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Conductive-paste-based high-yielding interconnection process for c-Si photovoltaic modules with 50 μm thin cells

Hyung-Jun Song[a], Tae Hee Jung[a,b], Soo Min Kim[c], Woo Gyun Shin[a], Ga-Eon Jin[a], Young Chul Ju[a], Kyung Taek Jeong[a], Hee-eun Song[a], Min Gu Kang[a], Jeong In Lee[a], Gi Hwan Kang[a,*]

[a] Photovoltaic Laboratory, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 34129, South Korea
[b] Electric Power New Industry Technology Center, Korea Testing Laboratory, 723, Haean-ro, Sangnok-gu, Ansan, Gyeonggi-do 15588, South Korea
[c] Gumi Electronics & Information Technology Institute, 17, Cheomdangieop1-ro, Gumi, Gyeongsangbuk-do 39171, South Korea

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ABSTRACT

Thin crystalline silicon (c-Si) photovoltaic (PV) cells (< 100 μm) have the potential to curtail manufacturing costs by reducing the amount of Si needed per wafer. However, thermo-mechanical stress induced by high-temperature (> 200 °C) soldering causes frequent wafer breakage in thin c-Si-based modules. Hence, in this work, we proposed low-temperature interconnection method using conductive paste (CP) for thin c-Si PV modules and systematically studied the modules' electrical and mechanical properties as a function of annealing temperature of CP. The potential advantage of this method is significantly reduced wafer *bowing* due to the low-temperature tabbing (< 150 °C) of CP dispensed cells to ribbons using heat and pressure during lamination. Module degradation and peel stress tests indicated that CP cured above its melting point provides stable (degraded 3.0% after 500 h damp heat test) and efficient current flow paths. By contrast, CP annealed below the melting point is vulnerable to thermal and humidity stress, leading to 7.8% degraded output after the test. Given these features, stable, large modules with thin c-Si cells integrated using a CP approach (laminated at 150 °C) were successfully realized without cell breakage.

1. Introduction

The interconnection of crystalline silicon (c-Si) photovoltaic (PV) cells is a key technology for gathering photogenerated power from each cell with small losses in PV modules. Among many suggested techniques, a contact-soldering (CS) process, during which a high-temperature (> 200 °C) tip is applied to solder-coated copper ribbons on busbars of PV cells, is the dominant tabbing method. In CS, solder alloy (i.e., SnPb, SnCuAg, and SnPbAg) coated onto copper ribbon reflows because of an applied high temperature and forms a strong bond with the metallization layer of a c-Si PV cell. The simple yet effective conventional CS process enables the generation of highly conductive and mechanically stable bonds between cells and ribbons at low cost [1–4]. Nevertheless, thermo-mechanical stress induced by different thermal expansion coefficients of the silicon and ribbon is unavoidable in CS [5–7]. The heating and cooling of cell and metallic ribbon during the CS provokes thermo-mechanical stress, resulting in micro-crack and bowing in the cell. In particular, as the thickness of wafer decreases, c-Si PV cells are more vulnerable to stress [8,9]. Thus, wafer breakage frequently occurs in thin (< 50 μm) cell-based modules integrated by the CS method. For instance, most of 50 μm cells were broken or bent during the optimized high-temperature CS process (~ 250 °C) for 180 μm samples. Additionally, micro cracks caused by the stress result in the premature ageing of modules under outdoor working conditions [10–13]. As a result, the low-yielding high-temperature process hinders the widespread use of thin c-Si PV cells despite their advantages of i) low cost resulting from reduced consumption of bulk Si and ii) excellent energy-harvesting ability [14–17]. Even this issue also arises in the cell fabrication process, modification of procedure can reduce the bowing and cracks in thin cell process [17,18]. However, the suitable approach to interconnect cells with reduced thermo-mechanical stress is not widely studied.

