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BP solar thin film CdTe photovoltaic technology

A.K. Turner *, J.M. Woodcock, M.E. Özsan, D.W. Cunningham, D.R. Johnson, R.J. Marshall, N.B. Mason, S. Oktik, M.H. Patterson, S.J. Ransome, S. Roberts, M. Sadeghi, J.M. Sherborne, D. Sivapathasundaram, I.A. Walls

BP Solar, Unit 12, Brooklands Close, Sunbury-on-Thames, Middlesex TW16 7DX, UK

Abstract

The paper describes the progress and current status of BP Solar's programme on Apollo [1] thin film CdTe modules. It covers the latest improvements in process yield and module reliability, and discusses recent results from investigations of the semiconductor material properties. Results show that more than 90% of the solar cells are produced with efficiencies above 8% on 300 mm × 300 mm low cost substrates where the tin oxide has been deposited on the float glass line. In addition to the single plate modules, multiplate modules incorporating six plates in a 3 × 2 format under a monolithic front glass sheet have been fabricated with aperture area efficiencies up to 7.8%. The reliability of module performance has been assessed using environmental tests based on the CEC Specification 701 for thin film modules. The efficiency stability of the modules is measured outdoors in Spain by automatic monitoring of current–voltage characteristics and indoors with an accelerated test. Results of both tests show stable module efficiencies above 8.0%.

1. Introduction

A heterojunction of n-CdS/p-CdTe on tin oxide coated glass forms the basis of the Apollo photovoltaic cell. The CdS (< 0.2 μm) is deposited by chemical bath deposition and the CdTe (< 2.0 μm) by electrodeposition [1]. The interconnect technology uses laser scribing with a 1.06 μm Nd-Yag laser throughout the process, including the isolation of the back contact. This has enabled the inactive

* Corresponding author.

[1] Apollo is a trade mark of the British Petroleum Company plc.

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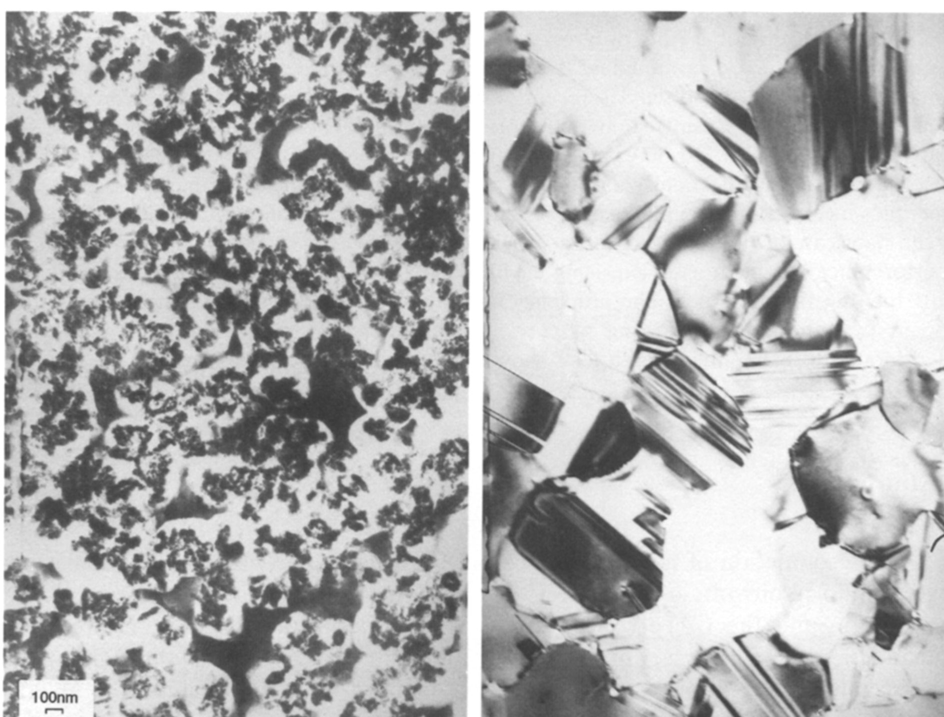
area between interconnected cells to be maintained routinely at less than 6% of the total area; currently the average inactive width between cells is 450 ± 50 μm.

2. Material properties

The as-grown CdTe is n-type and converted to p-type by an anneal in air at temperatures between 400 and 500°C for 15 min. We have previously reported [2] that the efficiency of the final cells, and the open-circuit voltages, are not sensitive to the anneal temperature in this range. Above the 400°C threshold for the onset of efficient photovoltaic response, significant changes in grain size of the CdTe film are observed with high resolution TEM. Fig. 1a shows the film before heat treatment and Fig. 1b after the film has been rinsed in de-ionized water and then annealed at 450°C in air; there have been no other process steps. The as-grown film appears speckled in the electron microscope with an estimated grain size of approximately 0.1 μm (Fig. 1a); the annealed film shows clear contrast within grains which are about 1.0 μm size (Fig. 1b).



