TRIPLE-JUNCTION AMORPHOUS SILICON ALLOY PV MANUFACTURING PLANT OF 5 MW ANNUAL CAPACITY

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ABSTRACT

A spectral-splitting, triple-junction a-Si alloy solar cell processor has been designed, built and optimized. A roll-to-roll process has been used to deposit two layers of back reflector, a triple-cell structure with nine layers of a-Si and a-SiGe alloys and a single layer of antireflection coating consecutively on a half-a-mile roll of stainless steel. The coated web is next slabbed and processed to make a variety of products. The design of the machine and processes used incorporate several key features developed for improving cell efficiency. In order to reduce manufacturing cost, higher deposition rates and thinner cells than are used in R&D have been used. The back reflector also consists of Al/ZnO rather than Ag/ZnO. Large-scale production has begun, and products are being shipped for a wide range of applications.

INTRODUCTION

There are four key factors for photovoltaic to be cost-effective and acceptable for large-scale terrestrial applications. These are: i) use of low cost material, ii) achievement of high light-to-electricity conversion efficiency with good stability, iii) development of a low-cost manufacturing process with good yield, and iv) use of technology and products that are environmentally safe. Thin films of amorphous silicon (a-Si) alloys are inexpensive; they are also environmentally safe. The challenge has been to improve the efficiency of a-Si alloy cells and modules. Investigation of a-Si alloy materials and their incorporation in device structures have received worldwide attention, and this has resulted in the recent achievement of 13% stable cell efficiency [1]. The highest efficiency has been achieved using a spectral-splitting, triple-junction cell technology incorporating i) high quality intrinsic and doped layers, ii) textured back reflector with low optical loss, and iii) bandgap profiling for the amorphous silicon germanium (a-SiGe) alloys used in the low bandgap cells.

In order to translate the R&D results to production, we have designed and built a manufacturing line capable of producing the complex cell structure using our proprietary roll-to-roll approach [2]. Products from the new manufacturing plant, which has an annual capacity of 5 MW, are now being shipped worldwide for a wide range of applications.

MANUFACTURING PROCESS

The manufacturing process consists of the following steps. A roll of stainless steel, half-a-mile long, 14″ wide and 5 mil thick, moves in a continuous manner at a speed of 2 foot a minute in four machines that serve the purpose of i) washing, ii) depositing the back reflector, iii) depositing the a-Si and a-SiGe alloy layers, and iv) depositing indium tin oxide (ITO) which serves as an antireflection coating. Both the transport of the web and the process parameters are computer-controlled ensuring reliable and low-cost operation. The coated web is next processed to make a variety of lightweight, flexible and rugged products. The processing steps involve i) cutting of the web into 9.4″ x 14″ slabs, ii) short and shunt passivation and etching of ITO to define strip-cell area, iii) attaching electrodes and grids, and iv) final assembly involving strip cutting, interconnection of the strips and lamination.

A brief description of the various operations is given below.

Wash Machine

The roll of stainless is washed in a roll-to-roll processing system which transports the web through a detergent cleaning station, multiple deionized water rinsing baths, and an infrared drying oven. The clean, dry and dust-free web is next loaded into the back reflector machine.

Back Reflector Machine

The back reflector machine sequentially deposits a reflective metal layer and a metal oxide "buffer" layer onto the cleaned stainless steel web by magnetron sputtering. The back reflector layers provide the ohmic contact between the stainless steel and the a-Si alloy. The layers are deposited at a high temperature to obtain a textured surface so as to facilitate multiple reflections.

Amorphous Silicon Alloy Deposition Machine

The web coated with the back reflector is next loaded

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into the a-Si alloy processor (Fig.1) which is 140′ long and has, in addition to the pay-off and take-up chambers, nine chambers to deposit the nine layers of the triple-cell structure. The adjacent chambers are separated by proprietary gas gates to eliminate contamination of the dopant gases in the intrinsic layers [3]. The individual layers are grown by plasma-enhanced chemical vapor deposition process at a pressure of about 1 torr, and all the layers are deposited simultaneously and consecutively on the moving web (Fig. 2) to complete the triple-junction cell structure. Special cathode designs ensure improved gas utilization and uniformity of the deposited layers. The gas manifolds for introducing disilane and germane for the a-SiGe alloy component cells are specially designed to facilitate bandgap profiling [4]. The process conditions used for the deposition of the *p*-type layer facilitates microcrystalline growth [5].

