Simplified Module Assembly Using Back-Contact Crystalline-Silicon Solar Cells

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ABSTRACT

We are developing new module concepts that encapsulate and electrically connect all the crystalline-silicon (c-Si) photovoltaic (PV) cells in a module in a single step. The new assembly process (1) uses back-contact c-Si cells, (2) uses a module backplane that has both the electrical circuit, encapsulant, and backsheet in a single piece, and (3) uses a single-step process for assembly of these components into a module. This new process reduces module assembly cost by using planar processes that are easy to automate, by reducing the number of steps, and by eliminating low-throughput (e.g., individual cell tabbing, cell stringing, etc.) steps. We refer to this process as "monolithic module assembly" since it translates many of the advantages of monolithic module construction of thin-film PV modules to wafered c-Si PV modules. Preliminary development of the new module assembly process, and some estimations of the cost potential of the new process, are presented.

INTRODUCTION

Photovoltaic (PV) modules are large-area optoelectronic devices that convert solar radiation directly into electrical energy. PV modules require good electrical and optical performance and, due to the low energy density of solar radiation, exceptionally low manufacturing and material costs to be competitive with other electrical-energy generation technologies.

Most PV modules presently use discrete crystalline-silicon (c-Si) solar cells that are connected in an electrical circuit and encapsulated with a glass cover and polymer backsheet for environmental protection. While very successful, the basic design and assembly process of present c-Si PV modules is *over 20 years old*. Current commercial c-Si PV modules and assembly processes use c-Si cells with front and back contacts. The module assembly using these cells requires several steps: solder tabs on the front contacts of the cells *individually*, electrically connect the cells into a circuit by *sequentially* soldering the cells into the circuit, transferring the fragile electrical circuit to an encapsulation work station, and then encapsulating the cell circuit in the module [1]. This process typically requires at least three work stations with low throughput and relatively expensive automation. This 20-year-old module design and assembly process was sufficient when the cost of the silicon substrates completely dominated the cost of the finished PV module. However, recent advances in c-Si growth and wafering have reduced the cost of the wafer such that the module assembly and materials is now the single largest cost element in a c-Si PV module for some PV manufacturers [2].

The automation difficulties in c-Si PV module assembly are due to the contact configuration of the solar cells. Solar cells with coplanar contacts on the back surface (i.e., back-contact solar cell) avoid the difficult automation and high stress points associated with front-to-back lead attachment, and allow for planar processes that operate on both contacts in the same step. The advantages of simpler module assembly using back-contact cells are obtained at the expense of increased complexity in the cell manufacturing. Several potentially low-cost methods for fabricating back-contact cells have been described [3,4,5]. For example, we are working on a back-contact cell concept that uses laser-drilled holes in the c-Si substrate to wrap the emitter from the front surface to the back surface [3]. It should be noted that back-contact cells are of interest for reasons besides simpler module assembly; in particular, back-contact cells can potentially achieve higher performance levels due to reduced and/or eliminated grid obscuration.

Besides simplifying the module assembly using current procedures, back-contact cells allow for radically new module assembly procedures that encapsulate and electrically connect *all* the cells in the module *in a single step*. This new module assembly would use back-contact cells, a module backplane that has the electrical circuit, encapsulant, and backsheet in a single piece ("monolithic backsheet"), and a single-step process for assembly of the module components into a module (Fig. 1). This process reduces costs by reducing the number of steps, by eliminating low-throughput (e.g., individual cell tabbing, cell stringing, layout, etc.) steps, and by using completely planar processes that are easy to automate. We refer to this process as "monolithic module assembly" (MMA) since it translates many of the advantages of monolithic module construction of thin-film PV technology to wafered c-Si PV technology.

This paper will report preliminary results of a project to examine module assembly using back-contact c-Si solar cells. Firstly, new assembly options using back-contact cells are described. Next, development of prototypes to demonstrate the principle of MMA is presented. Finally, we report on some preliminary cost estimates for the new assembly process.

