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ACCELERATED PUBLICATION

40% efficient sunlight to electricity conversion

Martin A. Green[1]*, Mark J. Keevers[1], Ian Thomas[2], John B. Lasich[2], Keith Emery[3] and Richard R. King[4]

[1] Australian Centre for Advanced Photovoltaics, University of New South Wales (UNSW), Sydney, NSW, Australia, 2052
[2] RayGen Resources Pty Ltd, 15 King St, Blackburn, Melbourne, Vic., Australia, 3130
[3] National Renewal Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401, USA
[4] Spectrolab Inc., 12500 Gladstone Ave, Sylmar, CA 91342, USA

ABSTRACT

Increasing sunlight conversion efficiency is a key driver for on-going solar electricity cost reduction. For photovoltaic conversion, the approach most successful in increasing conversion efficiency is to split sunlight into spectral bands and direct each band to a dedicated solar cell of an appropriate energy bandgap to convert this band efficiently. In this work, we demonstrate conversion of sunlight to electricity in a solar collector with an efficiency value above 40% for the first time, using a small 287-cm^2 aperture area test stand, notably equipped with commercial concentrator solar cells. We use optical bandpass filtering to capture energy that is normally wasted by commercial GaInP/GaInAs/Ge triple junction cells and convert this normally wasted energy using a separate Si cell with higher efficiency than physically possible in the original device. The 287-cm^2 aperture area sunlight-concentrating converter demonstrating this independently confirmed efficiency is a prototype for a large photovoltaic power tower system, where sunlight is reflected from a field of sun-tracking heliostats to a dense photovoltaic array mounted on a central tower. In such systems, improved efficiency not only reduces costs by increasing energy output for a given investment in heliostats and towers but also reduces unwanted heat generation at the central tower.

KEYWORDS

concentrators; spectral splitting; efficiency

***Correspondence**

Martin A. Green, Australian Centre for Advanced Photovoltaics, University of New South Wales (UNSW), Sydney, NSW, Australia, 2052.

E-mail: m.green@unsw.edu.au

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1. SPECTRUM SPLITTING APPROACHES

Jackson [1,2] first pointed out how splitting sunlight into spectral bands could improve photovoltaic performance in 1955. Two different spectrum splitting approaches have been demonstrated in earlier work [1–7]. As in Figure 1a, dichroic filters can reflect sunlight of energy above the solar cell response threshold onto a target cell while transmitting the rest to the next filter, where the splitting is repeated [3–5]. The second more elegant approach in Figure 1b involves stacking cells on top of one another, with the cell responding to the highest energy photons uppermost [1,2,6,7]. The gap in electronic states, a defining feature of the semiconductor constituting the cells, makes each cell transparent to photons of energy below its bandgap. This sub-bandgap light passes through to underlying cells, automatically finding its way to the correct cell for its most efficient conversion. Moreover, with bandgaps selected to ensure each cell absorbs approximately the same number of photons, stacked cells can be connected electrically in series without any significant loss. In principle, splitting sunlight into two bands with conversion by two cells can increase efficiency value by nearly 40% (relative) compared with a single cell [8], while splitting into three, four or a virtually infinite number of bands gives relative improvements of about 55%, 70% or 110% respectively [8].

The elegant cell stacking approach shown conceptually in Figure 1b has been the most widely used commercially. Monolithic three-cell multijunction stacks implementing this approach (Figure 1d) are used on most recent spacecraft [6], displacing earlier silicon cells. Starting with single-crystal Ge wafers (bandgap of 0.67 eV), higher bandgap Groups III–V GaInAs (bandgap of 1.41 eV) and

