Effects of Ultra-high Flux and Intensity Distribution in Multi-junction Solar Cells

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We report results of high-flux experiments on tandem solar cells, with a real-sun probe predicated on mini-dish fiber-optic concentrators. Experimental results and their interpretation focus on: (a) a striking insensitivity of cell efficiency to flux map; (b) the predictability of the flux values at which cell efficiency peaks; and (c) performance of the same cell architecture at markedly smaller cell area.

INTRODUCTION

Recent advances in both multi-junction photovoltaic (PV) devices¹–⁴ and high-flux optical designs⁵–⁹ prompt the need for measurements that probe how solar cell behavior depends on flux level and distribution. While modeling procedures have been proposed,⁶,¹⁰ there is a paucity of data with which the potential of these new technologies can be assessed.

Extending our earlier related studies,¹¹ we describe measurements of the performance of commercial solar cells developed for high-flux applications,³,⁴ in particular how PV behavior varied as power density and flux distribution spanned three orders of magnitude. The cells were tailored by the manufacturer to exhibit peak efficiency at around 200 suns (1 sun = 1 mW/mm²). Our observations indicate, however, that the efficiency of the same cell structure produced in markedly smaller cell areas would be only minimally compromised at flux levels of several thousand suns.

EXPERIMENTAL PROTOCOL

Our high-flux test facility¹¹,¹² is shown schematically in Figure 1. It allows localized irradiation tests where light projected beyond the fiber tip is negligible, and solar cell performance is monitored under strongly
inhomogeneous flux distributions. Radiation on the cell is moderated with an iris on the concentrator’s window. Our two fiber-optic mini-dish prototypes have different numerical aperture and construction\(^1\) — one fitted with a 1.0 mm diameter optical fiber (prototype 1) and the other with a 2.0 mm fiber (prototype 2). Their spectral throughput also differs slightly but non-negligibly from one another, as well as relative to the direct solar spectrum (Figure 2).

We measured current–voltage (\(I–V\)) curves for commercial monolithic concentrator cells with a uniform parallel-grid front metallization:\(^3,4\) square 16 mm\(^2\) tandem Ga\(_{0.35}\)In\(_{0.65}\)P/Ga\(_{0.83}\)In\(_{0.17}\)As (Figure 3). The two fibers could irradiate the solar cells either separately or together, such that solar power on the cell could be

![Figure 1](image_url)  
Figure 1. (a) Schematic of our experimental configuration. Sunlight is concentrated in a paraboloidal mini-dish \(\sim 20\) cm in diameter. A small flat mirror re-images the sun onto the tip of an optical fiber that guides the concentrated solar radiation to a solar cell located indoors. The cell is thermally bonded to a passive copper heat sink; (b) uniform irradiation is achieved with a square cross-section kaleidoscope; (c) direct fiber-cell contact is used for localized irradiation probes; (d) photograph of the direct fiber-cell contact in the localized irradiation probe

![Figure 2](image_url)  
Figure 2. Measured spectral input to the cell
varied from 0 to 16 W. Local concentration values up to 10000 suns were achievable with prototype 1 (close to 8 W from a circular fiber tip 1.0 mm in diameter). Near-perfect flux uniformity was achieved by coupling one or both fibers to a square kaleidoscope placed between the distal fiber tip and the cell. The kaleidoscope’s cross-section is identical to the active cell area. In this way, uniform-irradiation tests could be realized up to 1000 suns.

Measurements were repeated during clear-sky periods, two hours about solar noon, over the course of a full year in Sede Boqer, Israel, where the mid-day solar spectrum is nearly invariant and close to the AM1.5 spectrum.11 Irradiation on the cell $P_{solar}$ was measured with a pyrometer of 5% accuracy. Cell temperatures were measured at the center of the cell-to-heat sink contact area, and found to be up to 20 K above indoor ambient temperature, depending on solar power input.

The proportionality of cell short-circuit current $I_{sc}$ with $P_{solar}$—which we characterize by the current generation constant $G = I_{sc}/P_{solar}$—was measured for both prototypes. For prototype 1, $G = 0.150 \pm 0.008$ A/W, which is only 3% greater than with outdoor direct solar radiation, but 13% lower than with prototype 2—a consequence of differences in optical fiber spectral attenuation and mirror coatings. In the data reported below, the serendipitous spectral filtering effect of prototype 2 accounts for PV efficiency exceeding values reported by the manufacturer. Since we demonstrated that our measurements with prototype 1, at uniform irradiation, agreed with those of the manufacturer,3,4,11 those comparisons will not be repeated here.