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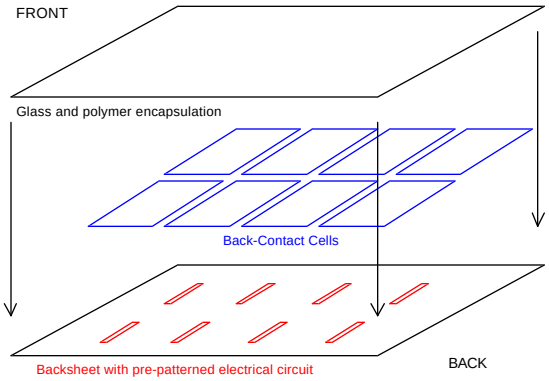

Figure 1. Illustration of monolithic module assembly.

REQUIREMENTS

The new assembly process must produce a module package that is reliable and durable. At a minimum, the new assembly process must pass commonly accepted environmental, mechanical, and electrical qualification test requirements [ASTM, IEA, IEEE, etc.]. In addition, the new assembly process must produce a PV module with good optical and electrical performance. Typical requirements include optical transmissivity of the front surface encapsulant greater than 95% over the useable spectral range, and a series resistance of less than 1 Ωcm^2 per series-connected cell for the complete module.

MODULE DESIGN

One of the more critical issues in MMA is selecting a material and process for interconnecting the cells that is compatible with the encapsulation of the back surface. We restricted our module development to encapsulation and backsheet materials that have already been used and/or specifically developed for PV modules, and to vacuum-pressure laminators that are commonly used in PV module fabrication. This restriction was to maximize the project's success and make the process easier to transfer to production. However, it should be noted that other assembly processes could be considered with new encapsulation materials and processes. In particular, roll-based encapsulation is a continuous process that has potentially very high process throughputs [6,7].

We considered the following interconnect technologies: solder, silver-filled conductive epoxies, and copper foils coated with either pressure-sensitive or thermosetting acrylic-based conductive adhesive. Solder is currently used in PV module fabrication, and considerable work has been performed to understand the quality and reliability of solder joints. However, we were concerned about obtaining good solder joints during the lamination cycle due to the fluid flow of the surrounding polymer encapsulants and the requirement to completely eliminate fluxes. Hence, we only examined conductive acrylic and epoxy adhesives for MMA.

The acrylic conductive adhesives are quite attractive; they meet our cost goals, can be precoated on the Cu strips, and are believed to be more compatible with the encapsulation materials and processes than the other interconnect options. The reliability of this interconnect is a concern. The conductive epoxies have excellent electrical and mechanical properties, and are believed to be capable of meeting our qualification tests; however, the cost of conductive epoxies is a concern.

We are examining two different assembly processes. The first assembly process is very similar to Figure 1. Cu foil traces are positioned and mounted on the backsheet. The Cu foil may be precoated with a conductive adhesive or conductive epoxy. After all the other components (backsheet, cells, front encapsulant, and glass) are positioned, the entire assembly is laminated with a programmed pressure-temperature cycle that initially flows the encapsulation materials and then cures the conductive adhesive and encapsulant. This process uses the same equipment (vacuum laminator) that is used for conventional PV module assembly.

We were concerned about the ability of the conductive adhesive to bond to the cell if the surrounding encapsulant melts – which occurs, for example, during a standard lamination cycle using ethylene vinyl acetate (EVA). Hence, we are using new materials for the backsheet and the front encapsulant with more desirable properties for this application [7]. These materials require a higher lamination temperature than typically used with EVA and Tedlar™. The higher temperature is also advantageous for reducing the curing time of the conductive adhesive. The resulting structure is shown in Fig. 2.

Figure 2. Exploded side view of conductors-on-backsheet MMA option.

The second assembly process uses a polymer screen to support the electrical circuit (Fig. 3). The screen prevents movement of the cell interconnects during lamination, provides positional accuracy of the interconnects, and allows the rear encapsulant to flow through and encapsulate the back surface of the cell. The advantage of this approach is that standard materials (EVA and Tedlar™) can be used. This circuit is also fabricated with the same pre-patterned copper foil used in the first design. After the components are positioned, the entire assembly is laminated using a conventional lamination process.

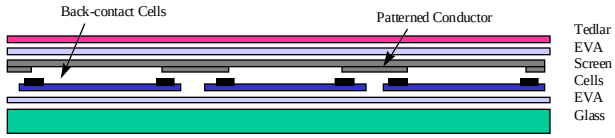

Figure 3. Exploded side view of conductors-on-screen MMA option.

MODULE DEVELOPMENT

We tested various aspects of the new module designs in order to demonstrate the concept and determine critical areas for further development.