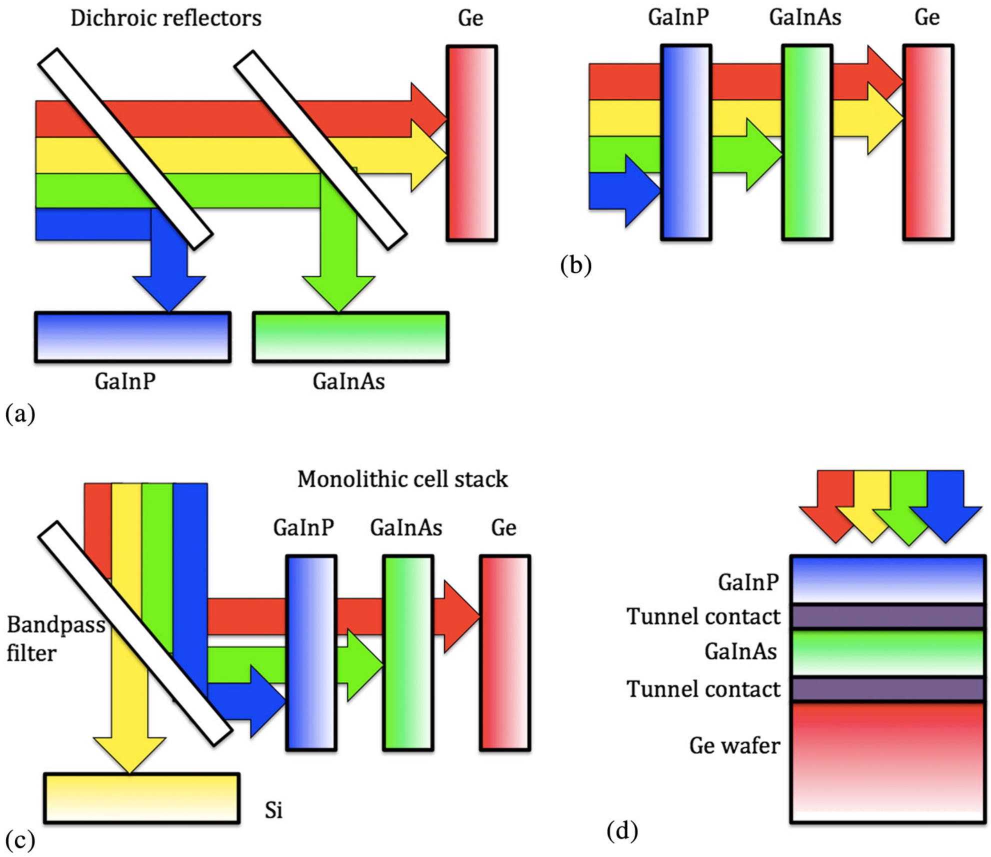

Figure 1. Sunlight spectrum splitting schemes: (a) dichroic reflectors reflect the high-energy part of the incident spectrum to dedicated cells while transmitting lower energies, (b) stacked cells provide automatic filtering if stacked in order of decreasing bandgap with the highest badgap cell uppermost, (c) combined scheme used in the present converter to compensate for the non-optical bandgap of Ge in commercial monolithic stacked cells, with a band-pass filter used to direct normally wasted energy to a commercial Si cell, and (d) schematic of a monolithic triple junction cell stack (colours are indicative only).

GaInP (bandgap of 1.88 eV) cells are grown sequentially and electrically interconnected in the process using tunnel junctions [6,7]. Because atomic lattice spacing within all three materials is similar, this combination allows epitaxial growth of the III–V cells on the Ge substrate [6,7], producing high-quality crystalline monolithic stacks. The same multijunction design is also the commercially preferred option for photovoltaic systems using concentrated sunlight [7], again displacing earlier Si concentrator cells. Although cell cost is much higher, this is offset by the appreciably higher conversion efficiency; reducing costs of other area-related components, in particular lenses, mirrors or other concentrating elements; as well as costs associated with sun tracking, essential once sunlight is appreciably concentrated.

2. BAND-PASS FILTERING

Despite the commercial dominance in these applications, one disadvantage tolerated in the interests of lattice matching is that the Ge cell absorbs many more sunlight photons than the III–V cells [7]. Consequences are apparent in Figure 2a where current–voltage output curves for individual cells are shown, together with their combined output. Because cells are series-connected, their combined output is found by selecting a current and adding cell voltages as indicated. The extra Ge cell current is essentially wasted because even if much lower as in Figure 2b, almost identical combined output results. The wasted energy is dissipated as heat within the cell, increasing challenges in maintaining low operating temperatures where the cells are most efficient. This shortfall stems from failure to date to identify lattice-matched semiconductors of bandgap intermediate between GaAs and Ge with sufficiently good material properties [7].

