Optical Losses and Durability of 4-Domed Optic for Concentrator Photovoltaics

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Abstract
The use of optical elements to focus light onto a smaller area of semiconductor material can enhance the cost effectiveness and electrical performance. Enabling ultrahigh concentration ratios for photovoltaic systems requires an optic bonded directly to the solar cell to further concentrate and homogenise the illumination, as well as to improve the acceptance angle. For many optical materials manufacture flaws are common, and difficult to prevent. An estimation of the effective external quantum efficiency of the receiver based on the material's transmissivity tells us the effect of added absorptivity from manufacture defects. Evaluating the module under a solar simulator under various angles yields information on how scattered light changes the optic's concentration ability. This study suggests sapphire has higher optical losses due to its higher refractive index compared to slygard-184. Thus, the need for a higher refractive index material must be considered carefully and matched with anti-reflective coatings if needed. The effective concentration of slygard-184 notably suffers when flaws are present, dropping up to 48.2%. Further, the optimum angle is difficult to predict. Minor flaws could be deemed acceptable in performance when high acceptance angles are not the primary design requirement.

1. Introduction
Focusing sunlight onto small receiver areas using relatively cheap optics is a cost-efficient way of deploying high quality multijunction solar cells. To reliably reach concentration ratios higher than 1500 suns, multi-staged optics are needed. In order to achieve these ultrahigh irradiance concentrations, secondary optics bonded directly to the solar cell are becoming a more common choice [1]. The use of optics bonded to the cell allows for an increased irradiance uniformity over the surface of the cell, a superior acceptance angle of illumination and an added concentrating effect. The drawback of this approach is the added optical losses through the material and difficulty of manufacture for the highly specific geometries used. Optical materials such as slygard-184 can easily produce bubbles during production which obscure the light's pathway through the optic. Other materials, such as higher refractive index sapphire, are more difficult to manufacture and are more fragile in comparison but can achieve higher concentrations due to its refractive index. This article aims to investigate the optical efficiency and power output of a 4-domed optic bonded to a 5.5 mm^2 multijunction solar cell as in [2–4]. By using different materials and featuring manufacture flaws, the ergonomic choice of optical material may be determined. Thus, confirming if the flawed optics could be deemed relatively well functioning, and if the more difficult manufacture process of other materials is worthwhile. Due to the geometry of this optic, the angle of incident irradiance can have a substantial effect on the focal spot of the optic, as can be seen in Figure 1(A and B). In some cases, this can direct light away from the solar cell. Consequently, the transmissivity and electrical performance at incident angles between 0° and 50° are investigated. This shall be an important consideration for when this optic is acting as a secondary optical element for an ultrahigh concentration photovoltaic system. This aspect shall be investigated further in the future, when the 4-domed optic shall be integrated and aligned with a Fresnel lens as a primary optic.

2. Experimental Approach
Optical and electrical characterisations of various flawed and unflawed samples were conducted. It is preferred for cells to be attached to the slygard during manufacture, so different sections use different samples with similar defects, photographs of the samples are shown in each section. The optical characterisation was conducted with a PerkinElmer spectrophotometer, evaluating transmissivity and reflectivity throughout the wavelength range 200 – 2000 nm. The samples used in the optical characterisation are flawless (no

