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7000 High-efficiency Cells for a Dream

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This paper reports on the fabrication of high-efficiency back-side contact silicon solar cells in large volume for the '93 World Solar Challenge. The cells were used exclusively on the winning car, the Dream, made by Honda R&D Company, Ltd. The cell efficiencies were between 20% and 22% (AM1.5G, 25°C) (G = global) and the average cell efficiency was greater than 21%. An important program of quality control was necessary to maintain a tight efficiency distribution and a high fabrication yield.

INTRODUCTION

One-sun silicon solar cells with efficiencies of over 21% have been known for some time; however, to date such cells have been fabricated only in laboratory quantities. Of course, reported record efficiencies are usually those of the best cells from the small, hand-made lots characteristic of laboratory production. For cells of area greater than 4 cm², only two types of cell have crested 21%, the PERL (passivated emitter with rear local diffusion) cell¹ and the BSC (back-side contact) cell.²

Early in 1993, SunPower Corporation was contracted by Honda R&D Company, Ltd. to supply 6528 BSC cells for the Honda *Dream*, a solar-powered racing car and winner of the 1993 World Solar Challenge in Australia.³ The World Solar Challenge is a 3013-km race across Australia, from Darwin to Adelaide, which started on 7 November 1993. The solar cars registered in the race must have a solar array of maximum 8 m², which corresponds to more than 4500 solar cells of 17.7 cm². Prior to this production experience, there was great concern about the manufacturability and reliability of BSC cells. These concerns arose from the thinness of the cell (160 µm), the reliance on a very high recombination lifetime (2 ms) for good back-side collection and high voltage, and the closely interdigitated back-side metal, which could be prone to shorts. This paper describes our experiences in this project. We will show that in a production environment it is possible to establish enough quality control to tighten the efficiency distribution and to increase the average efficiency close to the efficiency record. Indeed, SunPower produced the 7000 cells with an average efficiency of 21.1%.

BACKGROUND

Since 1983, the silicon solar cells based on the BSC design have been among the most efficient solar cells, for both 1-sun and concentrator applications. Several BSC cells, or derived designs such as the point-contact (PC) solar cells, held, or still hold, efficiency records. By 1985, an interdigitated back contact (IBC) silicon cell, designed for 50× concentration application, was reported⁴ to be 21% efficient under 1 sun (not independently confirmed active area efficiency). In 1986, active area efficiencies of 22% under 1 sun and 27.5% under 100 suns were reported with a PC solar cell.⁵ Eventually, the efficiency increased up to 22.7% for a large-area (8.525 cm² and 37.5 cm²) PC 1-sun cell^{2,6,7} and 28% at 15 W cm⁻² for a 0.15-cm² concentrator cell.⁸ Although subsequent recalibrations would modify some of these

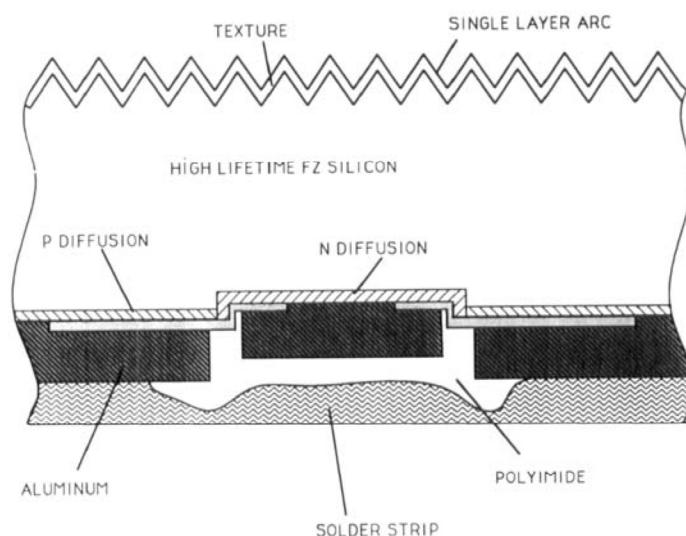


Figure 1. Simplified back-side contact solar cell

reported values,¹ it is impossible to give precisely the applicable correction factor. The PC design for solar cells still holds the efficiency record for silicon concentrator cells since 1986 and the near-record for 1 sun. However, these cells had never been produced in large quantities in an industrial environment. It was difficult to estimate how broad the efficiency distribution would be and how high the yield would be. Therefore, their fabrication cost was only estimated.