Fig. 1. a-Si alloy triple-junction cell deposition machine.

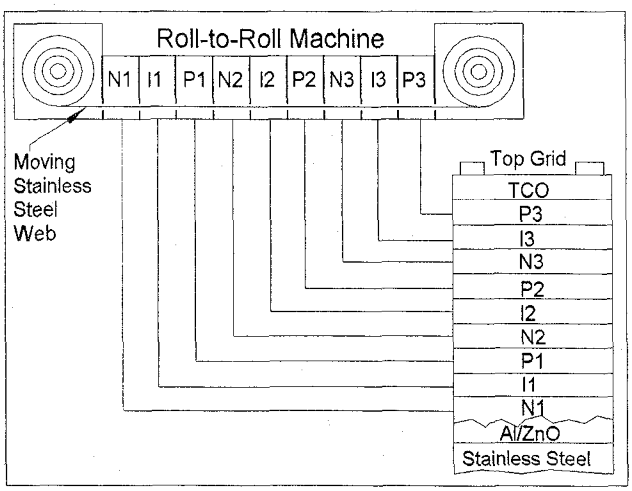

Fig. 2. The roll-to-roll operation for the deposition of the triple-junction cell.

Indium Tin Oxide Deposition Machine

The final step in the deposition process is reactive magnetron sputtering of ITO which serves as the antireflection coating and also provides the top conducting contact. Typical deposition temperature is 200 °C.

Module Assembly Operation

The module assembly operation is semiautomated to facilitate flexibility in the choice of the product line while ensuring low cost and reliability. The finished roll of the coated web is first cut into 9.4″ x 14″ slabs using a semiautomated press; small coupons (3.8″ x 14″) are also cut during the same operation at preset intervals along the length of the web. These coupons are processed off-line for QA/QC evaluation which will be discussed later. The slabs are then processed to define cell size, passivated to remove shunts and shorts [6] and tested to ascertain quality. Grid wires and contact pads are next applied, and the slabs are cut into predetermined cell sizes for the various product requirements. The cells are next interconnected and the cell block laminated to provide protection against outside atmosphere. Depending on the application, frames and junction boxes are added and the finished modules undergo a highpot test and performance measurement under global AM1.5 illumination before they are shipped out.

PROCESS OPTIMIZATION AND RESULTS

In order to reduce product cost, several important departures from the R&D design were made: i) The deposition rates for the intrinsic alloys were increased and the component cell thicknesses reduced to improve machine throughput, ii) the back reflector uses Al rather than Ag, and iii) deposition regimes were chosen in which the flow rates of the active gases such as germane and disilane were kept low. Imposition of the above constraints lowered the conversion efficiency of the cells and modules, but helped in improving the dollar per watt cost criterion.

The back reflector layers are deposited by sputtering from Al and ZnO targets; the optimization process involved changing the texture of the Al/ZnO by varying the process parameters and the layer thicknesses. Quantum efficiency measurements on both the bottom a-SiGe alloy cell and the triple-junction structure were used for evaluating the quality of the back reflector. The quantum efficiency plot for a triple-junction cell on an optimized back reflector made on a production run is shown in Fig. 3. The total current density of 22.74 mA/cm^2 and the quantum efficiency of 0.21 at 850 nm indicate the superior quality of the back reflector.

The optimization process for the a-Si alloy processor involved extensive experimentation on component cells, tunnel junctions and triple-cell structures to improve efficiency without sacrificing the machine throughput and gas utilization. Measurements on the QA coupons provide information about the quality and yield. An array of 2 x 10 cells of 10 cm^2 area are defined on each coupon, and the