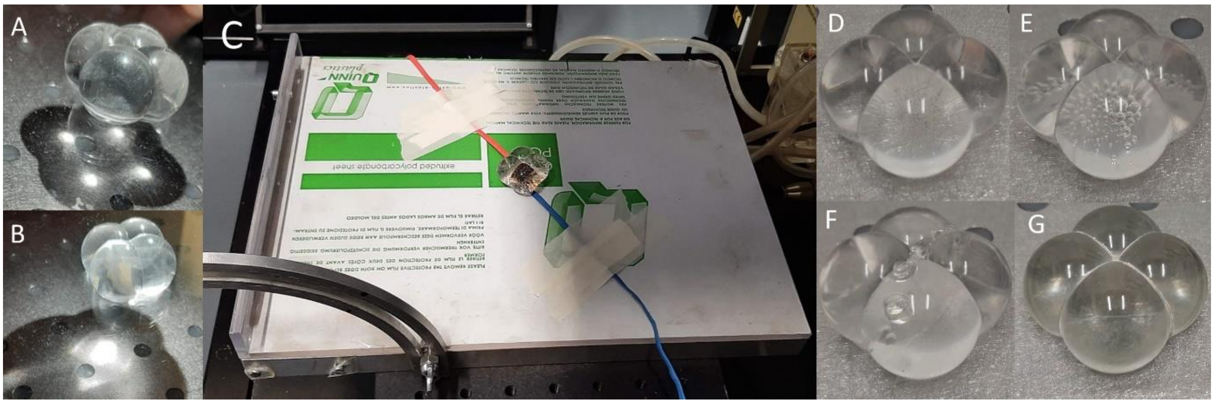

Figure 1 (A) Focal spot under direct illumination (B) Focal spot under angled illumination (C) 4-domed optic attached to cell on angular test apparatus (D) Flawless Slygard-184 optic (E) Bubbled Slygard-184 optic (F) Split Slygard-184 optic (G) Sapphire optic

bubbles/visible damages) slygard-184, slygard-184 with bubbles, slygard-184 which was split and glued back together, and a sapphire optic Figure 1(D-G). The samples are evaluated at various angles up to 50° with a step of 5°. The electrical characterisation of the photovoltaic (PV) cells was performed by exposing them under a solar simulator (WACOM) set to 1000 W/m^2. The optics in this case are bonded to a 5.5 mm^2 Azur Space multijunction solar cell [5]. The angle evaluation varies in steps of 5°, until the optimum angle is nearby, where the step changes for added accuracy, down to a minimum step of 1°. The angle is controlled using a custom mount shown in Figure 1(C). While slygard-184 is a common encapsulant material and can be bonded to the solar cell directly [6], the sapphire optic requires a separate encapsulant and so limits its analysis as described later. Neither optic is designed as a standalone concentrator but instead as a secondary optic to homogenise the irradiance distribution over the PV cell. As the sapphire was the lowest performing sample of optical characterisation, it was omitted from further testing.

3. Results and Discussions

3.1 Optical Characterisation

Using measurements of the transmittance (*%T*) at each angle over the cell's recommended wavelength range and the rated spectral response data of the solar cell, an estimation for the specific external quantum efficiency (EQE) of each optic-cell module can be found. Where:

$$EQE_{Specific} = EQE_{Cell} \times \%T \qquad (1)$$

The true specific EQE value will be different. This is due to the exiting of the transmissivity measurement being incomplete as the light must exit from a high refractive index to a low refractive index. Figure 2(A-C) show the optics' transmissivities, the EQE of the bare solar cell, and the modules' specific EQE. The bubbled slygard-184 surprisingly showed the highest average transmissivity value. However, the highest average specific EQE value was found in the flawless sample, ~1.5% higher than the bubbled sample. This suggests less light was lost in the bubbled optic overall, but more of the light with beneficial spectral response from the cell was absorbed or reflected, making it a worse choice for this application. The split slygard-184 showed similar performance to the bubbled optic. Notably the sapphire optic showed the worst performance by a wider margin, 6.5% lower than the flawless slygard-184 at each's optimum angle. This is likely caused by the added reflectivity upon entry and exit of the optic, due to the higher refractive index, as well as the higher absorptivity of the material. All slygard-184 samples have their optimum angle between 25° and 35°, The sapphire optic's optimum angle is found between 10° and 20° (Figure 2(D)).

3.2 Electrical Characterisation

While this optic is to be a secondary optic to multiple Fresnel lenses, only one section is illuminated in this characterisation rather than all 4. Given that the concentration ratio is generally low, and the exposure times are short, temperature is not expected to substantially effect the electrical efficiency of the solar cells. The 4 samples characterised are similar to the sylard-184 samples in the optical characterisation. These samples are flawless, lightly bubbled, heavily bubbled, and split (Figure 3(A-D)). The best representation of the effective concentration (C_{eff}) is in the short circuit current (*Isc*) where:

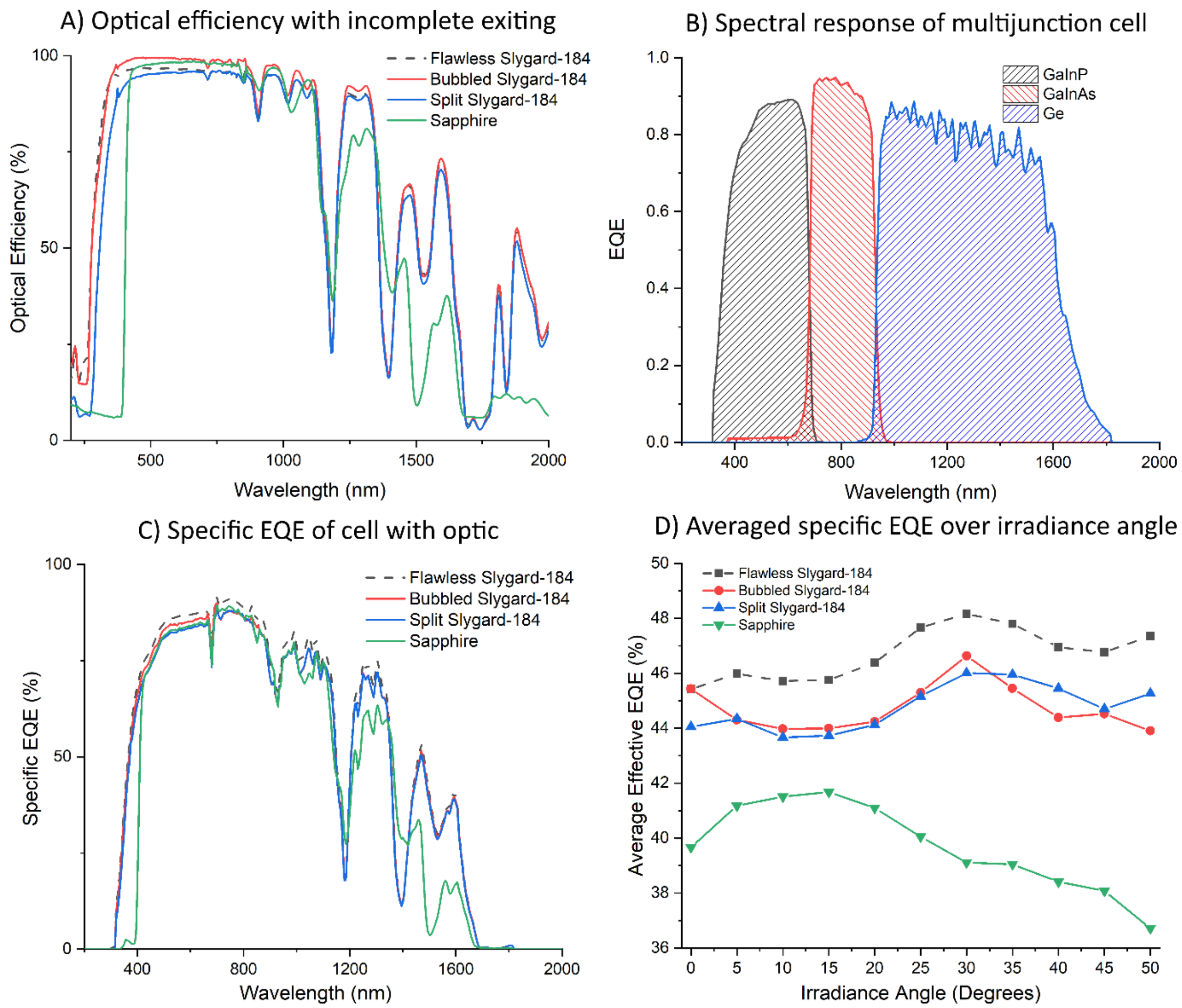

Figure 2 (A) Optical efficiency of each sample across wavelength (B) EQE of solar cell [5] (C) Optimum specific EQE of each sample (D) Average specific EQE of samples across irradiance angle

$$C_{eff} = {}^{Isc_{Module}}/_{Isc_{Bare\ cell}} \quad (2)$$

Optimum current-voltage and power-voltage curves of all samples at the respective optimum angles are shown in Figure 3(E). Fewer visible defects result in a higher generation of power at the optic's optimum angle. Optics with flaws have higher minimum power values as some of the light that is scattered reaches the cell, but at the optimum angle, this scatter directs light away from the cell. This is seen in the split sample, where the peak C_{eff} is 48.2% lower than the flawless sample but is higher at 0° (Figure 3(F)). An added benefit of the flawless slygard-184 is shown in the relatively stable range (38-44°) where a near peak C_{eff} is maintained (Figure 3(F)). Notably, even small defects result in different optimum angles. This means any optic with an observable defect would require a dedicated angular investigation.