The BSC design has an obvious advantage of no grid shadowing on the front side (Figure 1), but it is a very interesting design for several other reasons. In a BSC solar cell there is complete decoupling between the optical (front) side and the electrical (back) side of the cell. Therefore, the front side could be optimized for the highest light absorption and lowest carrier recombination without interference with the electrical characteristics of the cell, particularly the series resistance. The back side of the cell is totally covered with the two polarities of metal electrodes, which provide low series resistance and an excellent light reflector. Also, it allows single side interconnections between cells, which, in turn, allows a very high packing density with minimum space between cells. Finally, a double-layer metallization scheme could be used to reduce further the specific series resistance and make it independent of the cell dimension.⁹

The greatest challenge in developing large-area 1-sun solar cells with a BSC design was not the efficiency. The high efficiency has been demonstrated quite early. The size of the 1-sun BSC cells has been increased at a slow pace, however, because a high fabrication yield was difficult to reach over a large area.¹⁰ For this purpose, we developed a high-reliability double-level metallization using polyimide as an intermetal dielectric layer and copper as the top solderable metal. The double-level metal also reduces by a large factor the series resistance of the cell.^{10,11} The size of the BCS cells for high-value 1-sun applications, such as solar racing cars or solar-powered ultra-light airplanes, is based on the customer's requirements. Two sizes have been produced: 35 and 17.7 cm². The latter size was used for the *Dream*. These sizes correspond to one or two large rectangles inscribed within a 100-mm diameter silicon wafer.

The fabrication process of a high-efficiency BSC solar cell is quite long and complex. It requires not only four or five steps of photolithography, high-purity float zone (FZ) silicon wafers and a clean room environment of at least class 1000, but also a very good control of process-induced contamination. The latter is extremely important in order to maintain a long carrier lifetime, a low surface recombination velocity and a low emitter saturation current. However, this process is no more complicated than fabricating high-efficiency conventional (two-side contact) solar cells. Since the early installation of the

PC solar cell fabrication in an industrial environment, the process has been redeveloped completely to eliminate the dangerous pyrophoric and toxic gases and the cyanide-based solutions. These modifications to the process not only make it totally safe for the operators and reduce the chemical waste, but they also considerably simplified the installation of the production facility.¹¹

RACE SOLAR CELL STRUCTURE

The structure of the BSC solar cell, called the RACE cell for the occasion, is similar to that presented in a previous paper.¹² The structure is simplified (see Figure 1) in order to reduce the number of photolithography steps by one level without penalizing the efficiency too much. The total number of photolithography masks is five. The external cell dimensions are 72.5×24.4 mm, which make it possible to have two cells per 100-mm wafer. The interdigitated aluminum fingers that make the electrical contacts at a first-level metal are covered by a patterned polyimide insulating film. Two large copper busbars are then deposited on top of the polyimide film for soldering and interconnections (Figure 2). The front side

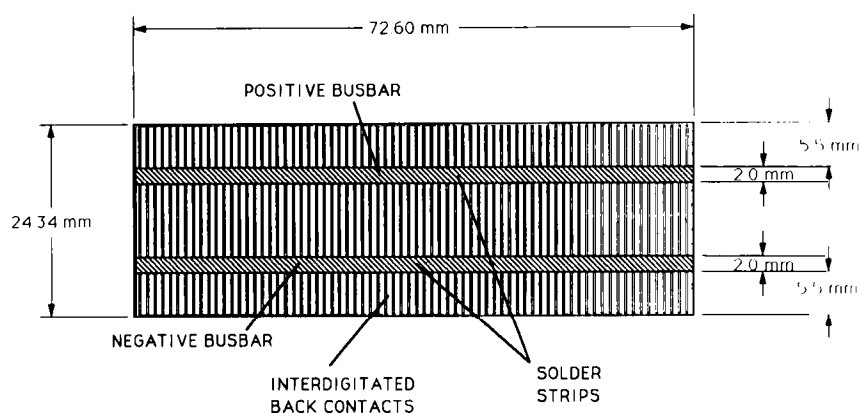


Figure 2. Metal contacts on the RACE solar cell

of the RACE cell is textured and covered with a single-layer antireflection coating optimized for the encapsulant.