The solution demonstrated in this work is to combine stacking and filtering in a different way. Rather than dichroic reflectors, a band-pass filter is used as in Figure 1c to divert some photons that would normally reach the Ge cell to an inexpensive Si cell. The shaded region in Figure 2b shows the extra power gained, without significant loss

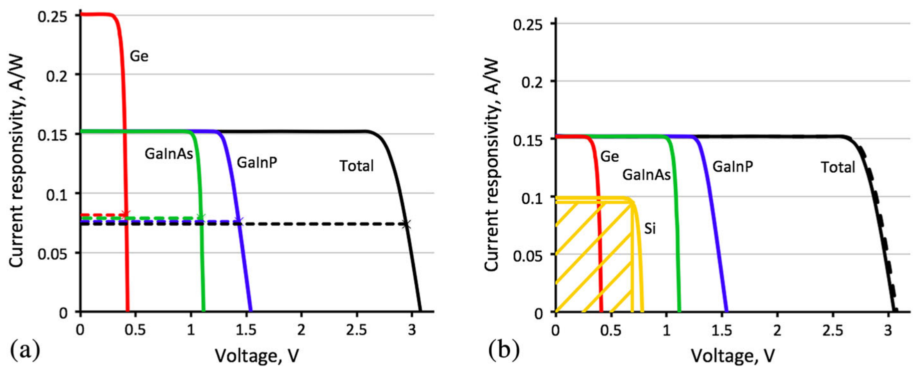

Figure 2. Output current responsivity versus voltage curves for individual cells and combined output for a monolithic three-cell stack (GaInP/GaInAs/Ge): (a) normal operation [6] with excess Ge current normally wasted, as seen by adding cell voltages at a fixed current; (b) the same three-cell stack with Ge cell current matched to the other cells by diverting excess photons to a separate Si cell.

in multijunction cell output. This differs from the approach in related earlier work [3–5], where either high-pass or low-pass filters are used rather than the present band-pass filter.

3. PROTOTYPE DESIGN

The converter demonstrating 40% efficiency was built as a 'proof of concept' prototype for a large power tower photovoltaic system [9,10] (Figure 3a). Power towers are well developed for concentrating solar thermal (CST) systems where sunlight reflected to the tower is absorbed as heat, then converted to electricity using conventional steam generators [11]. Although generally regarded as one of the lower cost CST approaches, sunlight to electricity conversion efficiency is typically about 22% [11]. An alternative CST approach, where heat drives a Stirling engine [11], gives higher efficiency with 31.3% efficiency reported in 2008, the highest for solar conversion to electricity at that time [12]. A photovoltaic power tower (Figure 3a) has the potential to exceed Stirling engine efficiencies, with this efficiency advantage leading to potentially lower costs than CST power towers.

A schematic of the prototype is shown in Figure 4a, with receiver details in Figure 4b. Both silicon and multijunction cells are located near the focal point of a 1-m focal length parabolic mirror. Reflective secondary concentrating mirrors were included in the design to allow better uniformity of light distribution on the cells but were not used in the results reported because no significant advantage was observed. A photograph of the actual system under testing is shown in Figure 5. Irradiance concentration is nominally 365 suns.

Optical details are given in Figure 6a showing the spectral photon flux in the standard air mass 1.5 solar spectrum, as well as cell spectral response curves, measured parabolic mirror reflectance and filter transmittance. The triple junction cell used in the prototype was a commercial Spectrolab [13] concentrator cell (C3MJ+ cell [14], nominally 39.2% efficient at 500 suns concentration, mounted on a ceramic substrate), while the Si cell was a SunPower back contact