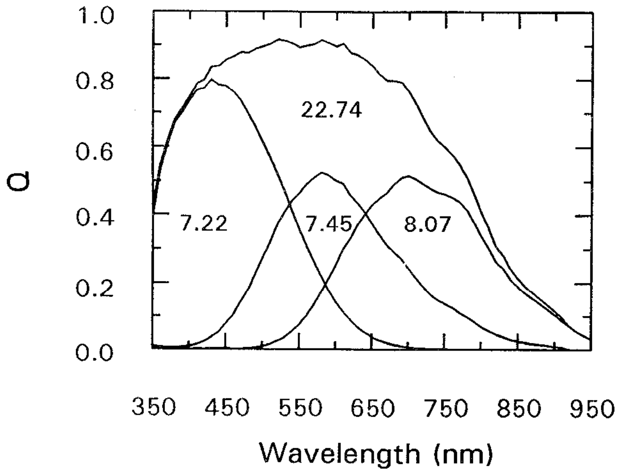

Fig. 3. Quantum efficiency of a triple-junction cell deposited on an Al/ZnO back reflector from the 5 MW line.

average subcell efficiency and the yield for a typical run are shown in Fig. 4. Many production runs have been made to date, and the efficiency and the yield numbers are extremely consistent.

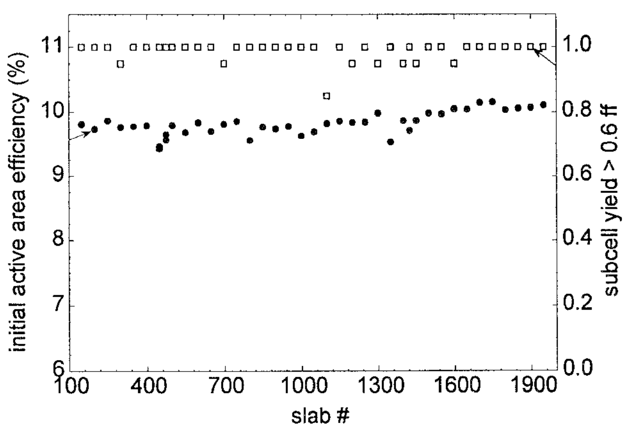

Fig. 4. Initial active-area efficiency (•) and subcell yield (□) versus slab number for a 2000 ft production run from the 5 MW line.

PRODUCTION STATUS

The manufacturing operation started in March, 1997, and because of the increased market demand, the plant has been running seven days a week on a round-the-clock basis. Both flexible and rigid modules of different sizes and power ratings are being shipped. The ratings for the standard products range from 3 to 64 W. The stable output from a nominal 4-square-foot module is 32 W with open-circuit voltage of 23.8 V, short-circuit current of 2.4 A, and fill factor of 0.56. The power output is backed by a 10-year warranty. The stabilized aperture-area efficiency is 7.5%. Several panels were shipped to National Renewable Energy Laboratory (NREL) for both indoor and outdoor light-soaking tests. After about 1000 hours of one-sun light soaking, the module efficiency was 7.8% showing stabilization after 400 hours. All the standard products have gone through IEEE-Std 1262 qualification testing and have recently obtained Underwriters Laboratory (UL) approval.

In addition to the above standard products, United Solar has also introduced two roofing products into the market. One, the PV Shingle, provides 17 W of power and emulates the asphalt shingle. They can be installed on the roof deck in an overlapping manner similar to the conventional shingles. The other roofing product is the Standing Seam PV metal roof which is available in power ratings of 64 and 128 W. These are direct substitutes for conventional metal roofing.

PRODUCT ADVANTAGE

For any new product, it has to compete against the more mature products which have been around for a long time, and a-Si alloy products are no exception. During the last few years, however, several new, attractive features of a-Si alloy products have been established resulting in a wider acceptance of these products. Since the bandgap of a-Si alloy is much higher than that of crystalline or polycrystalline silicon, the power output from an a-Si alloy panel is remarkably independent of temperature. For example, for a typical ambient temperature of 30 °C, the module temperature can be 60 °C. The power output from an a-Si alloy panel barely changes [7] in this temperature range, whereas that for a crystalline silicon panel can change by about 20%. For the same power rating, a-Si alloy PV products, therefore, perform much better than the crystalline counterparts under normal outdoor conditions. This is a significant advantage both for grid-connected and battery charging applications. Independent studies carried out in Phoenix, Arizona by Photocomm, Inc. [8] on United Solar a-Si alloy panels show that the battery charging capacity is 30% higher than that of a polycrystalline panel of the same power rating. As can be seen from Fig. 5, the daily output from the polycrystalline panel is 45 Amp-hours whereas that for the United Solar triple-junction module is 60 Amp-hours. These advantages of a-Si alloy technology are not very widely known. Thin-film products can, of course, be made lightweight and flexible, and there is a tremendous opportunity for these products in the building-integrated PV market.