PRODUCTION

The fabrication of high-efficiency solar cells, particularly the BSC cell, is more similar to the fabrication of integrated circuits than of conventional flat-plate solar cells. It requires photolithography steps and a high level of cleanliness. As described in a previous paper, a Class 100 research and production facility has been built utilizing existing surplus production equipment from the semiconductor industry.¹¹ A periodic particle density survey shows that in most parts of the working area the clean room is actually Class 10. The elimination of dangerous and poisonous chemicals from the fabrication process, such as pyrophoric gases and plating solutions, resulted in a safer manufacturing facility.¹¹

Within 2 months of starting the contract with Honda in March 1993 we had designed a new cell based on the client requirements, fabricated the new mask set, acquired new pieces of equipment and modified some existing ones, modified the deionized water system and improved the particle level of the clean room, hired the necessary operators and production manager from the electronics industry and, finally, we paid special attention to training them to do the processing of ultrathin wafers with minimum

contamination in order to maintain a very high carrier lifetime. Within 2 months we went from a 25-wafer per week R&D operation to a moderate-volume production facility.

One of the most important tasks was to train the new operators in high lifetime processing and thin wafer handling. They were all accustomed to thick silicon wafers (around 500 μm) and integrated circuit processing, for which avoidance of particle defects is much more important than a lifetime of several milliseconds. The second most important task was to modify recently acquired equipment for thin wafer handling. Although the RACE cell wafers were 160 μm thick, the equipment with automatic handling features was qualified only when it could process 500 80- μm wafers without any breakage.

The production volume varied between 700 and 1000 1-sun cells per week, which corresponded to starting 500–600 wafers per week with a two-shift operation. The total cycle time of manufacturing, i.e. the time evolved between the first and the last step of the process, including testing and packaging, was around 5 weeks. The first cells came out of the fabrication line in May 1993 and were used for efficiency calibration, soldering tests, encapsulation practicing and assembly experiments.

During the production, the inventory volume was kept as small as possible, at 1500–2000 wafers. We set up a computerized work-in-progress (WIP) tracking system in order to control the flow of wafer lots and the start of new lots and to set up the priorities for every day. The entire process flow counted a total of 34 steps (activities), and we had to produce a minimum of 2400 activities per day in order to meet our goal. The ratio of activities to inventory gives a good idea of the average number of process steps that the wafers moved every day. In our example, the moves per inventory ratio, M/I , was targeted to be 2.0. A daily production meeting was aimed at reviewing and resolving production problems, setting up the production priorities, deciding on new starts of wafer lots and balancing the fabrication line. A well-balanced line was, in this case, the most important characteristic. It is a very complex function of: the inventory, moves per inventory ratio, the number of bottlenecks and their locations in the process flow, and the status of the equipment.¹³ Throughout this production, we tried to balance the line so that the WIP never piles up in front of any station, so that the WIP was well distributed throughout the process flow and so that the bottlenecks were always fed with wafer lots.

QUALITY CONTROL

In order to meet the specifications on the cell delivery, the quality control was the most important aspect of this production. During the fabrication of every cell, no less than 65 process parameters were recorded on the runcards.¹⁴ These parameters were, for example: the bath temperature; the etch rate at each etch step; the diffusion sheet resistivity; a specific critical dimension (CD) linewidth; the aligner used at each photolithography step. This information was gathered and some of it introduced into a data base for analysis.¹⁴ A small part of this data base is presented below (see Figures 4 and 5). The effectiveness of this data base has been demonstrated when we observed an increase in shorted cells. During the course of the production, it was discovered that a high percentage of cells from about 12 lots were shorted owing to a mask defect. In 2 days we were able to tell when the defect was created and on which mask, and which lots were affected, and to give Honda the serial numbers of the cells that could present the defect, even if they had a good efficiency.

