PRISMATIC COVERS FOR BOOSTING THE EFFICIENCY OF HIGH-CONCENTRATION PV SYSTEMS

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ABSTRACT

Prismatic cover experiments were performed on GaInP/Ga(In)As/Ge triple-junction concentrator solar cells having grid designs with up to 39% metal coverage. The devices were characterized both before and after the application of optically-clear silicone covers patterned with cylindrical-lens microstructures. In solar-simulator LIV measurements at 1 sun and at 500 suns, we observed a boost in the efficiency of prism-covered cells, relative to before covering, of up to 34%, depending on the grid coverage fraction. The spectral response of the cells before and after covering was also characterized, and the observed boost in external quantum efficiency was found to be consistent with the LIV performance gains. Also studied were the lateral tolerances allowed by the prismatic covers, for alignment to the underlying cell grid structure, as a function of the maximum angle of incidence of the light impinging onto the cell. Ray-tracing simulations were performed, and found to be consistent with preliminary angular-dependence spectral response measurements done under monochromatic illumination.

INTRODUCTION

One of the most significant loss mechanisms in concentrator solar cells is shadowing due to the top-contact gridline structure, an effect that reduces the generated photocurrent by as much as 10%. Therefore, traditional grid design for CPV cells tends to focus on the trade-off between two competing requirements: 1) for narrow, sparse grid lines, which minimize the shadowing effect; and 2) for wide, densely spaced grid lines, which minimize the contact and series resistance. However, by using prismatic covers, a type of micro-patterned coverglass, this trade-off can be completely eliminated.

Prismatic covers are optical micro-elements which steer the incident light away from the top contacts, allowing for the elimination of shadowing losses even for relatively wide, and hence low-resistance, grids. The current paper describes the preliminary experiments we have performed towards establishing the viability of prismatic covers as a way to significantly increase the efficiency of solar cells for high-concentration CPV applications.

The cells used in these experiments were GaInP/Ga(In)As/Ge triple-junction concentrator devices, having a variety of grid designs with up to 39% top-metal coverage. The cells were characterized both before and after the application of optically-clear uncoated silicone covers patterned with cylindrical-lens microstructures. In normal-incidence solar-simulator LIV measurements at 1 sun and at ~500 suns, we observed a relative boost in the efficiency of prism-covered multijunction solar cells, as compared to uncovered ones, of up to 34%, depending on the grid coverage. The spectral response of the cells before and after covering was also characterized, and the observed boost in external quantum efficiency was found to be consistent with the LIV performance gains. Also studied were the lateral tolerances allowed by the prismatic covers, for alignment to the underlying cell grid structure, as a function of the maximum angle of incidence of the light impinging onto the cell. Ray-tracing simulations were performed, and found to be consistent with preliminary angular-dependence spectral response measurements done under monochromatic illumination.

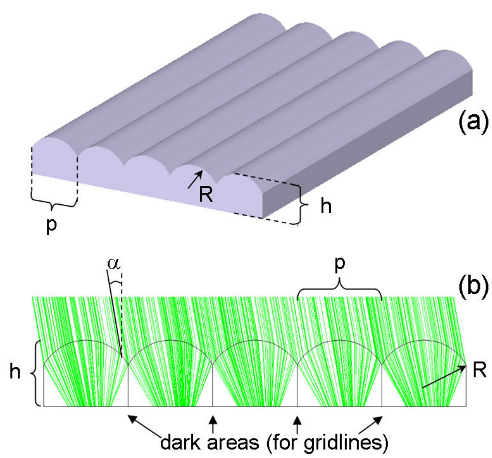

Figure 1. Cylindrical micro-lens prismatic covers for concentrator solar cells: (a) 3D rendering; (b) cross-section schematic with incident rays shown in green.

While a variety of prismatic-cover designs have been proposed [1,2], we will focus the present discussion on the periodic cylindrical-lens pattern proposed by Entech [3], shown schematically in Fig. 1. Typical dimensions include a pitch (i.e., center-to-center spacing) of p = 254 μm = 10 mil, convex-lens radius of curvature R = 145 μm, and total cover thickness h = 205 μm. This design assumes that the gridlines run parallel to the cylinder axes (i.e., into the page in Fig 1b), and that they are aligned with the dark regions underneath the "valleys" in the prismatic-cover structure.

