.7	N/A	6.7	1.9
Five cell combination	—	—	—	—	—	53.9	42.72.5

[a] Normalized to 1 kW/m^2 irridiance , [b] Based on total irridiance

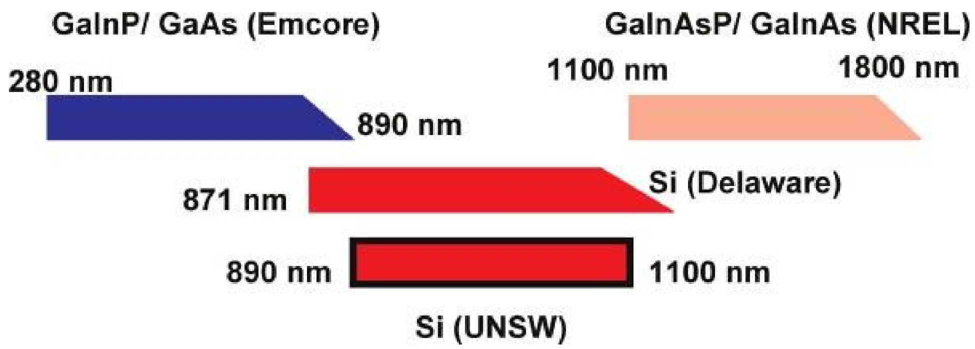
Table 1. summary recently reported split – spectrum report

in the filters, which is negligible as noted, but the non-ideal reflection and transmission properties of these filters. The transition from reflective to transmissive behaviour occurs over a finite wavelength range rather than abruptly and filters do not always partition their response between reflection and transmission as exactly as desired for other wavelengths of interest. For example, in the experiment described by Moon et al. about 5% of the light that would ideally be transmitted to the AlGaAs cell was instead reflected onto the silicon cell. Here it was converted at 06V rather than 1.1V. This is the main component of a total 2–performance of a monolithic concentrator cell stack. Moreover, there are compensating operational advantages expected from spectral-splitting as opposed to cell stacking. The larger cell footprint would allow better thermal control. Interestingly, in the work of Moon et al. , wasted infrared wavelengths were directed at the AlGaAs cell which had a lower temperature coefficient of performance, an additional advantage. The larger cell footprint also means better response to diffuse and stray light that will, to first-order, depend on the ratio of cell to aperture area. Operationally, there will be less spectral mismatch loss if cells are connected in voltage-matched assemblies rather than current-matched as normally for monolithic tandem cells Given the small additional losses and these compensating benefits, there would seem to be no good reason for discriminating against idealised split-spectrum concentrator results relative to similarly idealised stacked cell results since unavoidable losses involved in the practical use of either are similar in magnitude. There are likely increases in system complexity and component cost with the split-spectrum approach, although substantially higher efficiency could more than offset these at the system level. Monolithic tandem cells represent a subcategory that may have practical advantages, in the same way that silicon may have practical advantages over III–V cells, but would not be expected to be able to match the efficiency of a similarly well-developed split-spectrum combination. What requirement should there be to ensure selfconsistency of such split-spectrum results? Measurement of cell response over a restricted spectral range is a wellposed measurement issue unlikely to cause any major additional measurement uncertainty. There have been some objections to measurements at different points in time at possibly different measurement laboratories rather than measurement of the cells as a group.However, measurement at different certified laboratories should be compatible and the performance of the III–V and silicon cells generally involved should be stable. Independent measurements, moreover, statistically reduce the uncertainty in the composite cell value. Furthermore, the work of Moon et al. shows that competent assembly allows the expected advantages to be obtained in assembled packages. Equal cell area, as in this work of Moon et al. , might be thought to be another requirement. However, different cells could be placed at different distances in the uncollimated beam from the lenses, so uniform cell area would seem non-essential. In Figure 1(a), all the cells are illuminated by wavelengths extracted from a common beam hence the same ‘aperture’ (actually normalised irradiance used in the cell measurement times the cell area) might be another possible requirement. However, cells could also be illuminated by light from multiple beams, with the number of beams differing from cell to cell. Hence equal aperture also seems non-essential, at least at the conceptual level. Another issue might be the spectrum under which the cells are measured. There is presently no consensus standard for concentrator cell measurements . The results of Table I were reported under the ASTM G173 global solar spectrum. Other recent 40% cell results have been reported under an interim ‘low aerosol optical depth’ spectrum which boosts their performance relative to the previously prevailing standard ASTM G159. Although used as the basis of future international standards, this ‘low aerosol optical depth’ spectrum is now unlikely ever to become one. Hence, the better documented ASTM G173 global spectra may have some advantages. It appears that the ASTM G173 direct normal spectrum may be accepted as an international standard in the future and hence may be preferable for future concentrator cell measurements, although there have been few concentrator cell measurements to date relative to it.