Cell performance was insensitive to the location of the localized irradiation spot. In addition, the absence of any damage or pronounced deterioration of cell performance even at 10000 suns with a local current density $J_{sc} = 1.5$ A/mm$^2$ (with $I-V$ curves traced both from open- to short-circuit and vice versa) is evidence of the integrity of the tunnel diode (in contrast to recent findings where tunnel diodes in multi-junction concentrator cells did not withstand such high flux levels12).

RESULTS AND DISCUSSION

We aimed to detect and interpret the principal trends in PV behavior at ultra-high flux—especially those with highly localized irradiation—with as simple a model as possible: a one-dimensional equivalent circuit with a
lumped series resistance \( R_s \), diode quality factor \( n \) and zero shunt conductance \( 1/R_{sh} \). The last assumption is confirmed by an essentially horizontal low-voltage regime in the experimental \( I–V \) curves (Figure 3). From the equivalent-circuit analysis:

\[
I = I_{\text{ph}} - I_0 \left( e^{\frac{q(V + IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{diode}} \simeq I_{sc} - \frac{V + IR_s}{R_{diode}} - I_0 \left( e^{\frac{q(V + IR_s)}{nkT}} - 1 \right)
\]

\[
V \simeq -IR_s + \frac{nkT}{q} \ln \left( 1 + \frac{I_{sc} - I}{I_0} \right)
\]

\[
V_{oc} \simeq \frac{nkT}{q} \ln \left( \frac{I_{sc}}{I_0} \right)
\]

where \( I_{\text{ph}} \) is the photo-generated current, \( I_0 \) denotes the reverse saturation current, \( k \) is Boltzmann’s constant, and \( q \) is the magnitude of electron charge.

While we recognize that three-dimensional modeling is required for rigorous analysis, the measurements reported below support the explanatory and predictive value of such an uncomplicated model. Namely, application of the one-dimensional model is not advocated in general; yet it captures the essential features for the particular class of high-quality concentrator cells studied here, including the predictive capability evidenced presently in Figures 4 and 5.

\( R_s \) and \( n \) are approximated as constants independent of flux; and \( R_s \) is treated as the ratio of an unvarying specific series resistance to active cell area. While this comprises an imprecise idealization, it is not inconsistent with any of our observations, and can be viewed as suitable when the relative contribution of contact metallization to \( R_s \) is negligible. Were resistive losses from the metallization non-negligible, the \( I–V \) curves in localized irradiation tests would display a perceptible spatial dependence, the most pronounced difference being between the center and edge of the cell. However, the \( I–V \) curves in all localized irradiation measurements were insensitive to fiber location on the cell.

Figure 4. Measurements of open-circuit voltage \( V_{oc} \) vs the log of: (a) local concentration; (b) \( I_{sc} \) (proportional to \( P_{\text{solar}} \)). Determination of diode quality factor \( n = 2.21 \) is restricted to the lower irradiation regime where temperature corrections to \( V_{oc} \) are tolerable and \( kT/q = 0.027 \text{ V} \). Deviations from linearity at large \( I_{sc} \) correspond to non-negligible cell heating, the effect of which could not be determined accurately.
Total cell performance then constitutes the sum of contributions from each equi-intensity areal element, which, with localized irradiation, consists of the area-weighted sum of: (a) the uniformly irradiated spot (a fraction \( f \) of active cell area); and (b) the remaining dark region. In prototypes 1 and 2, \( f = 0.049 \) and 0.196, respectively.

Cell temperature was not maintained constant. Several key assessments are possible for the restricted temperature range achieved with passive cooling (as in Figures 4 and 5). Accurate determination of the small parameter \( R_s \), however, is acutely sensitive to such deviations, exacerbated by the additional experimental uncertainties in measuring solar cell performance. Hence the standard prescribed methods for estimating \( R_s \) yielded physically tenuous values. Our main objectives comprise the presentation of new approaches in high-flux tests and elucidating key trends. Precise determinations of \( R_s \) are inessential to our findings or conclusions, and hence not explored further.

We can establish a value of 2.21 for \( n \) (Figure 4)—close to the ideal value of 2 for a tandem cell—and can draw conclusions regarding the impact of flux distribution on cell performance. The weaker test is the prediction that semi-log graphs of \( V_{oc} \) as a function of local concentration should comprise parallel straight lines displaced by \((nkT/q)\log(f)\) (Figure 4a) which, when plotted against total irradiation on the cell, should collapse to a single line independent of flux map (Figure 4b). Relative to cell efficiency, \( V_{oc} \) exhibits a weak spectral dependence; so accounting for the variations of efficiency with flux level and distribution offers a more demanding check.