The stability of a-Si alloy modules under normal outdoor condition is also not an issue any longer. NREL has been monitoring the performance of an array consisting of 102 United Solar modules since April, 1993. Another array consisting of 64 modules is being evaluated since January, 1994. The long-term data show degradation less than 1% per year [7] which is "equal to or better than crystalline silicon systems."

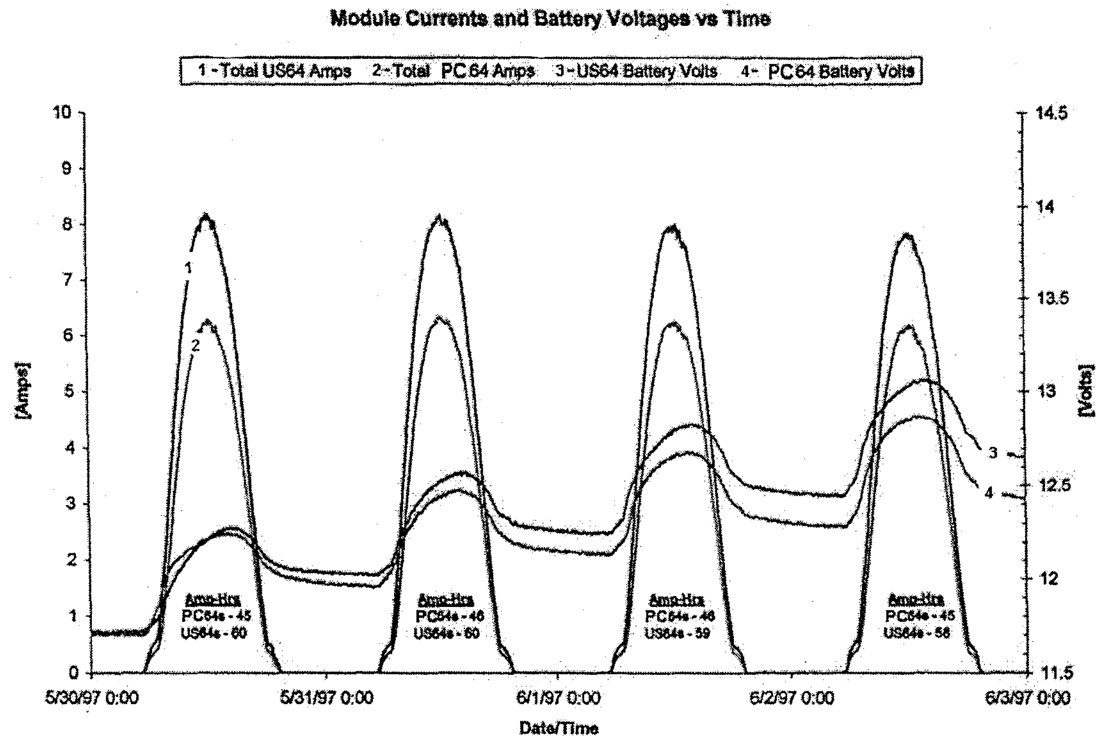

Fig. 5. Comparison of battery charging performance of United Solar a-Si alloy solar panel with that of a commercial polycrystalline solar panel with the same standard power rating (64 W).

CONCLUSION

We have designed and built a triple-junction a-Si alloy PV manufacturing plant of 5 MW annual capacity. The cell design and the processes use several cost-saving measures to reduce cost per watt. The plant is in full production, and a wide range of UL-approved rigid and flexible products are being shipped from the plant. The products carry a 10-year warranty and the guaranteed stable efficiency of 7.5% has been confirmed by NREL. The superior temperature performance of these products has been confirmed by independent tests demonstrating a 30% increase in battery charging capability of a 64 W triple-junction product over a polycrystalline silicon panel of the same power rating. Future plans include a continuous improvement program aimed at further increases in efficiency and throughput. This will be carried out without affecting the regular production schedule.

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