The interconnect technologies are a significant departure from existing PV assembly technologies. We therefore examined the resistance of the different interconnect technologies (Fig. 4). The measured resistance included the bulk resistance of the interconnect material and the interfacial resistances. All of the materials met our performance goal, although none of the new materials could achieve a resistance as low as Pb:Sn solder. We also performed pull tests on both the acrylic conductive adhesives. The strength of the acrylic-adhesive bonds was about

50% of the strength of our typical die-attach epoxy bonds, which was considered sufficient to further investigate acrylic adhesives.

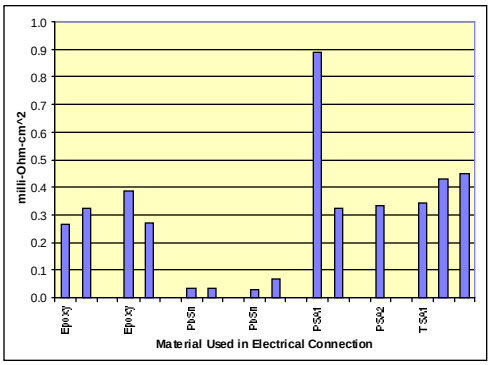

Figure 4. Resistance between copper tabs and a solar-cell silver pad for the following interconnects: silver-loaded epoxy, Pb:Sn solder, two types of pressure-sensitive conductive adhesives (PSA), and thermosetting conductive adhesive (TSA). Several samples of each type were measured. All the interconnects met the target resistance of less than 1 mΩcm^2.

Mechanical prototypes of each design (Fig. 2 and 3) were fabricated and thermal cycled (Fig. 5). The mechanical prototypes used electrically inactive "cells"; i.e., the "cells" were resistance devices with the same grid structure as an actual solar cell. The mechanical prototypes typically had four devices connected in series. The resistance of the mechanical prototypes was monitored to check the assembly process and to monitor changes during thermal cycling. The mechanical prototypes were thermal cycled from -40°C to +90°C, with a dwell time at each temperature of 30 minutes and a total cycle time of 3.5 hours. The mechanical modules were visually examined after 120 cycles.

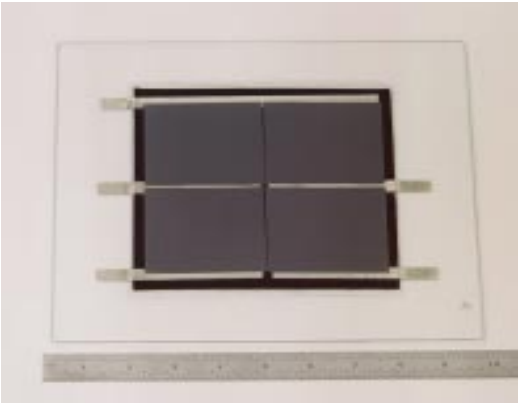

Figure 5. Photograph of the front surface of a MMA mechanical prototype. This module used the conductors-on-backsheet design (Fig. 2).

All the mechanical prototypes had low electrical resistance prior to thermal cycling, which demonstrated the positional accuracy of the new assembly processes and the good bonds at room temperature. The samples using thermosetting conductive adhesive, however, failed the thermal cycling tests. The resistance of these samples increased dramatically with temperature, and some of these samples would reversibly open circuit. Our particular "thermosetting" adhesive contained, in fact, a significant fraction of pressure-sensitive adhesive (PSA) resins. Samples using 100% thermosetting acrylic adhesive will be tested next, and may perform better than the PSA. It should also be noted that conductive PSA'a have been used in applications with similar reliability requirements. We believe that the PSA may require a different application method (e.g., roll lamination) to be successful.

Resistance versus the thermal cycling for three mechanical modules using conductive epoxy is shown in Fig. 6. These samples all used the screen-mesh and EVA construction. The epoxy worked better than the conductive adhesive, but there is still a trend towards higher resistance with longer thermal cycling. Conductive epoxies are used in die-attach applications with much more severe thermal cycling requirements. For example, we have used epoxy bonds in applications that required passing thermal cycling tests between -65°C and +175°C. Since we know that the epoxy bond is capable of meeting our technical requirements, we believe that the encapsulation cycle will need to be further tuned to obtain more fully cured bonds. Other issues, such as fatigue, will also need to be investigated. Visual inspection of the modules after 120 cycles showed no delamination of the contacts or encapsulation.