In parallel with the production, the specific carrier lifetime of the process line was measured on a weekly basis. For that purpose, test wafers were cleaned and oxidized in every furnace at least once a week. The carrier lifetime, surface recombination velocity and emitter saturation current of these test wafers were measured using the contactless photoconductivity decay method.¹⁵ Any degradation of one of these parameters would have the effect of stopping the fabrication line and of mobilizing the entire engineering staff in order to search for the source of the contamination.

Every cell was measured, visually inspected, delivered with a protective tape and packed in an individual box. A specification sheet accompanied each shipment, listing the efficiency, short-circuit current, open-circuit voltage, fill factor, output power, maximum power point voltage and current measurement values. The cell efficiency was measured on a custom-built solar simulator with an

Extra Long Hours Quartz Halogen (ELH) lamp. The reference cells were BSC cells of the same dimensions and were fabricated by the same process in order to have the same spectral response. Three early cells were sent to Sandia National Laboratories for calibration. One of these cells was sent to Honda as a reference cell for their solar simulator. The two others were kept at SunPower: one as a reference cell, the other as a back-up reference to check any possible degradation of the daily-used reference cell. The efficiency measurements were repeatable within 1.5%. In order to check the accuracy of the cell efficiency measurement, a reference cell was measured before every lot of 50 cells. The ELH light bulb of the solar simulator was changed if its intensity, at the level of the cell, was diverging from the 1-sun intensity by more than 2% or if the short-circuit current of the reference cell was measured to be more than 1.5% above or below the Sandia measured value. The comparison of measurements done at SunPower, Sandia, NREL and the Fraunhofer Institute for Solar Energy showed that our efficiency measurements were accurate to within 3%.

FABRICATION YIELD

At the starting point of production, the most important unknown was the fabrication yield of the BSC cells. The yield may be defined as the product of four terms:

- (i) the *production line yield*, which is the complementary of the wafer loss due to breakage, misprocessing or other process problems;
- (ii) the *electrical yield*, counting the functioning solar cells. For this yield we decided to set an efficiency limit of 18%; all the cells presenting a lower efficiency were assumed to be either shunted or shorted;
- (iii) the *cosmetic yield*, which is the complementary of the cell loss due to cosmetic defects on the front side of the cell, even if the impact on the efficiency is small enough to not reject it;
- (iv) the *efficiency yield*, counting the cells meeting the specifications, i.e. presenting an efficiency higher than 20%.

The goal was set to reach an overall fabrication yield that was greater than 75%, with the following partial yields:

- (i) production line yield, greater than 90%;
- (ii) electrical yield, greater than 92%;
- (iii) cosmetic yield, equal to 100%;
- (iv) efficiency yield, greater than 91%.

Although we had much lower yields at the beginning of this RACE cell production, we discovered that the improvement of yield was quite easy and we even finished with a higher yield than targeted. The yield improvement was achieved by carefully studying the causes of low yield, their relative importance in number of lost cells and by applying the appropriated counter-measures, beginning with the most important cause of low yield. The technique of 'quality improvement (QI)' was used in this research for higher yield.¹⁶ Figure 3 shows the Ishikawa (fishbone) diagram of the root causes of low yield. This technique helped us to investigate the root causes and to discover, for example, that the equipment with automatic handling of the thin wafers was the principal cause of breakage or mechanical stress. An important program of preventive maintenance, equipment modification, training of operators and modification of procedures allowed us to bring the overall fabrication yield above the objective of 75%, which comprised a production line yield of 90%, a cosmetic yield of 100% and a combined electrical–efficiency yield of 84%.

RESULTS

The 17.7-cm² RACE cells were fabricated on high-resistivity FZ silicon wafers. The cell thickness was 160 μm . The efficiencies of the cells have a very tight distribution between 20% and 22.1% (Figure 4).