For the experiments described herein, the prismatic covers were made of flexible, optically-clear silicone without anti-reflection coating, and were provided to Spectrolab by M. J. O'Neill. Most of the covers used had 10-mil pitch, although a small number of 5-mil pitch covers were also used. The solar cells were GaInP/Ga(In)As/Ge triple-junction concentrator devices with metal coverage fractions of 3-39%, grid pitch of 5-10 mil (chosen to match the existing prism-cover pitch, rather than to optimize the cell performance), and 1.0 cm^2 aperture area.

The experiments consisted of 1) measuring the illuminated current-voltage (LIV) and external quantum efficiency (EQE) curves of uncovered cells; 2) manually aligning and bonding prismatic covers onto cells with matching grid pitch, using a clear adhesive; and 3) re-measuring the LIV and spectral response performance of the covered cells. As controls, we used both uncovered cells for the purpose of ensuring measurement repeatability, as well as cells with prismatic covers aligned perpendicularly to the gridlines, in order to separate any reflectance glassing gains from the effects due to focusing light away from the metal. Photographs of representatives from the three cell types, taken under a 50X magnification optical microscope, are shown in Fig 2.

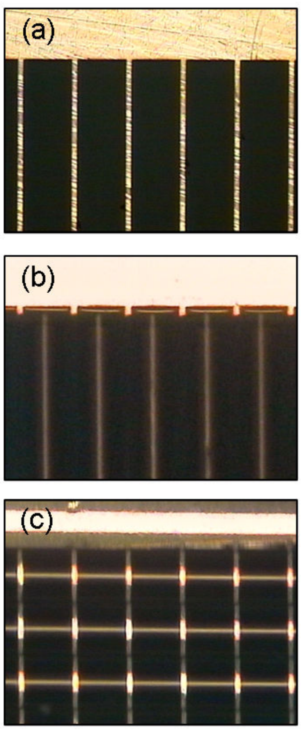

Figure 2. Concentrator cells for prismatic-cover experiments (detail of region near bus-bar): (a) uncovered control cell; (b) cell bonded with parallel-aligned covers; (c) control cell bonded with perpendicularly-aligned covers.

All three panels in Fig. 2 show a cell portion including part of one of the ohmic bus bars running horizontally, and some of the gridlines, which are oriented vertically. The gridlines are clearly visible on the uncovered cell in Fig. 2a. In Fig. 2b the grids are only visible in the immediate vicinity of the bus-bar, after which they disappear under the parallel-aligned prismatic cover, since the viewing light is deflected away from them; also, the imaging light appears focused onto the space midway between the grids. Finally, in Fig. 2c, the gridlines are once again visible, since the perpendicularly-aligned covers only succeed in redistributing the light in a direction orthogonal to the grids. For these photos, all the cells had a 10-mil grid pitch and 25 µm grid width.