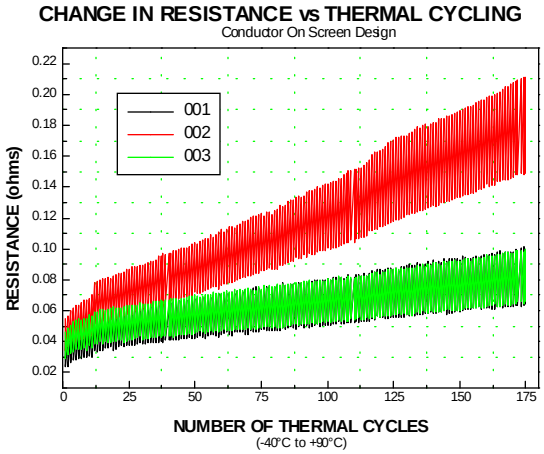

Figure 6. Thermal cycling data for three mechanical modules using conductive epoxy.

Finally, we fabricated a minimodule using the screen-mesh approach and conductive epoxy (Fig. 7). The minimodule had four series-connected back-contact 42-cm^2 emitter wrap-through (EWT) cells. The fabrication sequence for the EWT cells is described elsewhere [8]. The average fill factor of the four EWT solar cells was 0.662, while the fill factor of the encapsulated minimodule was 0.663. Hence, the module interconnects in the MMA module introduced negligible additional series resistance or shunt conductance. The relatively poor performance of the EWT cells is due to the early development of back-contact cells.

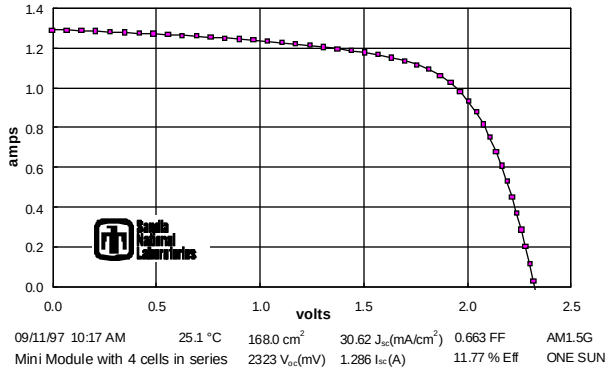

Figure 7. One-sun performance of MMA module.

COST ANALYSIS

It is difficult to estimate costs for a process that is not fully developed. However, the motivation for work on MMA can be demonstrated through some simple cost comparisons.

For the first products that use MMA, most of the material costs for the module assembly will be similar to present technology (e.g., glass, encapsulant, and backsheet). Also, we assume that encapsulation equipment and throughputs similar to present industry standards are used for MMA. Hence, the difference in cost is due to differences in the electrical circuit assembly. MMA will use pick-and-place equipment to lay the cells out for encapsulation, which will replace the cell tabbing machines, cell stringers, and layout work stations of the present process. We estimate that MMA equipment could achieve a 2X improvement in throughput at half the capital cost of current tab/string machines. We also believe that MMA would have improved yield compared to current processes because the processes are more planar. Consequently, a cost reduction of nearly 50% is estimated for labor and capital in the module assembly area of the PV module manufacturing plant.

The monolithic backsheet with the integrated circuit, encapsulant, and backsheet is manufactured using high-volume roll-to-roll style equipment, which will probably be performed by a vendor. The monolithic backsheet will therefore appear as an increase in material cost to the PV module manufacturer. Conservatively assuming an added cost of $15/m^2 for the manufacture of the monolithic backsheet (i.e., cost in addition to the material cost of the encapsulant and backsheet), the net savings with MMA compared to the current process is estimated to be between 10% and 20% at the module level. Any increased costs for fabrication of the back-contact cell would reduce this potential cost savings. On the other hand, including advanced roll-based encapsulation techniques with MMA could achieve even further cost reductions [6,7].

The space photovoltaic community uses back-contact c-Si solar cells due to their advantages in array assembly. Cost reductions at the array level of 25% have been reported for large space PV arrays by using back-contact rather than bifacially contacted solar cells [9].

CONCLUSIONS

We described some new module assembly concepts using back-contact c-Si solar cells. The new module assembly concepts have the potential to significantly reduce the manufacturing costs of the module assembly.

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