(a) (b)

Fig. 1. Transmission electron micrographs, at the same magnification of a CdTe film: (a) before anneal, and (b) after 450°C anneal in air.

3. Cell performance

Efficiencies are measured with a Spire solar simulator calibrated against reference CdTe modules measured at the Fraunhofer Institute in Freiburg. The stability of the module efficiency is measured externally, in Spain [2], and internally using an accelerated test.

3.1. Efficiency

Fig. 2 shows the illuminated current voltage characteristics at 25°C obtained at the Fraunhofer Institute from a typical small 12 cell, 100 mm × 100 mm CdTe module; at the moment this is the maximum size that the Institute can calibrate accurately, i.e. within ±3% for CdTe. The illumination was AM 1.5 global at 100 mW/cm^2 intensity. The aperture area efficiency was 9.4% which corresponds to an active area efficiency of 10.0%. Aperture area efficiencies of more than 10% have been reported previously [2] for cells of 706 cm^2 aperture area. More recently best aperture area efficiencies of 10% for cells of this size (Fig. 3) have been confirmed using the smaller modules measured at the Fraunhofer Institute as secondary references. The cell of Fig. 3 had the highest fill factor we have measured for a cell of this size, 0.69.

3.2. Process yield

As with many other thin film technologies, commercially available tin oxide coated glass is used as the substrate. However, unlike some technologies, the final cell efficiency is not very sensitive to the exact nature of the tin oxide coated glass. This has enabled a transfer of the technology, without any loss in cell efficiency,

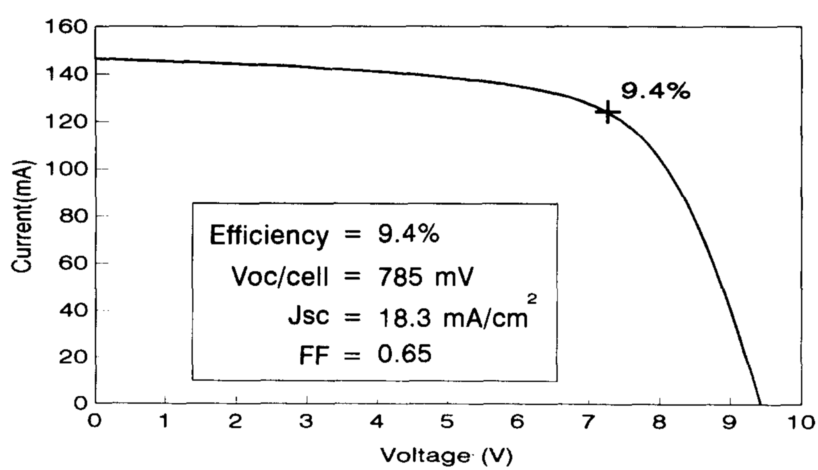


Fig. 2. Illuminated current–voltage characteristic of a twelve cell module (100 mm × 100 mm) measured at the Fraunhofer Institute using 100 mW/cm^2 AM 1.5 global at 25°C.

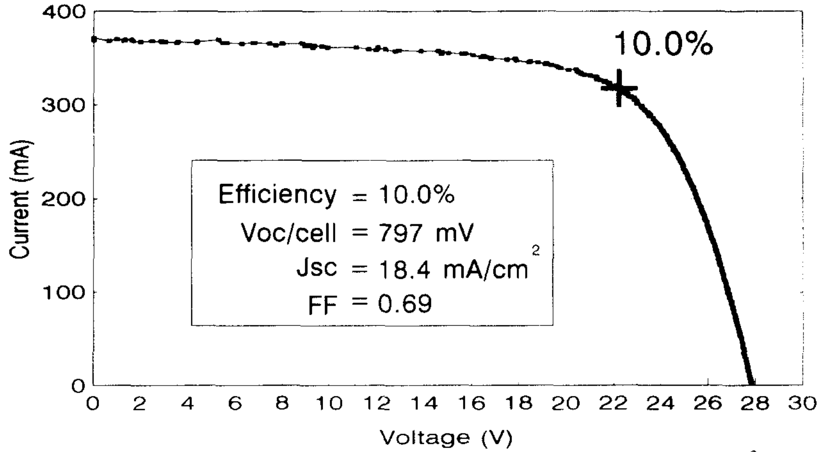


Fig. 3. Illuminated current-voltage characteristic of CdTe cell of aperture area 706 cm^2 (100 mW/cm^2 AM1.5 global, at 25°C).

from a relatively expensive substrate, on which tin oxide is deposited off the float glass line, to a cheaper substrate which is coated on the float line. Efficiency distributions are compared in Fig. 4; each with more than 130 plates of aperture area 706 cm^2. The figure shows little difference in either the efficiency distributions or the mean efficiencies, which were $8.3 \pm 0.8\%$ for the more expensive substrate and $8.3 \pm 0.6\%$ for the less expensive one. In both cases, different device fabrication processes were being assessed using some experimental processes. More recently, using the cheaper glass, and operating a single process on 100 plates a mean efficiency of $8.7 \pm 0.5\%$ was obtained. This represents our current status with the standard process yielding 97% of cells above 8.0% efficiency, Fig. 5.