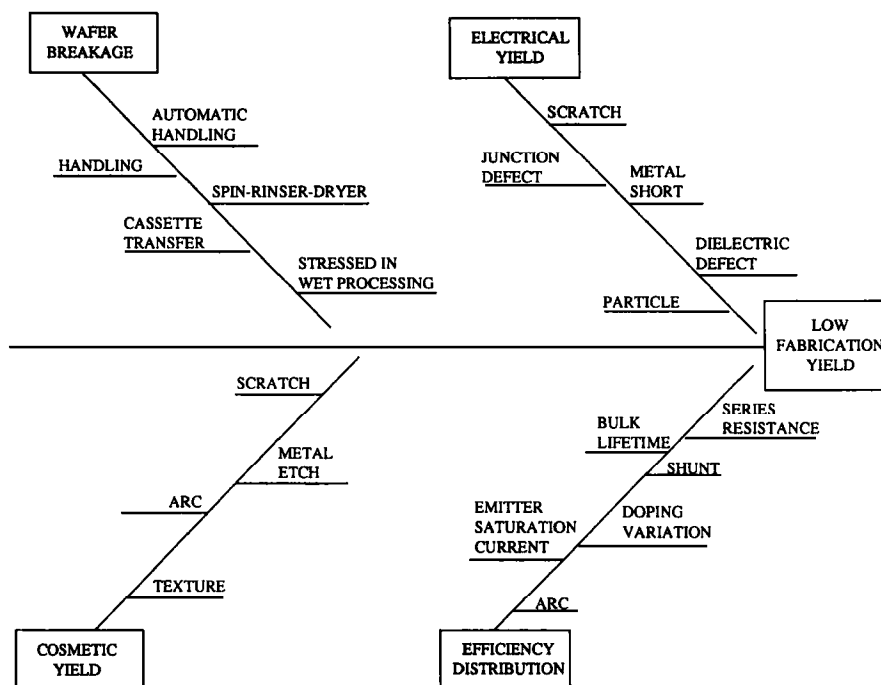


Figure 3. Ishikawa (fishbone) diagram of the root causes of low yield

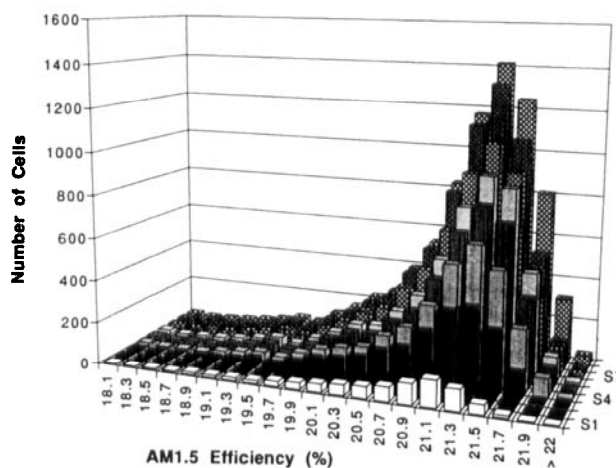


Figure 4. Efficiency distribution of the RACE and its evolution with time. S1 to S9 data correspond to weekly results giving the integration of all the cells produced since the beginning of the RACE cell production

With time, represented on the Y axis of Figure 4, the average efficiency increased from 21% to 21.3%. The best cells have a 22.1% efficiency (not confirmed independently) with a 0.395-A W^{-1} responsivity, a 0.690-V open-circuit voltage and an 81% fill factor, which results in a high power-to-weight ratio of 592 W kg^{-1} for a non-concentrating terrestrial solar cell. The light trapping into the cell is particularly good, with an effective number of passes between 25 and 30 for the long-wavelength photons. The internal back-surface and front-surface reflection coefficients were around 93% and 92%, respectively. The average efficiency, short-circuit current and open-circuit voltage of every wafer lot are presented in Figure 5. It is worth noting that the quality control program allowed these parameters to be kept in a very tight window.