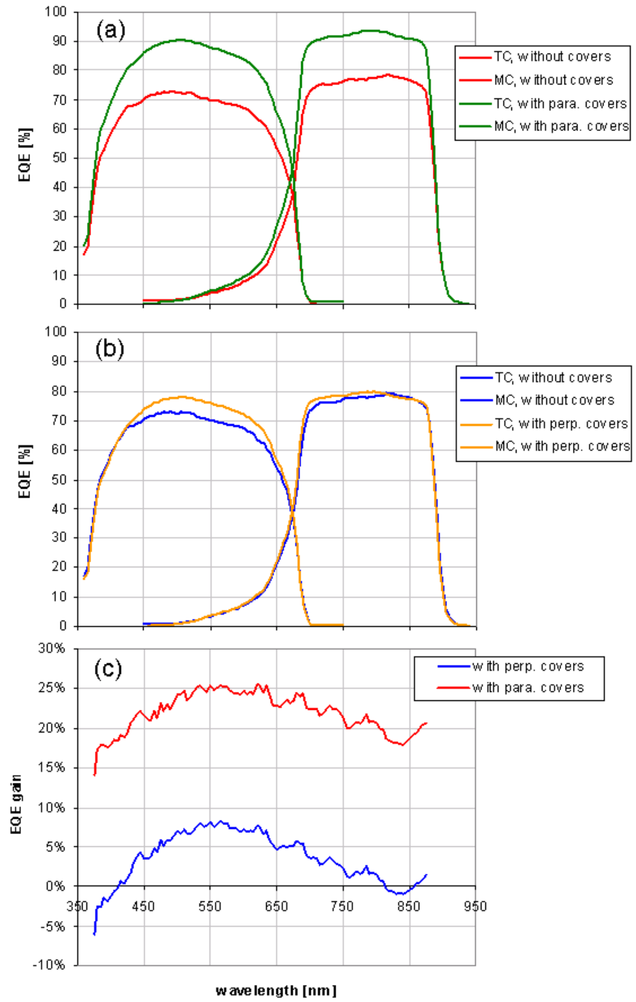

Figure 3. Spectral response of 20%-metal-coverage cells with prism covers aligned (a) parallel; (b) perpendicular to the gridlines; (c) gain in EQE relative to the uncovered-cell case for parallel- and perpendicularly-aligned covers.

SPECTRAL RESPONSE RESULTS

Figure 3 gives a typical example of the behavior we observed in the spectral response measurements done as part of these experiments. Shown are a pair of cells that exhibited nearly identical pre-covering external quantum efficiency (EQE) for the top and middle subcells. Both cells had a grid pitch of 254 µm (10 mil) and a gridline width of 50 µm, i.e. a metal coverage fraction of approximately 20%. One cell was bonded with a prismatic cover aligned parallel to its grids (Fig 3a), whereas the other cell was used as a control, by bonding it with a purposefully-misaligned cover oriented perpendicularly to the cell's grids (Fig 3b).

For the parallel-aligned case of Fig 3a, as expected, the prismatic cover significantly boosts the quantum efficiency across the entire spectrum, however the gain observed is higher in the top cell current density J_{top}, with an increase of +24% relative, than in the middle one J_{mid}, which increased by only +20%. Consequently, whereas before covering (red curve), the multijunction structure was significantly top-cell limited with a J-ratio J_{top}/J_{mid} = 0.94, after covering (green curve) the structure becomes more nearly current-matched with J_{top}/J_{mid} = 0.97.

The observed boost in current generation is a combination of the geometric steering of light away from the gridlines, which should be roughly spectrally flat, and of any reflectance changes, which should be wavelength-dependent and responsible for the increase in the J-ratio. The measurement reproducibility was checked using uncovered control cells (curves not shown), for which the EQE repeatability at each point was found to be within 0.5% relative for the ~375-875 nm spectral region of interest.

For the perpendicularly-aligned case of Fig. 3b, the covers are expected to change the overall reflectance in the same way as the parallel-aligned ones, but without the benefit of the light being steered away from the gridlines; however, some of the light that hits the gridlines may end up back into the cell's active area, by way of total internal reflection off of the prism structure. What we do observe is that once again, the J-ratio increases, from J_{top}/J_{mid} = 0.94 before applying the covers (blue curve) to J_{top}/J_{mid} = 0.98 after (orange curve), due to a J_{top} relative increase of 6%, as opposed to a J_{mid} increase of only 2%.

Figure 3c details the relative EQE gain with respect to the uncovered cells for both the properly aligned prism-covered cells (red curve), and for the perpendicular controls (blue curve). From the comparison, we conclude that, of the total relative increase in generated top-cell current density, the geometric light-steering effect contributes 18%, whereas the reflectance glassing-gain effect contributes 6%. Also, since for these structures the top-subcell current density sets the overall current for the multijunction stack, we will expect the relative LIV I_{sc} gains achieved by way of prism covers (see next section) to closely match the J_{top} relative gains observed via EQE, for both the parallel and the perpendicular-control cases.

