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Flexible silicon solar cells

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ABSTRACT

In order to be useful for certain niche applications, crystalline silicon solar cells must be able to sustain either one-time flexure or multiple non-critical flexures without significant loss of strength or efficiency. This paper describes experimental characterisation of the behaviour of thin crystalline silicon solar cells, under either static or repeated flexure, by flexing samples and recording any resulting changes in performance. Thin SLIVER cells were used for the experiment. Mechanical strength was found to be unaffected after 100,000 flexures. Solar conversion efficiency remained at greater than 95% of the initial value after 100,000 flexures. Prolonged one-time flexure close to, but not below, the fracture radius resulted in no significant change of properties. For every sample, fracture occurred either on the first flexure to a given radius of curvature, or not at all when using that radius. In summary, for a given radius of curvature, either the flexed solar cells broke immediately, or they were essentially unaffected by prolonged or multiple flexing.

1. Introduction

Certain niche photovoltaic (PV) products require one-time or multiple flexure of solar cells. Examples of one-time flexure products that require the mounting of solar cells on curved substrates include curved PV modules in architectural applications, battery charging micro panels for rigid hand-held consumer electronic devices such as mobile phones and MP3 players, and unmanned solar-powered aeroplanes. Examples of products that require multiple flexures of solar cells include roll-up panels for remote power and wearable solar panels.

Single or large-grained multi crystalline silicon is the dominant photovoltaic material for several reasons, including the abundance and non-toxicity of silicon, the high and stable cell efficiencies achievable with silicon, and the ability to share research, skills, materials and infrastructure with the electronics industry.

Crystalline silicon wafers are usually brittle, but become flexible when sufficiently thin. Conventional silicon solar cells have thickness in the range 200 μm, which is too thick to be flexible. Niche applications for flexible solar cells are currently serviced with non-conventional cell types, such as cells fabricated using amorphous silicon or other thin film materials deposited on flexible substrates.

Very thin crystalline silicon solar cells can be created by a variety of means, but currently do not have a significant mainstream market share. Flexible thin single crystalline silicon solar cells could have a large performance advantage over similarly flexible thin film cells. However, the effect of flexing thin single crystalline silicon solar cells needs to be determined. The radius of curvature at which the cells fracture needs to be known, as well as the effect of multiple flexing of cells to a radius of curvature a little larger than the fracture radius. This paper describes the mechanical and electrical effect of multiple flexures upon efficient single crystalline silicon solar cells of varying thicknesses.

The particular design of cells used in the study was the SLIVER solar cell [1]. However, the results are expected to be generally applicable. SLIVER cells are long (50–100 mm), narrow (0.5–1.5 mm) and thin (20–50 μm), and are fabricated from single crystalline silicon. Efficiencies of up to 20% have been achieved with this design [2], although the efficiency of the simplified cells used in the study averaged 15%. A strong cost driver for SLIVER cells is the pitch of the grooves located between each cell. If this pitch is halved, then the yield of cells per wafer is doubled and the silicon consumption is approximately halved, but without a significant increase in processing cost. An additional benefit is that the thickness of each cell declines, resulting in an increase in flexibility.

2. Mechanical stress

The manner in which silicon fails under tensile loading is brittle fracture, rather than plastic deformation which is the most common failure mode for most metals and plastics. The internal stress of curvature is the stress at which a crystal undergoes

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irreversible plastic deformation. The minimum survivable radius of curvature ρ for a curved piece of silicon means the radius of curvature that will cause the silicon to fracture

$$\rho = E^* x/\sigma \tag{1}$$

Here E is the modulus of elasticity (~168 GPa, [3]), x is the half-thickness of the piece of silicon and σ is the tensile yield strength (~7.0 GPa, [4]).

In a practical material, the minimum survivable radius of curvature is considerably larger than the theoretical limit. Of the factors limiting the minimum fracture radius, the presence of stress concentrations is the most significant. The anisotropic etching process used in the experimental samples is rarely perfect and often introduces some potential fracture-forming points. Silicon wafers in the IC industry usually have edge contouring applied in order to reduce the potential for slip lines and other flaws to occur at the edges. SLIVER cells, being thin and narrow, have long edges relative to the volume of material used. These long edges can potentially provide opportunities for cracks, slip lines and other defects to form during processing or handling. Furthermore, high-temperature treatments can create internal stresses within the silicon, which also work to reduce material strength. Each defect creates a weakness which significantly reduces the tensile yield stress of the bulk material.