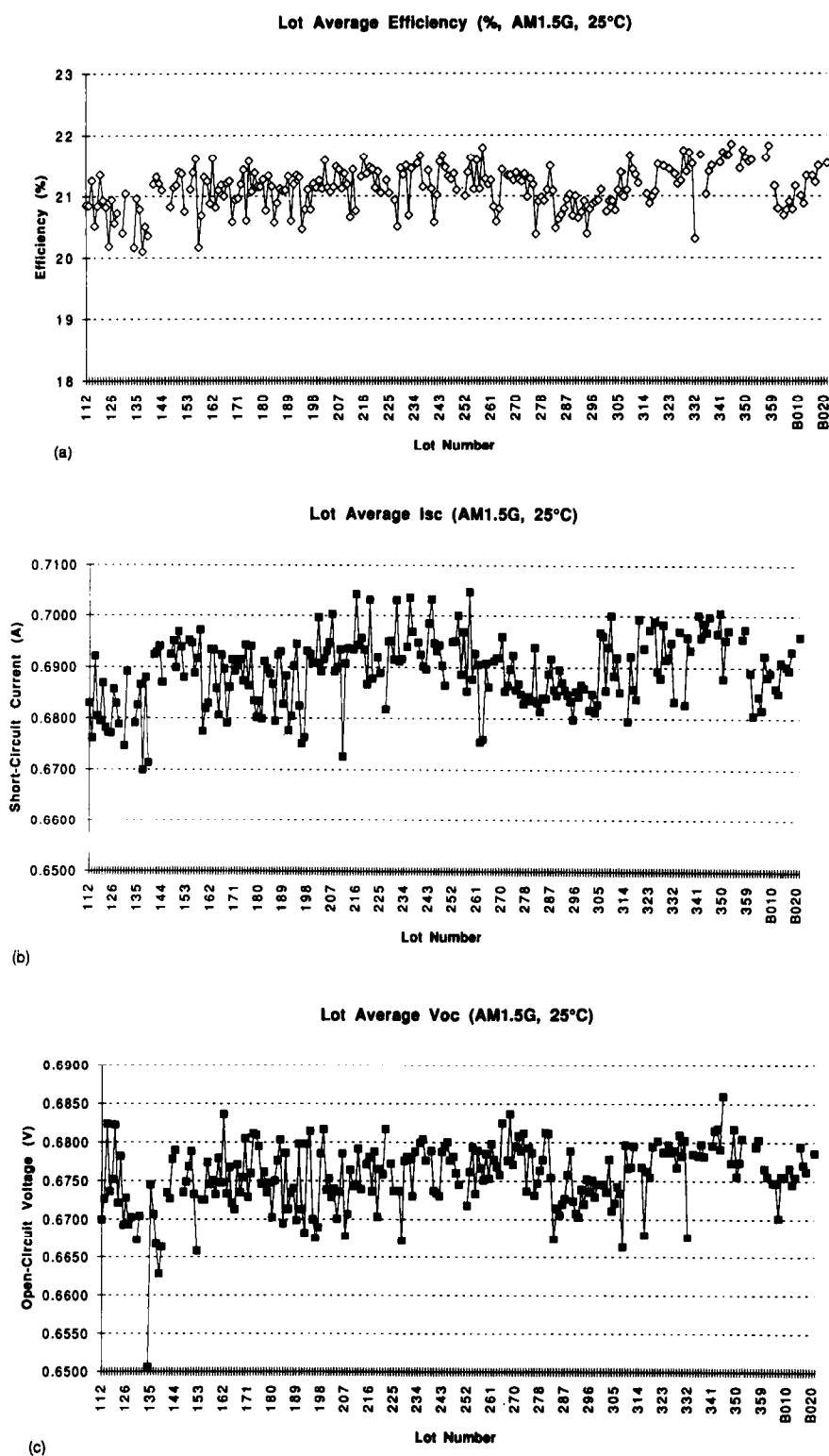
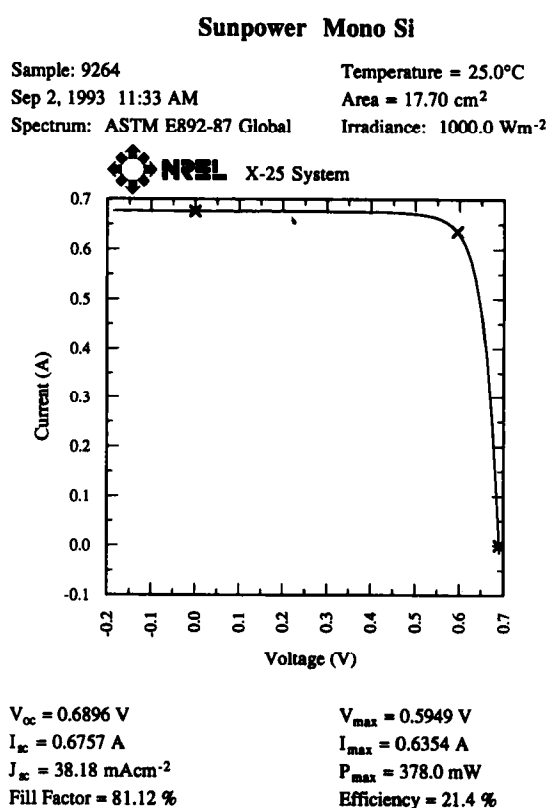