Besides, a cell-string-based module process in the CS approach triggers increased losses when applied to thin cells. Because the melting point (T_M) of the polymer encapsulant (< 110 °C) sandwiching the ribbon-attached cells is lower than the process temperature of CS, the interconnection of cells should be completed before the lay-up [19]. Consequently, ribbon-attached PV cells are normally connected to a cell string whose length is similar to that of a column of the PV module. For instance, a cell string consists of 12 cells in widely used 72-cell modules

* Corresponding author.
E-mail address: ghkang@kier.re.kr (G.H. Kang).

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(12 × 6). Unfortunately, such an extended string has a higher chance of failure than a shorter one because of an increased number of connections regardless of cell thickness. However, the chance of failure is larger, as the thickness of cell is thinner because of aforementioned cracks and bowing in a thin single cell [8,9,11]. Intensive studies have been conducted to obviate the cell-string-based high-temperature CS approach in the module process by introducing, for example, a pre-patterned conductive layer [20–22], metallic micro ball-embedded conductive paste [23–25], or laser welding [21]; however, none of these methods provides a production-ready approach in terms of yield and cost. Previous work related to a precious metal (silver) based conductive paste (CP) method has substituted high-temperature soldering with the CP approach rather than modifying a string-based module process, whereas misalignment of cells and ribbons arising from inevitable external force should be solved in laser and pre-patterned layer approaches. For the aforementioned properties, a high-yielding interconnection process, including low-temperature soldering without cell-string, is urgently required for utilizing thin cell-based modules.

Hence, we here present an alternative route for interconnecting thin cells by employing CP consisting of SnBiAg microballs and epoxy. The key feature our approach is the integration of CP-implemented thin cells using low-temperature annealing (~ 150 °C) during the lamination process to diminish cell breakage. Moreover, a cell-string can be eliminated by laying CP dispensed cells onto pre-positioned ribbons without soldering, as shown in Fig. 1. The resulting low-temperature and simplified CP approach might lead to the interconnection of thin cells with high yield, compared to CS method. Moreover, as costs of bulk Sn (~$20/Kg) and Bi (~$15/Kg) are much cheaper than that of silver (~ $500/Kg), previously suggested material for paste, this method guarantees to fabricate thin cell based module with low cost [27]. To utilize the module with our approach, the electrical and mechanical properties of module were characterized and compared with the CS method. Furthermore, the degradation of interconnection based on CP approach was examined under harsh condition depending on its annealing temperature. Finally, the PV modules with thin cells using CP method are constructed and characterized.

2. Experiment

2.1. CP-based interconnection process

Fig. 1 exhibits the via CP and CS fabrication procedures of modules, respectively. In CS, ribbons are attached to the busbar of a cell using a high-temperature contact tip (> 200 °C). Before the lay-up of tabbed cells with other parts, a ribbon-attached cell was connected to neighbouring cells to construct a cell string. After being inspected and transferred, the cell string was sandwiched by encapsulant film such as ethylene vinyl acetate (EVA). Moreover, back-sheet and front glass were added. Finally, the modules were fabricated using a laminator (480–1222 S, Nisshinbo Mechatronics, Inc.) with 10 min of pre-annealing at 110 °C, followed by 5 min of hot pressing at 150 °C under high pressure (~ 1000 mbar). Due to the low T_M of EVA, all high-temperature processes, including CS, should be conducted before the lay-up process to prevent bubbles and delamination in the module [10,28]. Thus, a cell string is mandatory in CS, which imposes additional costs associated with a tabbing-stringer and increases the chance of failure. Furthermore, this high-temperature process in CS mitigates the advantage of thin cells by causing cracking in wafers.