It is possible that repeated flexing of thin silicon solar cells could eventually lead to changes in stress-related defects causing degradation in electrical performance or an increase in the minimum survivable radius of curvature. Alternatively, permanently mounting a cell with a radius of curvature close to the minimum survivable radius of curvature could lead to slow degradation.

3. Single flexure and fracture

The minimum survivable radius of curvature of our samples was determined by bending slices of silicon around cylindrical moulds with a range of different thicknesses until fracture occurred. Samples were bent around cylindrical moulds of decreasing radius until fracture. Twenty samples of each thickness were used. The results are presented in Fig. 1.

The cells tested in this section were "dummy" SLIVER cells, identical in dimensions to real cells but without post-etching treatment. They do not function as solar cells, but their mechanical properties are similar to completed solar cells. For this experiment, all samples had the same width (1 mm) and length (50 mm), but five different thicknesses were used: 120, 100, 77, 53 and 33 μm.

Since the usual failure mode of silicon is brittle fracture which is dependent on the size and placement of random defects, we would expect a degree of variability in individual sample fracture radii. The collected data shows a correlation coefficient of 0.89, indicating a likelihood that the relationship between fracture radius and SLIVER thickness is linear, as predicted by theory. The accuracy of measurement of the diameter of the cylindrical moulds is 1–2 mm, which introduces only minor uncertainty relative to other factors.

The least-squares regression line crosses the y-axis at −2.9, which is close to the expected value of 0.0 from the mechanical theory.

4. Multi-flexure

The previous tests showed an approximately linear relationship between sample thickness and the radius of curvature at fracture. The next step was to determine whether the ultimate strength of the samples is affected by repeated flexures. This experiment determined firstly whether the strength of the samples is affected by repeated bending and secondly whether the linear relationship is preserved.

Each sample was subjected to 1000 flexures at each of numerous decreasing flexure radii until all samples had broken. A total of ten samples of each thickness were tested. Starting with a radius of curvature well clear of the likely fracture radius, each sample set was flexed around a cylindrical mould of a given radius 1000 times, and then the experiment was repeated for a radius of curvature that was 2 mm smaller, and so on until no samples survived.

It was observed that all breakages occurred on the first of the 1000 flexures. This is evidence that repeated flexure does not lower the yield strength of the sample. Fig. 2 shows the fracture radius of curvature as a function of sample thickness. Fig. 3 is a comparison of the lines of best fit from Figs. 1 and 2 (least squares regression) together with mean values.

In order to test whether a large number of flexures eventually weakens samples, ten samples of 33 μm thickness and another set of ten samples of 53 μm thicknesses were exposed to 100,000

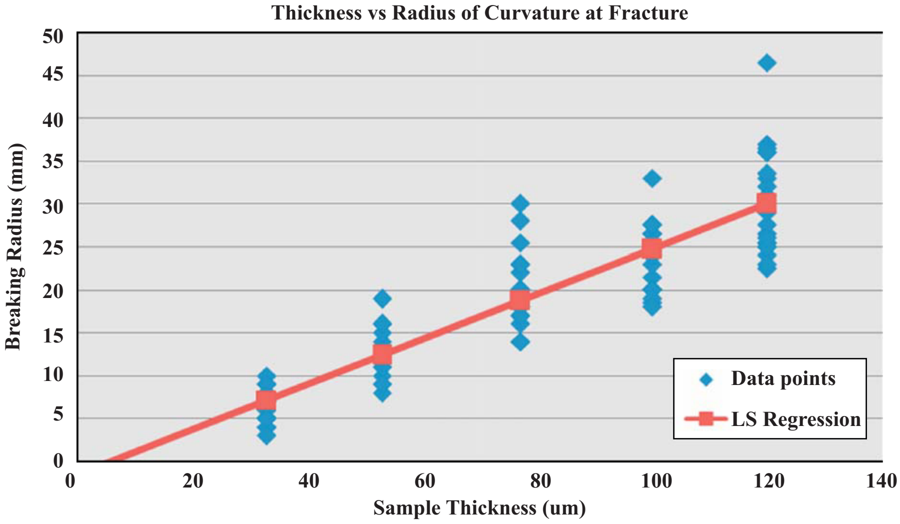

Fig. 1. Thickness vs. radius of curvature at fracture.