Approximately 30 cells, with 10-mil grid pitch and grid coverage fractions of 3%, 10% and 20% were included in the prismatic-cover EQE measurements, with both parallel covers and perpendicular controls. For each grid type, the cell having the best-aligned prismatic cover, as quantified by the increase in the top-subcell current, was singled out for summarizing in Fig. 4a. The spectral response of the top and middle subcells were integrated against the AM1.5D (ASTM G173-03) spectrum, both before and after applying the covers, and the relative change in each subcell is shown as a function of the grid metal coverage fraction. As expected, for both subcells the current boost given by the parallel covers increases linearly with the grid coverage fraction. Interestingly however, even the perpendicular controls have an (albeit weaker) dependence on the grid fraction, which is presumably explained by the above-mentioned reflections from the metal gridlines. Therefore, the perpendicular controls most likely overestimate the contribution to the current boost of the change in reflectance, and lead to an underestimation of the geometric light-steering contribution of the parallel covers. Even so, as plotted in Fig. 4b, for either subcell the extra current boost seen in the parallel-covered cells over the perpendicular-covered ones closely approximates the grid coverage fraction, which means that the grid shadowing effect is almost entirely eliminated.

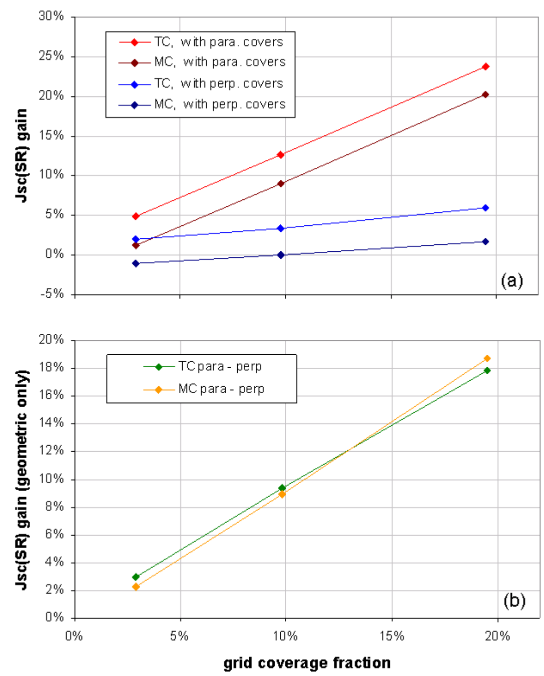

Figure 4. Spectral response gain for 10-mil-pitch covered cells as a function of the grid metal coverage fraction: (a) total gain; (b) geometric light-steering contribution only.

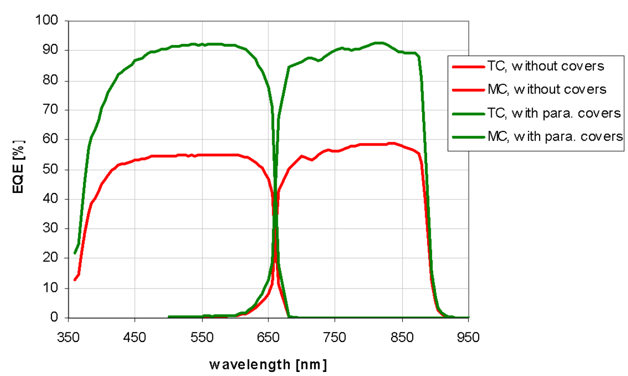

Figure 5. Spectral response boost from prism-covering for a cell grid configuration with 39% metal coverage fraction.

In addition to the 10-mil pitch cells, a small number of 5-mil pitch cells with grid coverage fractions of 6%, 20% and 39% were also included in the EQE measurements. These cells were bonded with parallel-aligned prismatic covers, but no perpendicular controls were created. As an example, in Fig. 5 we show the results for a cell with 39% of its aperture area covered by metal. The striking EQE boost resulting from the application of prism-covers leads once again to an almost-complete cancellation of the top-contact shadowing.