In the limit \( R_s \to 0 \), the \( I–V \) curves should be independent of flux distribution at fixed \( P_{solar} \), and semi-log plots of efficiency as a function of concentration will be linear. For concentrator cells of the type investigated here, with small but discernible \( R_s \), \( I–V \) curves should remain unaffected by flux map in the lower-concentration regime where the \( IR_h \) product in Equation (1) contributes negligibly. At sufficiently large \( P_{solar} \) (high current), \( IR_h \) becomes non-negligible, and the influence of intensity distribution becomes noticeable. Fill factor—which depends on \( R_s \) and \( f \)—worsens as the flux map becomes more strongly peaked (localized irradiation represents an extreme case). The flux dependence of fill factor is implicit in our results because: (1) the flux behaviors of \( V_{oc} \) and efficiency are reported; and (2) \( I_{sc} \) is proportional to \( P_{solar} \).
The voltage drop that stems from series resistance \( IR_s \) is proportional to current rather than current density. Hence losses in a localized irradiation test at 10000 suns are comparable to those in a uniform irradiation test at 490 suns (\( f = 0.049 \)). So despite the immense current density in the localized 10000-sun experiment, \( R_s \) losses remain relatively small. With uniform irradiation at 10000 suns (or even just several thousand suns), pronounced \( R_s \) losses would be incurred, hence a substantially lessened efficiency. The implication is that cells of this constitution, produced at approximately 1 mm\(^2\) active area, would maintain the relatively small \( R_s \) losses at thousands of suns that their large (16 mm\(^2\)) counterparts display at hundreds of suns.

Semi-log plots of efficiency as a function of flux (Figure 5) should exhibit linear behavior in the lower-flux regime, with a slope proportional to the product of: (1) \( G \) (stemming from \( I_{sc} \)); and (2) the effective thermal voltage \( nkT/q \) (from the contribution of \( V_{oc} \)). These plots should also feature: (a) a nonlinear decrease at sufficiently high flux due to \( R_s \) dissipation; and (b) a maximum that reflects this trade-off.

So the flux level at which efficiency peaks is governed by \( R_s \). In recent generations of multi-junction concentrator cells, peak efficiency is reached at flux levels of hundreds of suns.\(^1\)\(^-\)\(^4\) Test reports that do not probe concentration levels of the order of \( 10^3 \) and above barely explore the regime of decreasing efficiency.

The key features noted above for the behavior of efficiency are summarized in Figure 5. In prototype 1 (with essentially the same \( G \) value as in the manufacturer’s experiments), as the light distribution changes from uniform to highly localized, there is an upward shift of \( \log(1/f) \) in the flux value at which efficiency peaks. The larger \( G \) value for prototype 2 accounts not only for increased efficiency values, but also for a greater slope in the lower-flux linear regime. Similarly, the upward shift in the concentration at which efficiency is maximized with prototype 2 is \( \log(G_1/(G_2f)) \). In fact, correcting for spectral response \( G \) and viewing efficiency as a function of \( P_{solar} \), we should find that all measurements reduce to a single curve, independent of flux distribution at least up to the region of peak efficiency, as illustrated in Figure 5b.

**SUMMARY**

A renewed interest in ultra-high-flux PV systems has created the need for measurements with which cell performance can be assessed over a broad range of concentration and flux distribution. It also poses the question of how device performance will vary with cell size, and whether all the phenomena unique to the regime of intense irradiation have been identified. Fiber-optic mini-dishes allow localized irradiation real-sun tests to be conducted indoors under controlled conditions at concentration values up to \( 10^4 \) suns.

The photovoltaic behavior of the commercial tandem concentrator cells evaluated here is emblematic of high-efficiency multi-junction cells\(^1\)\(^-\)\(^4\),\(^1\(^1\),\(^1\(^2\) in: (a) their relative insensitivity to flux distribution even at elevated concentration; and (b) exhibiting only a modest efficiency decrease at solar intensities of thousands of suns with localized irradiation. Their \( I-V \) curves attest to essentially zero shunt losses and low series resistance dissipation, with near-ideal diode quality factors. Such desirable traits are not always the rule, and one can apply the localized irradiation method to map inhomogeneities in cell as well as tunnel diode behavior.\(^1\(^2\) Were the same cell architecture manufactured in smaller cells, the flux value at which efficiency peaks would be shifted significantly, and predictably, upwards, from hundreds to thousands of suns.

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