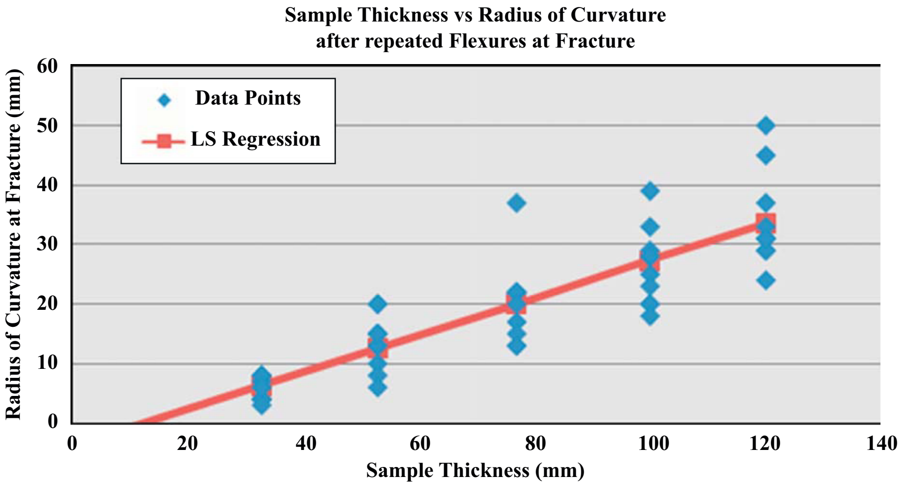

Fig. 2. Sample thickness vs. radius of curvature at fracture after repeated flexures.

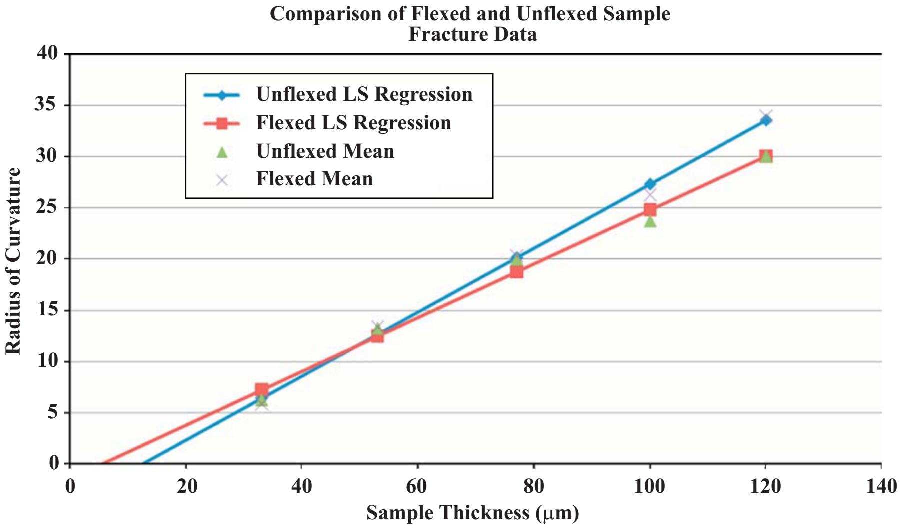

Fig. 3. Comparison of flexed and unflexed fracture data.

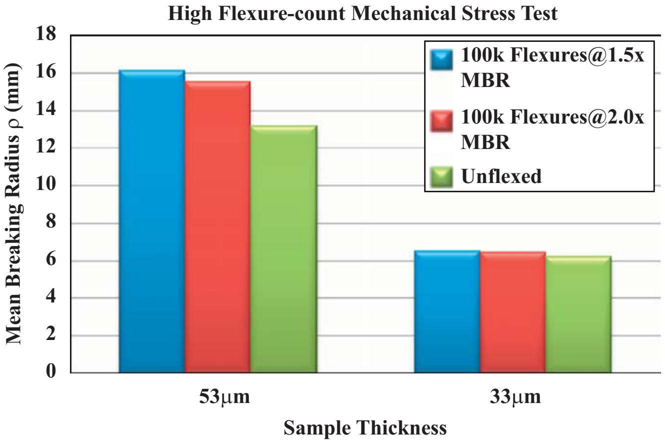

Fig. 4. High flexure-count mechanical stress test showing only a small effect upon fracture radius resulting from 100,000 flexures. MBR refers to the previously determined mean breaking radius.

flexures at a fixed radius of curvature. The radius of curvature was determined from previous data to be twice the mean breaking radius for the specified thickness of the sample in question. In the case of the 33-mm-thick samples, this was 18 mm, whilst for the 55-μm-thick samples the radius of curvature was 30 mm. Following the flexures, the samples were tested for their fracture radius using the same procedure described above. These tests were then repeated for a fresh set of samples, but this time with the radius of curvature chosen as a more aggressive 1.5 times the average breaking radius for the specified thickness. As shown in Fig. 4, there is no substantial difference resulting from 100,000 flexures of a 33-μm-thick sample compared with a single flexure, and only a small difference in the case of a 53 μm thick sample.