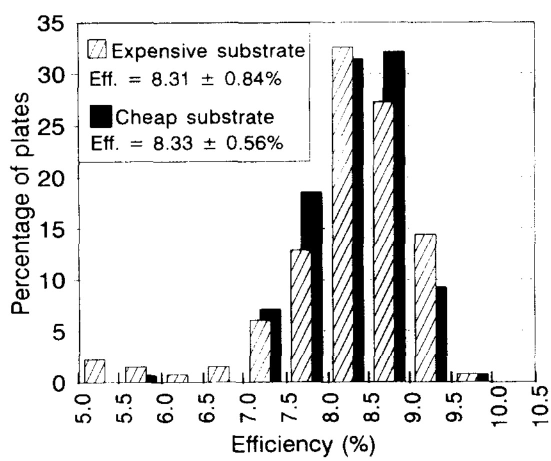


Fig. 4. A comparison of efficiency distributions using two types of substrate.

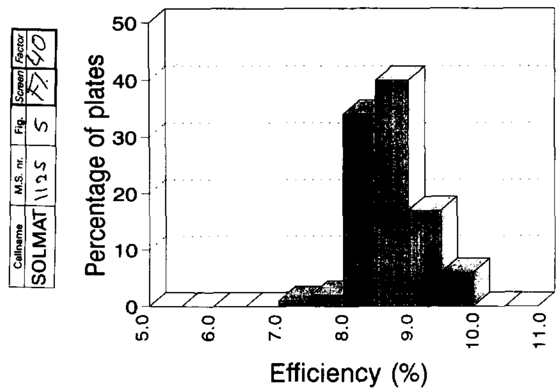


Fig. 5. Efficiency distribution for 100 plates using a single process on the cheaper substrate.

The distributions shown in Figs. 4 and 5 are for single plate devices. We also combine plates by laminating to a common front glass to obtain higher module powers with the plates connected in parallel. Fig. 6 shows the illuminated current–voltage characteristic for a six plate module, aperture 890 mm × 510 mm. The output is 35.6 Wp with an aperture area efficiency of 7.8%.

3.3. Stability

We have published in the past [2] stability data for earlier modules which were initially around 6.0% efficient and remained stable for more than two years on external test. More than one year's data for a more recent module, which was initially more than 8.0% efficient, is shown in Fig. 7. These measurements were made automatically on the roof of our factory in Spain [2]. The output has been

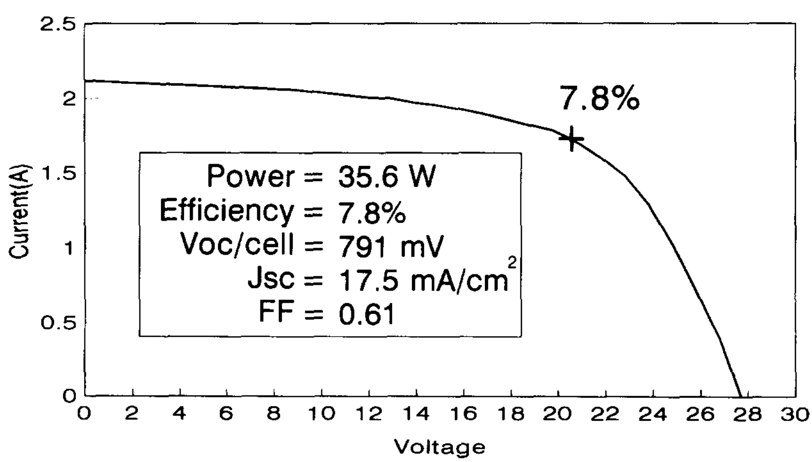


Fig. 6. Illuminated current–voltage characteristic of a six plate module (100 mW/cm^2, AM1.5, at 25°C).