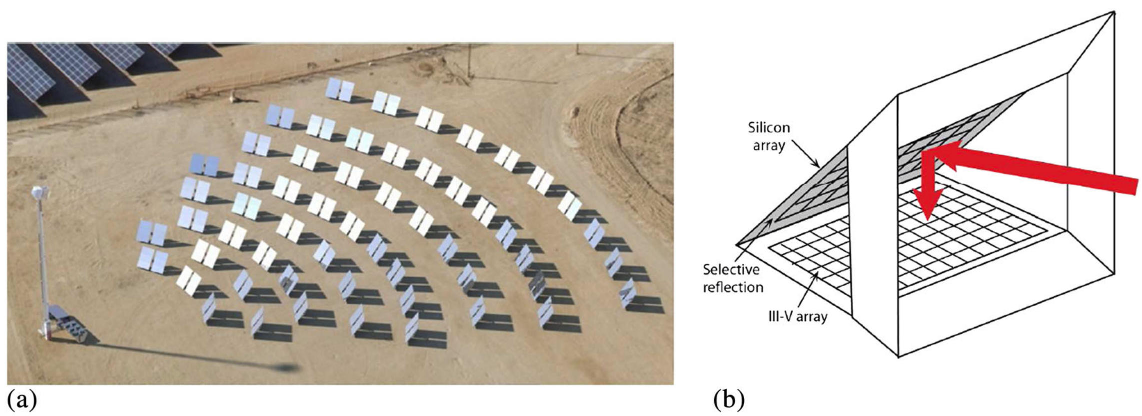

Figure 3. Photovoltaic power tower: (a) a heliostat field directs sunlight to a central tower housing a dense photovoltaic array receiver (artist's impression); (b) possible design of an advanced receiver implementing the demonstrated improvements at scale.

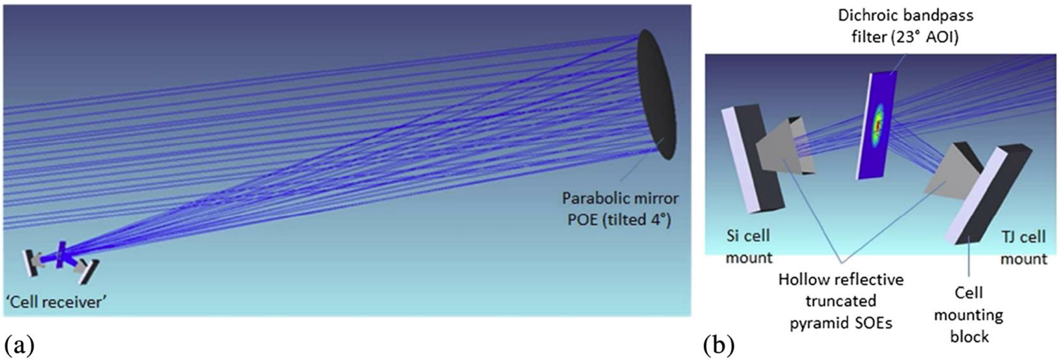

Figure 4. Schematic of prototype design: (a) a parabolic mirror of 1-m focal length directs sunlight to the receiver consisting of a dielectric band-pass filter, a Si cell and a three-cell tandem junction stack; (b) receiver details. Both cells are mounted on ceramic substrates and water-cooled heat sinks. Secondary optical elements were not used for the measurements reported (irradiance concentration of 365).

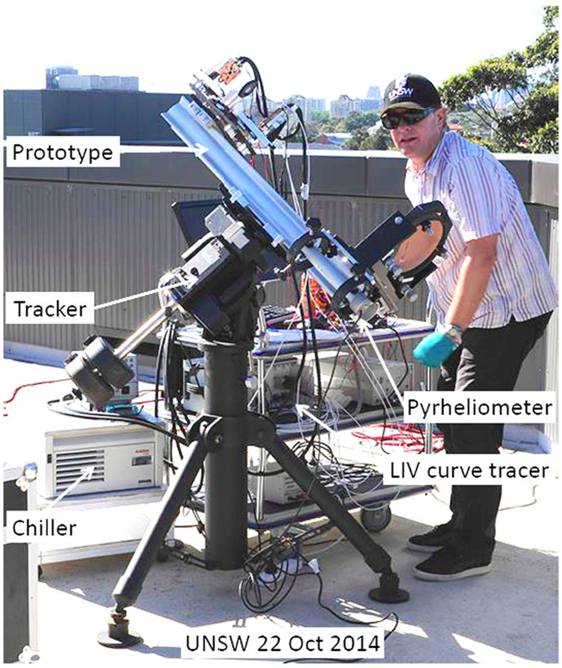

Figure 5. Photograph of the prototype under testing at UNSW on 22 October 2014 with an (unconfirmed) efficiency value over 40% measured on that day.

cell of circa 1998 vintage [15,16] (nominally 26% efficient at 200 suns), mounted on a ceramic substrate and encapsulated under glass by ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile) [15,16] , followed by MgF_2 antireflection coating at University of New South Wales (UNSW).