4. Conclusions

The optical and electrical characterisations of flawed 4-domed optics have been conducted to evaluate performance as a secondary optical element for CPV systems. Regarding transmissivity, minor flaws bring down the optical efficiency, but not necessarily to the extent that necessitates disposal. The lightly bubbled slygard-184 sample reduced the effective concentration by <17%. It is difficult to estimate the effect on power generation from visual inspection alone. Similar looking flaws can produce significantly different optimum angles. Consequently, a dedicated angular test is recommended if any flaws are present. The scattering of light rays which is generated by these defects also leads to a lower range of irradiance angles which yield high C_{eff} values. If the primary requirement of this optic is to enable higher acceptance angles, flawless samples are required.

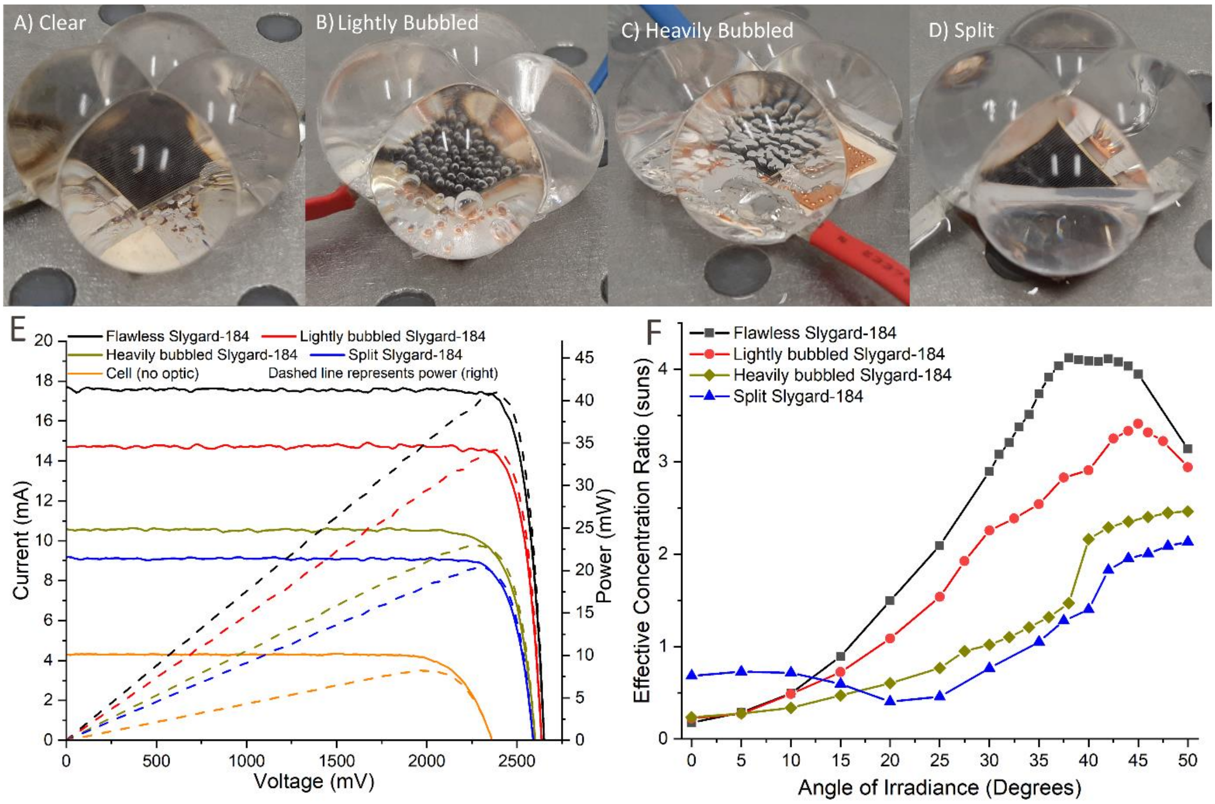

Figure 3 (A) Flawless slygard-184 optic (B) Lightly bubbled slygard-184 optic (C) Heavily bubbled slygard-184 optic (D) Split slygard-184 optic (E) Current-Voltage and Power-Voltage curves of Slygard-184 modules and bare cell (F) Effective concentration of optic over angle of irradiance.

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