One very definite cell requirement for composite cell measurements is that total energy illuminating the cells is not larger than the energy in the reference spectrum i.e. portions of the solar spectrum are not used twice. Examination of the results in Table I shows that this requirement is met in principle but not in detail for this data set. The silicon cell involved was measured under an ‘idealised GaAs cell filter’ with a sharp cut-off wavelength of 871nm (1.42eV). The difference in performance expected from a sharp cut-off filter compared to a more gradual filter transition is small, so no difficulties arise on this account. The problem arises since no cut-off at 871 nm was applied to the higher bandgap GaInP/GaAs cell combination which was reported as measured over the 280–890nm range. This means there was an overlap in the 871–890nm range in terms of the energy available to the cells. The authors recognise this limitation but suggest that, as the GaInP cell is the current limiting cell, this overlap is not important. Even if correct, however, the overlap would improve the voltage and fill-factor of the combination, at least marginally. Similarly, the low bandgap GaInAsP/ GaInP cell combination was filtered by an ‘idealised silicon cell filter’ with a sharp cut-off at 1100nm. Again, a similar cutoff does not seem to have been applied to the silicon cell which would have some response to circa 1200nm. Hence there is another overlap in the 1100–1200nm range. These overlaps are shown schematically in Figure 2. The impact of these overlaps readily can be estimated. At 100% external quantum efficiency (EQE), the current. Available in the ASTM G173-03 spectrum in the 890– 1100nm range is 10.3 and 11.6mA/cm^2 in the 871– 1100nm range. An average EQE of 90% would be very creditable for a silicon cell over these ranges. The corresponding current measured experimentally for the silicon cell in the split-spectrum combination of Table I is 11.7mA/cm^2, immediately confirming a contribution from wavelengths beyond 1100nm. Correcting for this would result in about 10% relative reduction in performance (0.5% absolute efficiency reduction). Correcting for the overlap in the 871–890nm range would result in a similar further reduction. Considering that the GaAs cell in the high-bandgap cell stack might not be at full response over this range, as argued by the authors , it can be concluded that the two regions of overlap inflate the absolute efficiency reported for the silicon cell and hence for the cell combination by 0.5–1%

absolute. This is within the estimated measurement uncertainty of2.5% in absolute efficiency. The loss due to correct treatment of the overlap can also be more than recovered by considering the use of other silicon cells in the split spectrum combination with higher independently measured performance.

locally-diffused (PERL) cell ZT-1-4E. As shown in Figure 3, this cell has essentially 100% internal quantum efficiency (IQE) over the 800 – 1060nm rangewith the EQE determined almost entirely by reflection loss over this range. The cell also benefits from a thicker than standard double layer anti-reflection coating that reduces this reflection loss at long wavelengths (as well as heavier than normal emitter diffusion that reduces resistance losses slightly impacting the visible wavelength response but not the infrared). Using independent measurements by Sandia National Laboratories of the cell's spectral response and efficiency under the ASTM E892-97 spectrum, cell response over the 890–1100nm range of the ASTM G173-03 global spectrum can be calculated using standard techniques . Given the particular 'quantum radiametric' features of the IQE over the energy range of interest, this conversion can be made extremely accurately giving a final result of 5.70.2% efficiency at 4.21 kW/m^2 irradiance (a conservative 3% error