Critical to the present approach is the energy selective band-pass filter. Because operating under several hundred times sunlight concentration, a non-absorbing illuminated surface dielectric interference filter is used. As the multijunction cell is the primary contributor to high efficiency, it is important not to reduce sunlight intensity either on the III–V cells or on the Ge cell at energies below the Si bandgap. Because dielectric filters are more readily designed for near 100% reflection than for 100% transmission, an early design decision was to reflect light onto the multijunction cell, while transmitting the diverted light to the Si cell. Transmission is non-critical, because more light is potentially available for diversion to the Si cell than needed.

The filter was custom designed by Omega Optical, Inc. [17] for an angle of incidence of 23° and half-cone angle of 6°. Performance for off-angle light is relevant both to accommodate the angular divergence of the incident beam and to allow fine tuning of the band-pass filter, achieved by tilting from the 23° design point. Design specifications were refined in an iterative process based on simulations of specific designs by Omega Optical. The final design consisted of 158 alternating layers of Nb_2O_5 and SiO_2 (20 μm total thickness) deposited onto an ultraviolet grade non-absorbing silica substrate, with measured characteristics of filters supplied (refer to Figures 6a and 6b) closely matching design values.

Figure 6b shows details of measured filter transmission at various incident angles for a typical filter. Because filters are essentially non-absorbing, these curves demonstrate close to 100% reflectance at all wavelengths for angles near 23°, except at wavelengths where only Si and Ge cells can both respond. As previously mentioned, the detailed filter response at these wavelengths is non-critical because of many more photons being available in this shared range than the number able to be diverted to the Si cell without upsetting the triple junction cell current balance.

The other key optical component is the parabolic mirror simulating the heliostat field output. An 'enhanced silver' coating (Ag plus a two-layer Al_2O_3/Ta_2O_5 dielectric overlayer) was applied by Optical Coating Associates [18]. Measured reflectance is compared in Figure 6c to the design value. Because the reported efficiencies are based on direct sunlight incident on the mirror, this high reflectance contributes to the overall performance.