By contrast, our CP-based system does not induce cell breakage because soldering is performed under low temperatures during lamination. Moreover, the elimination of cell strings allows us to simplify the module fabrication process, which may result in increased yield. Here, the CP (ESP150PT4, Hojeonable) is a mixture of metallic microballs (42Sn57.6Bi0.4Ag with radii from 20 to 50 μm) and a polymer with a solvent, as marked in the scanning electron microscopy (SEM) images in Fig. 1(c). The weight ratio between the metallic balls and the polymer was 9:1. In the CP approach, the CP was printed onto the front and rear busbars of the cell at room temperature using a needle-incorporated air pulse dispenser (needle radius = 0.3 mm, dispenser speed of 40 mm/s, air pressure = 500 Kpa) without any additional heating. Then, approximately 0.3 mm (height) × 0.6 mm (width) of CP was uniformly dispensed onto the surface of a busbar (width = 1.2 mm). Cells with dispensed CP were laid on pre-positioned ribbons, located on a stack of EVA and glass. In this experiment, cells and ribbons were manually assembled; however, an automated pick-

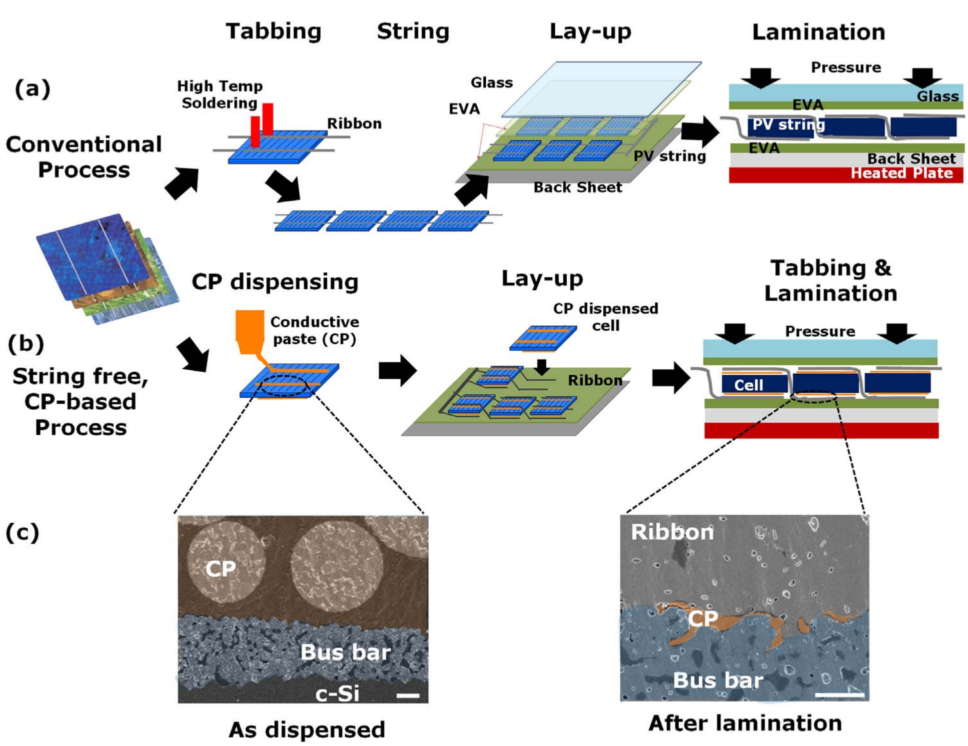

Fig. 1. Schematic of the fabrication of a PV module with (a) CS and (b) CP methods. In the CP approach, a CP-dispensed cell lies on pre-positioned ribbons at an EVA/glass stack without construction of a cell string. Additional ribbons are placed in front of arranged cells. Finally, ribbons are permanently attached to cells during lamination as a result of heat and pressure. The annealing temperature is lower than that for the CS process, which might results in fewer cracks in thin cells. (c) Cross sectional scanning microscopy image (SEM) of as-dispensed and laminated conductive paste. In as-dispensed sample, radii of metallic micro-ball are 20–50 μm, while they are totally compressed and fill the gap between ribbon and busbar after lamination process. Here the scale bar is 5 μm and the CP was laminated at 150 °C.