ILLUMINATED CURRENT-VOLTAGE RESULTS

In addition to the spectral response measurements described in the preceding section, we also performed LIV measurements at 1-sun using an XT-10 solar simulator, as well as at 500 suns using a HIPSS (pulsed) simulator, both calibrated to the AM1.5D terrestrial solar spectrum.

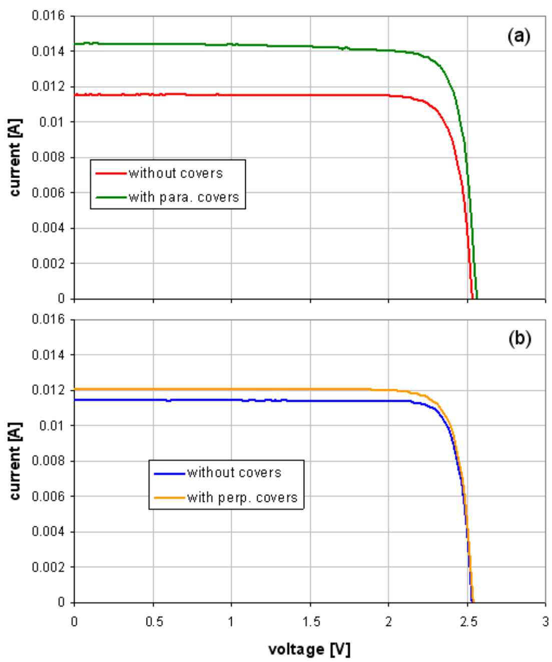

Figure 6. One-sun LIV curves of 20%-grid-coverage cells, with prismatic covers aligned (a) parallel; (b) perpendicular to the gridlines, compared to the uncovered-cell case.

Figures 6 and 7 show a typical example of the LIV measurement results obtained in these experiments, at 1X and 500X respectively. Shown are a pair of cells that exhibited nearly identical pre-covering short-circuit currents Isc. Both cells had a 10-mil grid pitch and metal coverage fraction of approximately 20%, same as in Fig. 3. One cell was bonded with a prismatic cover aligned parallel to its grids (curves shown in Figs. 6a and 7a), whereas the other cell was used as a perpendicular control (curves shown in Figs. 6b and 7b).

In Figs. 6a and 7a, we note the significant short-circuit current improvement observed in the cells bonded with parallel covers (green curves) as compared to before covering (red curves), consisting of an I_{sc} boost of 26% at 1-sun and 24% at 500 suns. The fill factor experienced a decrease of 1% at 1X and of 3% under concentration, resulting in an overall relative efficiency boost of 24% and 21% respectively. For comparison, the uncovered controls (curves not shown) tested at the same time for the purpose of quantifying the measurement reproducibility error registered relative changes in efficiency of -0.2% at one-sun, and -0.9% under concentration.

In Figs 6b and 7b, we show the LIV curves for the control cells bonded with perpendicularly-aligned prismatic covers. As compared to the results obtained prior to the application of the covers (blue curves), the perpendicularly-aligned cells (orange curves) experienced a relative current boost of 6% both at 1-sun and at concentration, and fill factor drops of 2% at 1-sun, and 1% at concentration. The resulting control-cell overall relative efficiency boost was 4% at 1X and 5% at 500X.

Based on the comparison of the parallel and perpendicular case, we conclude that the short-circuit current gain in LIV due to the prismatic-cover light steering effect only, separate from the reflectance effects, is 20% at one-sun, and 18% at 500 suns.