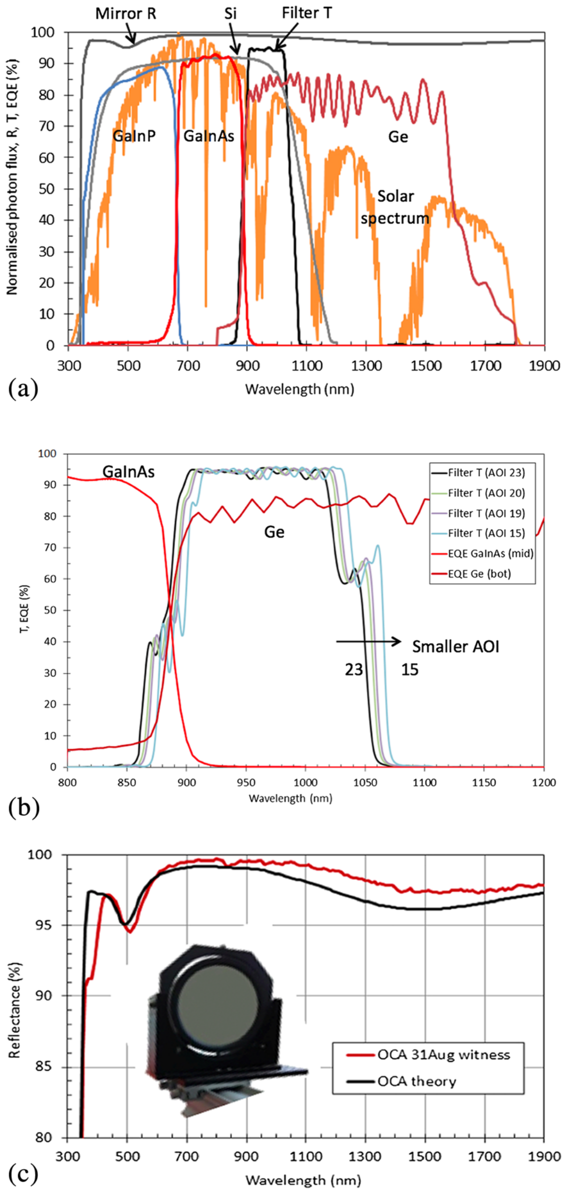

Figure 6. Optical performance of prototype elements: (a) normalised spectral photon flux, external quantum efficiency (EQE) for all cells and filter transmission (dashed line); (b) filter transmission for various angles of incidence around the design value of 23°, showing variation relative to GaInAs and Ge EQE curves; and (c) reflectance of the parabolic mirror (inset), measured on a planar witness sample, compared with design value.

4. PROTOTYPE TESTING

The prototype was initially tested in Sydney with 40.1 ± 1.5% efficiency measured in a four-terminal configuration in outdoor testing on the afternoon of 22 October 2014 under an air mass 2.3 spectrum corresponding to 795–798 W/m^2 direct irradiance. The largest measurement uncertainty in this case arose from uncertainty in the measurement of the direct beam irradiance, estimated as ±2% relative. Uncertainties in cell output power measurements are smaller (estimated as better than ±1.0%). Because measured in a system that was custom designed for this purpose, cell temperature could be held close to the desired 25°C value, introducing little additional uncertainty on this account. The triple junction cell contributed 35.7% to the final efficiency value, with the Si cell contributing an extra 4.4%, representing a 12% relative performance boost. The triple junction performance under the same test conditions, when placed directly in the beam path without the use of the filter, was estimated as 36.8%, slightly higher than with the filter present. This is mainly because of the increased fill factor in this case because of the overdriven Ge cell, reducing the boost of the filter configuration to 9% relative.

The system was then transported to the US National Renewable Energy Laboratory (NREL) in Golden, Colorado, where it was re-assembled and independently tested at NREL's outdoor test facility, again in a four terminal configuration. An efficiency value of 40.4 ± 2.8% was certified for measurements made on the morning of 6 November 2014 under pressure-corrected air mass of 2.5 (direct normal irradiance of 883.7 W/m^2), referenced to 25°C cell temperature. The multijunction cell efficiency value was 35.7%, while that of the Si cell was 4.7% (Figure 7), based on direct sunlight incident on the system aperture (the efficiency of the Si cell was calculated as a much higher value of 43.1% based on the energy actually striking it, because only a small fraction of the incident light is directed to the Si cell as in Figure 6a). Overall efficiency varied only slightly with irradiance and air mass, decreasing slightly as the latter decreased, with a 39.9% efficiency value measured later in the day under pressure-corrected air mass of 1.5 (direct normal irradiance of 1003 W/m^2), again referenced to 25°C cell temperature.

The higher uncertainty in the case of the NREL measurements, despite much lower uncertainty in the measurement of direct irradiance (0.4%) and of cell current–voltage curves (0.25%), is partly because of increased uncertainty assigned to the cell temperature correction (1–2% relative) and tracking error effects (1% relative). The major contributor to the reported measurement uncertainty, however, relates to uncertainties introduced in referencing the measured data to Concentrator Standard Testing Conditions (direct normal AM1.5 spectral irradiance consistent with IEC 60904-3, referenced to 1000 W/m^2 irradiance and a cell temperature of 25°C). This was not attempted for the UNSW measurements. An additional 1% uncertainty is assigned in referencing to the higher irradiance, with 2–3% uncertainty introduced in the spectral correction factor because of uncertainties in the measured spectral irradiance, quantum efficiency and filter functions. An additional 1% uncertainty is estimated in the fill factor because the photocurrent ratios were not what they would be under the standard direct beam spectrum. A similar level of uncertainty applies to all recent multijunction cell measurements when referencing to a standard spectrum [19].