Figure 5. (a) Evolution of the average efficiency of each wafer lot (efficiency measured under ELH lamp simulator, relative to Sandia calibrated reference cell). (b) Evolution of the average short-circuit current of each wafer lot. (c) Evolution of the average open-circuit voltage of each wafer lot

Table I. Characteristics of seven BSC cells measured at Sandia, NREL and the Fraunhofer Institute for Solar Energy (FSE)

Cell no.	V_{oc} (V)	J_{sc} (mA cm ⁻²)	Fill factor	Efficiency (%)	Laboratory
2071	0.681	38.81	0.813	21.5	FSE
2813	0.686	37.91	0.811	21.1	NREL
2818	0.685	38.46	0.810	21.3	NREL
2830	0.681	38.93	0.804	21.3	Sandia
5710	0.679	38.92	0.806	21.3	Sandia
5714	0.679	39.01	0.805	21.3	Sandia
9264	0.690	38.18	0.811	21.4	NREL

Figure 6. The I - V curve of a typical RACE cell measured at NREL.

Several months after starting this large-volume production, we sent several RACE cells to three different calibration laboratories: Sandia National Laboratories, NREL and the Fraunhofer Institute for Solar Energy. The efficiencies were all between 21% and 21.5% (AM1.5G, 25°C). Table I presents the cells' characteristics and Figure 6 shows the I - V curve of a typical cell measured at NREL.

The RACE cells were a key element in the victory of Honda at the '93 World Solar Challenge in Australia.³ The modules, fabricated by Honda and containing between 60 and 120 cells, had efficiencies of 19–21%. The entire solar array of 8 m² (Figure 7) had a total power of more than 1600 W and an unconfirmed efficiency of 20.3%.¹⁷ Honda smashed the record of the race, eclipsing the previous record



Figure 7. A rear view of the Honda *Dream*, showing particularly its solar array (photograph: M. H. Brown)

set by GM's *Sunracer* in 1987 by 9.5 h. The *Dream* had an average speed of 84.9 km h^{-1} and took 35 h 28 min to travel 3013 km. The peak racing speed was 112 km h^{-1} , and the peak power generated by the solar array during the race was 1860 W.

The reliability of the BSC cells, used for the first time in a solar array, was another question that we could not answer with complete certainty before the race. The interdigitated BSCs of the cell, with, in addition, a double-level metal structure, could be prone to shorts. It appeared that the reliability of the BSC cell was very good: only 50 cells (less than 1% of the cells) were shorted after encapsulation and no cells failed during the race. The RACE cells also exhibit excellent mechanical robustness.

CONCLUSIONS

The '93 World Solar Challenge gave the efficiency-record BSC solar cell the chance to be fabricated in quantity for the very first time. This experience of moderate-volume production shows that a good quality-control program allows the production of high-efficiency solar cells with an excellent fabrication yield, a tight efficiency distribution and an average efficiency close to the efficiency record. The cells were used exclusively on the winning car, the *Dream*, made by Honda R&D Company, Ltd. The cell efficiencies were between 20% and 22% (AM1.5G, 25°C) and the average cell efficiency was larger than 21%. The efficiencies of seven cells have been measured independently by three different laboratories. They were between 21 and 21.5%. The overall fabrication yield was greater than 75%, comprising 10% wafer breakage and 84% of the cells above 20% efficiency.

We believe that large cost reductions can be achieved in the future through simplification and automation of the fabrication process, and that BSC cells will eventually evolve to compete cost effectively in a broad range of applications. We hope that this paper will help other people to improve solar cell production towards high efficiency. This was the main objective of this paper.

Acknowledgements

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