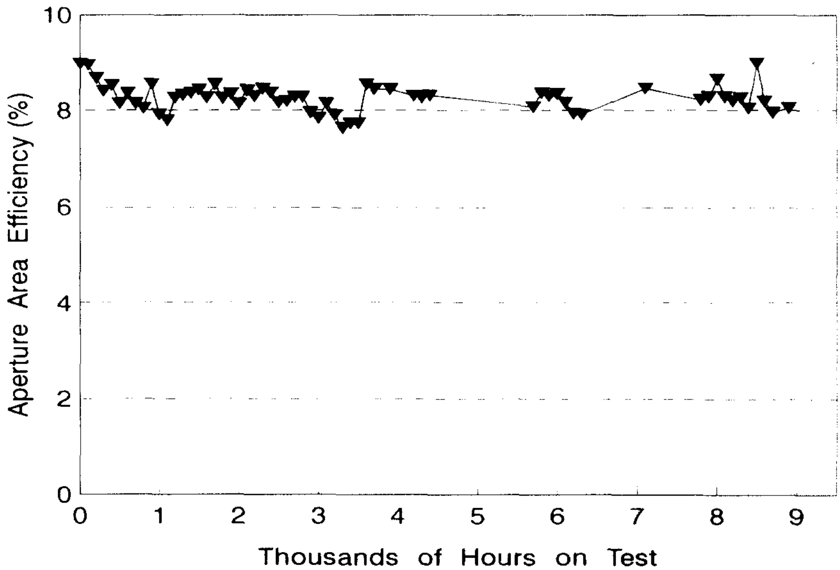


Fig. 7. Module efficiency on external test in Spain.

corrected for the natural variations of temperature, light intensity, and spectrum. The last correction is made by comparing the light intensity measured using GaAs and Si reference cells mounted on the external rig. It reduces the magnitude of the apparent cyclic seasonal variation in efficiency which we have shown in earlier publications [1,2].

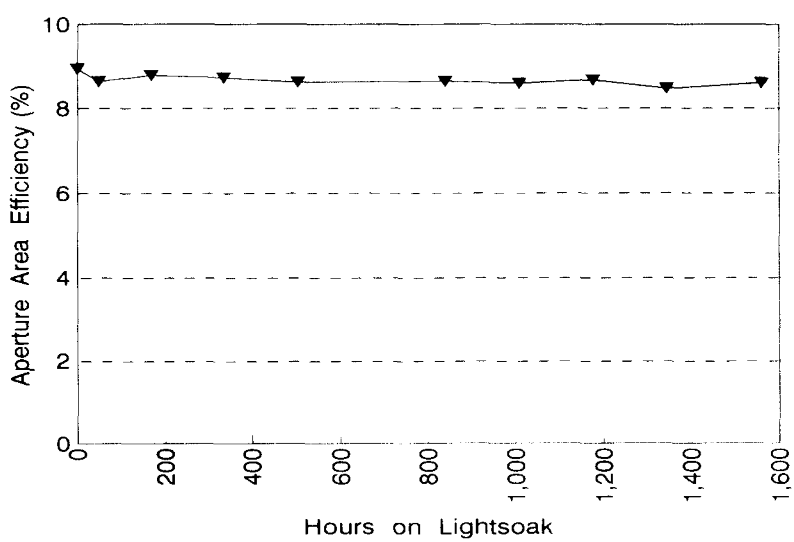


Fig. 8. Module efficiency on internal accelerated test.

Table 1
Average efficiency of a batch of ten modules during environmental tests

Initial	After 50 thermal cycles	After "damp heat" soak
8.60 ± 0.20%	8.53 ± 0.23%	8.63 ± 0.21%

Information can be obtained more quickly using internal accelerated testing of modules under constant illumination of around 100 mW/cm^2, from metal halide lamps, and at module temperatures maintained between 60 and 70°C. Again stable behaviour above 8.0% efficiency is observed, Fig. 8. The internal test for the module in Fig. 8 is thought to be equivalent to an outdoor test in Spain of 1 to 2 years. An acceleration factor of between 8 and 12 is estimated from the total exposure to peak light intensities of more than 50 mW/cm^2.

3.4. Environmental tests

Modules are made by laminating oversize glass to the front and back of the cells with EVA. We have established that 2 mm thick untoughened glass on the front of the cell is enough to withstand the hail impact test at ISPRA (CEC Spec 701). Glass lamination to the rear of the cell serves as an effective encapsulation. The change in average efficiency and standard deviation for a batch of ten modules first thermally cycled 50 times from −40°C to 85°C, then heated at 85°C for 15 days at 85% relative humidity is shown in Table 1.

4. Conclusions

* Best efficiencies above 10.0% have been obtained for BP Solar's Apollo CdTe cells of 706 cm^2 area using modules measured at the Fraunhofer Institute as references.
* High yields of cells with efficiencies above 8.0% have been consistently obtained using a cheap substrate.
* Stable efficiencies above 8.0% have been observed for modules on both external and internal accelerated tests.

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