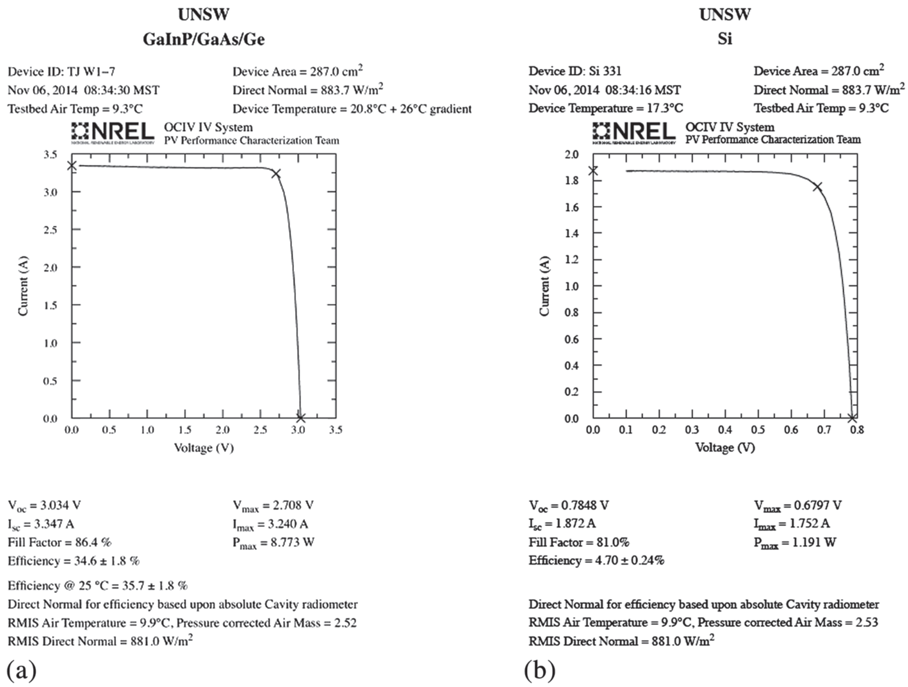

Figure 7. Independent confirmation of prototype performance at NREL: (a) output current–voltage curve of triple junction cell corresponding to 35.7% efficiency referenced to 25°C; (b) output current–voltage curve of Si cell, contributing an additional 4.7% to combined efficiency.

5. SIGNIFICANCE AND CONCLUSIONS

The significance of this result lies not only in the landmark efficiency reported but also in its achievement using commercial cells, making the demonstrated efficiency improvements readily accessible. Power towers are particularly suited to implementation because of the small number of large receivers, the correspondingly large heat quantum to be dissipated, the better tolerance to spectral variation of sunlight offered by this four-terminal approach and the opportunity to improve on this advantage by varying the relative tilt of the arrays in Figure 3b during the course of the day. The large numbers of cells in each dense array also provide flexibility in voltage-matching Si and multijunction cell outputs at the tower by different series/parallel wiring of each of these arrays.

Although detailed costings of this approach have yet to be undertaken, initial estimates are encouraging. In photovoltaic power towers, the costs of receivers based on standard triple junction cells represent only a small fraction of total system costs (estimated as 15–20% of the latter). Hence, a 10% efficiency gain in system output from improved receiver performance would justify a much larger increase in the receiver costs of 50–70% (discounting savings from reduced heat loads). The additional costs of the silicon array obviously fall well within this budget, because far below those of triple junction cells (US\$5/cm^2 is a common estimate for the latter in volume). Estimates for filter costs in moderate volume (70 m^2) are around US\$1/cm^2, also considerably less than those of triple junction cells.

The previously highest reported result for sunlight conversion by a solar system was 38.5 ± 1.9% for a small 0.2-cm^2 aperture area converter [4], over 1000 times smaller than the present prototype. This converter used a dichroic reflector-based spectrum splitting approach in combination with specialised research cells. Efficiency values up to 46.0 ± 2.2% have been recently reported for small area (0.05 cm^2) quadruple junction, wafer-bonded cells [19], although these results are measured under uniform light from a flash simulator and do not include optical and electrical losses associated with their use in an actual system. An 830-cm^2 module using 52 cells of a similar design, about three times larger than the present prototype, has recently demonstrated 36.7 ± 2.6% efficiency values [20], the highest ever for a module of this size.

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