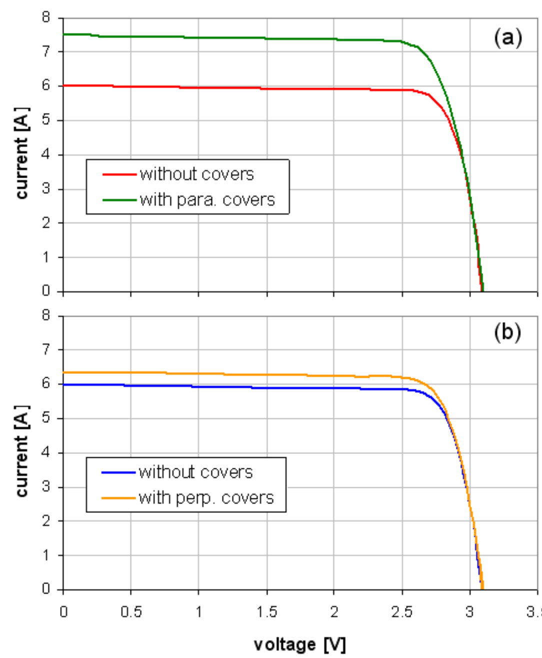

Figure 7. Concentrated LIV measurements at 500-suns, taken on cells with 20%-grid-coverage, and with prismatic covers aligned (a) parallel; (b) perpendicular to the gridlines, compared to the uncovered-cell case.

Figure 8 summarizes the effect of the grid coverage fraction on the current boost at 1X and at 500X, for the 10-mil-pitch cells used in the LIV measurements. As expected, due to the linearity of the solar cell response with the incident power density, the relative increases in current at the two concentrations are very similar, both for the parallel-aligned cells and for the perpendicular controls. Also, as predicted in the previous section, we see Isc relative increase values which closely match those measured via EQE for the current-limiting top-subcell current density, for each cell grid type. In other words, we have excellent quantitative agreement, within the measurement uncertainty, between the current-boost predictions made using the spectral response measurements in the previous section (Fig 4a), on the one hand, and the LIV results in the current section (Fig 8), on the other. We can once again calculate the contribution of geometric light steering by the prismatic covers, separated from the reflectance contribution, as the difference in short-circuit gain between the parallel- and the perpendicular-covered cells; we find that the gain due to the geometric effect only closely approximates the grid coverage fraction, meaning that the top-metal shadowing effect is almost entirely eliminated by the prismatic covers.

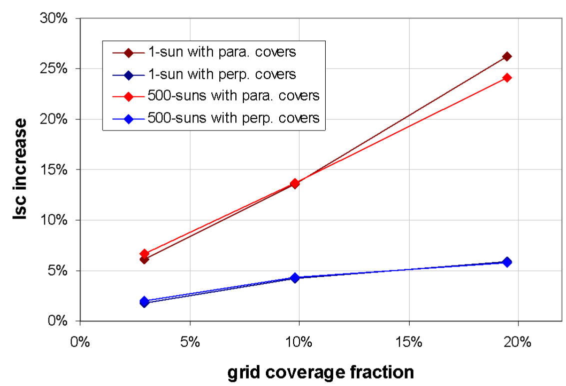

Figure 8. Short-circuit current gains due to the application of prismatic covers, at 1X and at 500X concentration, as a function of the grid-metal coverage fraction.

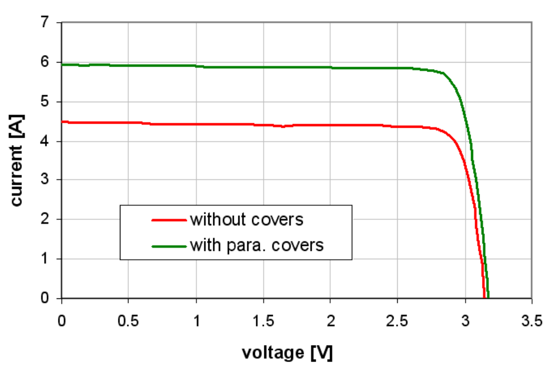

Figure 9. Concentrated HIPSS-LIV measurements at 500-suns of a cell with 39%-grid coverage, before and after applying the prismatic covers.

We also did HIPSS-LIV measurements on the small number of cells with 5-mil pitch and 50 μm wide gridlines, of the type illustrated in Fig. 5. One example of LIV at 500X on such a cell, having a grid coverage fraction of 39%, is shown in Fig. 9. Compared to before bonding it with a prismatic cover, this cell shows an Isc increase of 33%, 0.0% change in FF, and a resulting overall boost in efficiency of 34%. Although this performance gain is very significant, it is still less than that obtained in EQE (see Fig. 5), presumably due to the smaller surface area being measured in SR versus LIV. Therefore, further experiments on the 5-mil pitch covers should focus on improving their alignment and bonding uniformity to the solar cells.