5. Multi-flexure cell efficiency test

There is little evidence that multiple flexure seriously affects the minimum survivable radius of curvature of a sample. The next step was to determine whether solar cell performance is affected by multiple flexure. The thickness of the cells used in the test was 66 μm. Three different values of radius of curvature were tested, corresponding to 1.25 × , 1.5 × and 2.0 × the mean breaking radii calculated from the previous work; 20, 25 and 33 mm, respectively. Measurements of cell performance were made after nil, 1000, 10,000 and 100,000 flexures. Results are presented in Fig. 5.

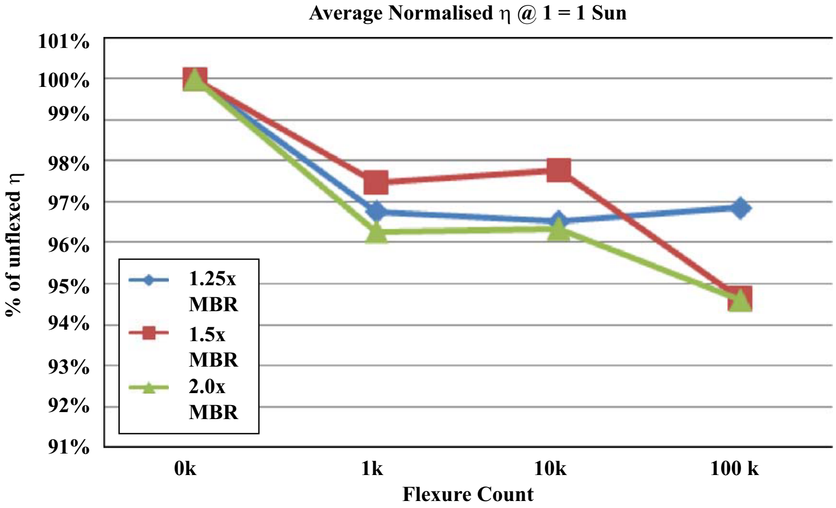

Fig. 5. Average normalised efficiency after multiple flexures.

The relative measurement uncertainty is estimated to be ±1% based upon repeated testing of the same cells.

There is a small but noticeable decrease in efficiency with respect to initial values in all cases, but the magnitude of decrease is inconsistent across different flexure counts and bending radii of curvature. There was almost no change in open circuit voltage, a small change in fill factor and a larger change in short circuit current.

It is possible that repeated flexure around the cylindrical moulds introduced slight scuffing or soiling of the surface of the cells, leading to a small decrease in optical absorption. This was studied by taking advantage of the fact that SLIVER cells are perfectly bifacial. Groups of cells were measured from both sides before and after flexure. The efficiency was the same (to within 1% relative) when measured from either surface. Since both surfaces are contacted during the flexing process, this does not exclude the possibility of surface damage. The cell performance is known to be stable over the time scale of these tests, and so degradation due to ageing could be excluded.

6. Static test

In addition to the multiple-bend tests, another set of samples was bent to a specified radius a single time and left for approximately one week to determine what effect, if any, one-time flexure has on cell performance. When 66-μm-thick cells were bent around a 33 mm radius of curvature mould, the relative change in performance after one week was less than 3%.

7. Conclusion

Compared with conventional solar cells, thin silicon solar cells exhibit mechanical flexibility due to their relative thinness. The mechanical strength of thin SLIVER solar cells was found to be largely unaffected by repeated non-destructive bending, indicating that their behaviour is essentially elastic. In every case it was found that cells either break on the first flexure to a given radius of curvature, or will not break even after 100,000 additional flexures to the same radius of curvature.

The range of fracture radii demonstrated for the samples is probably the result of defects randomly introduced in the etching process or during handling, but further research is needed to pinpoint the exact cause.

The electrical performance of SLIVERS is slightly affected by repeated flexure. The degradation is primarily in the current, and could be due to slight soiling or scuffing of the surface.

Cells can also be mounted on a curved surface for an extended period of time without significant loss of performance.

Acknowledgement

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