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Si	UNSW	890–1100	4.00	4.21	16.8	9.7	5.7
GaInAsP/GaInAs	NREL	1100–4000 1100–	N/A	—	—	—	5.6
(three terminal stack)		1350	N/A	40.1	N/A	7.8	3.7
GaInAsP GaInAs		1350–1800	N/A	41.7	N/A	6.7	1.9
Five cell combination	—	—	—	—	—	51.9	43.01.9

Table 2: II. New composite split spectrum concentrator cell result

II. HIGH INFRARED RESPONSE SILICON CELLS

The authors' group has had considerable experience in fabricating high infrared performance silicon solar cells, both for monochromatic converters with record conversion efficiency of 46.3% at 1.04mm wavelength and in the related inverse problem of demonstrating high-efficiency silicon light emitting diodes . One of the best performing UNSW solar cells at infrared wavelengths that has been measured independently is passivated emitter and rear

bound is assigned based on a broadly-based discussion of errors in a primary calibration method where the illuminating source had a peak in a similar 900–1000 nm range). Although only independently measured at a single intensity, efficiency of such a PERL cell would increase with increasing irradiance to a peak at 15–20kW/m^2, making the above result conservative in terms of ultimate potential.

When combined with previously reported results (Table II), this gives a self-consistently summed conversion.

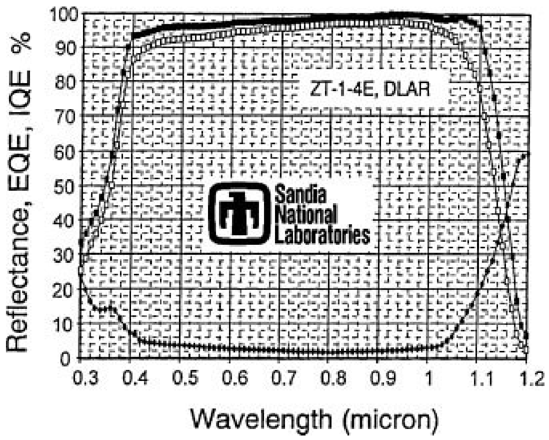

Fig3: Reflectance and EQE and IQE of UNSW PERL Cell ZT-1-4E as measured by Sandia National Laboratories.

Efficiency of 43.0 1.9% under the ASTM G173-03 global spectrum. Note that the uncertainty in this measurement (about 4% relative) is smaller than in measurements of monolithic tandem cells (typically 6% relative) since current matching issues are relaxed. The efficiency of the silicon cell in converting its assigned energy in the 890–1100 nm range is a very creditable 44.3%, showing this cell's role in boosting the efficiency of the combination. Despite lower current than the Si cell in the previous combination due to the spectral constraints imposed, both open-circuit voltage and fill factor are higher under the respective irradiance levels reported in Tables I and II (708 mV versus 667mV and 83.1% versus 69.3%, respectively). Assigning a larger part of the spectrum to the cell would further improve overall efficiency. This new result has the advantage over previously reported results not only in being higher but also in being determined self-consistently.

III.CONCLUSION

Recent work has shown the potential of the spectral splitting approach for producing substantial photovoltaic concentrator cell efficiency improvement. Requirements upon combining results from different cells are discussed. Recently reported results are shown to involve regions of spectral overlap that appear to unduly boost estimated efficiency, although this still lies within the published error band. An improved combination of independently confirmed results gives a composite efficiency of 43% under the global ASTM G173-03 spectrum, the highest reported to date from any such combination of photovoltaic devices. Losses associated with implementing the spectral splitting approach with dichroic filters are discussed with the conclusion that, although the 43% efficiency value is inflated relative to the performance expected from any system utilizing the cells (as well as relative to the performance of non-concentrating cells), this is not to any significantly larger extent than for other concentrator cell results. The main contributor to the reported improvement in performance is a silicon cell that converts energy in its assigned energy range with 44.3% efficiency.

IV. ACKNOWLEDGEMENTS

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