ANGULAR DEPENDENCE RESULTS

One important consideration in investigating the viability of any prismatic cover design is its tolerance to alignment errors. For example, in the cylindrical-lens design we have been focusing on so far, the gridlines need to be aligned within the dark regions underneath the valleys in the prismatic pattern. The width of each of these dark regions therefore sets the lateral alignment tolerance for the grid lines, and it typically depends strongly on the light angle of incidence onto the cell (denoted by α in Fig. 1), which is in turn dictated by the overall concentrator system design.

We have performed Zemax ray-tracing simulations on this and other prismatic-cover designs in order to study their alignment tolerance as a function of the maximum angle of incidence. In Fig. 10a, we show the result of one such simulation for 10 mil pitch, and find that this particular design will work well in systems with maximum angles of incidence onto the solar cell up to α ≈ 50°.

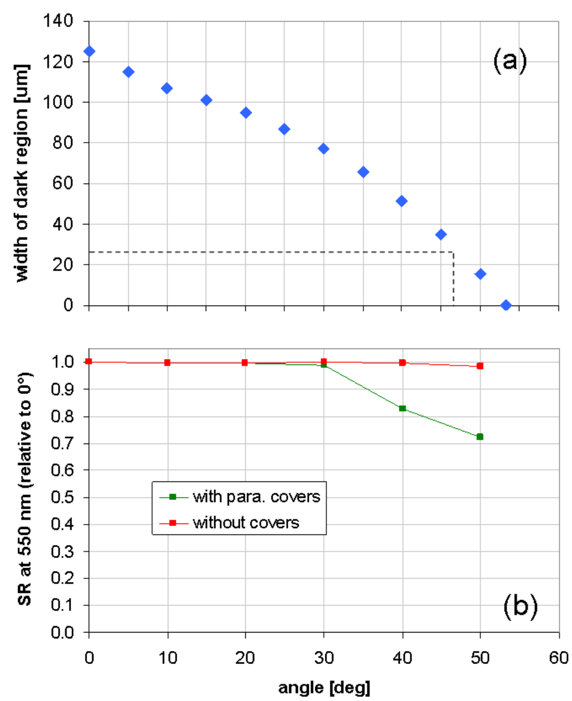

Figure 10. Dependence on incidence angle: (a) simulation of lateral alignment tolerance; (b) measurement results of spectral response at 550 nm.

In particular, we find that, in order for the dark region to accommodate a gridline with a width of 25 μm without any shadowing losses, the angle of incidence needs to be kept ≤47°, as indicated by the dashed lines in Fig. 10a. In other words, in the case of a perfectly aligned cover, we would expect the performance of such a cell to start deviating from that of an uncovered cell at $\alpha \approx 47°$. As a preliminary verification of this prediction, we have performed spectral response measurements under monochromatic illumination at 550 nm. The measurements were done on a prism-covered cell with 10-mil pitch, 25 μm grid width, and 10% grid coverage fraction, as well as on an uncovered control cell. Note that in these measurements the beam is always entirely confined within the cell aperture area regardless of the angle of incidence, so no significant $\cos(\alpha)$ dependence is expected or observed. The measured generated current, as a function of the angle of incidence, relative to its value at normal incidence, is plotted in Fig. 10b. We see that the covered-cell performance starts deviating significantly from that of the uncovered control at around 40°, which is in reasonable agreement with our prediction.

CONCLUSIONS

Although these initial results are very encouraging, additional studies are needed in order to demonstrate the full potential offered by prismatic covers. Aside from furthering the measurements described herein, future work should include performing the degradation analysis on the prism cover and its bond to the cell under long-term exposure to high-concentration sunlight and other environmental factors; investigating the feasibility of automated micro-patterned cover manufacturing and alignment; and experimenting with and system-optimizing a variety of cover designs, coatings, and materials.

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