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Thermomechanical-stress-free interconnection of solar cells using a liquid metal

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ABSTRACT

Research efforts to overwhelmingly fortify the economics of photovoltaics have focused on increasing the light-to-electricity conversion efficiency and reducing the overall manufacturing costs. Since lowering the consumption of silicon has the potential to greatly curtail the material costs, studies on wafering thin silicon substrates have been performed. However, current methods to interconnect solar cells with metal ribbons are not sufficient to employ thin silicon wafers. Therefore, this study explores a novel route to interconnect solar cells with metal ribbons without thermomechanical stress using a highly conductive liquid metal. Galinstan, which is notoriously difficult to print, is successfully harnessed to be printable by suspending submillimetre-sized Galinstan droplets in the carrier vehicle, as aided by the yield stress. By mechanically sintering the Galinstan paste with gentle mechanical pressure, solar cells are interconnected with metal ribbons at room temperature. Albeit the averaged maximum power of the unit modules interconnected using the Galinstan paste was significantly degraded after just 100 thermal cycles due to the possible formation of resistive intermetallic compounds of Galinstan, the power degradation of the best unit module using the Galinstan paste is −0.9%, which is smaller than the averaged one of the unit modules using a conventional soldering method (-1.35%), implying the thermomechanical-stress-free interconnection method using a liquid metal has a chance to be improved for being a comparable competitor to the conventional soldering method.

1. Introduction

To gain more favourable economics for the utilization of photovoltaics, especially for crystalline silicon solar cells, which are the most prominent photovoltaic product in the market, efforts have been made to increase the light-to-electricity conversion efficiency by minimizing the various sources of optical and electrical losses, such as nanostructuring the frontal silicon surface to absorb more sunlight [1], reducing recombination by surface passivation [2], introducing heterojunctions [3] or tandem structures [4], and constructing high-aspect-ratio front metallization [5–7].

Other efforts have been made to consume less silver using advanced printing and busbar-less interconnection technologies [8–10] as well as to consume less silicon using either advanced wire sawing or kerf-less wafering technology [11,12]. Specifically, to reduce the cost of a silicon wafer, which accounts for approximately 40% of the cell price [13], the as-cut silicon wafer (currently approximately 180 µm) and the limit of cell thickness in the module technology are anticipated to become as thin as 140 µm and 110 µm, respectively, by the year 2027 [13,14].

However, reducing the thickness of a silicon wafer renders it more vulnerable to thermomechanical stress. When thin solar cells are interconnected with solder-alloy-coated metal ribbons at a typical process temperature of at least 200 °C, thermomechanical stress is developed due to the different coefficients of thermal expansion of the solar cell and the metal ribbon, likely resulting in either the instantaneous breakage of the thin solar cells or development of micro-cracks inside the cells, which culminates in the breakage of the thin solar cells during long-term operation. Although intensive studies have been conducted to minimize thermomechanical stress during the interconnection process of solar cells with metal ribbons, the developed interconnection methods such as laser welding, ultrasonic bonding, and gluing with conductive adhesives require processing temperatures of 225 °C, 177 °C, and 125 °C, respectively [15–18]. Therefore, none of these methods have offered a completely thermomechanical-stress-free

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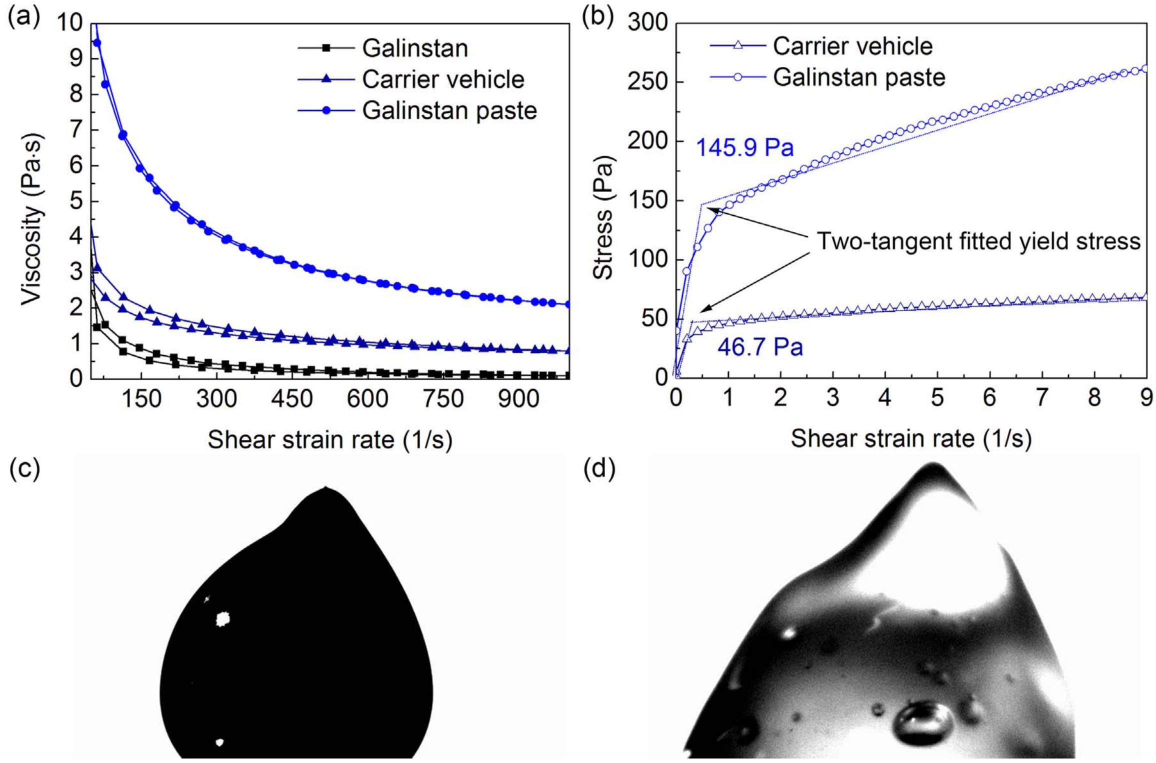

Fig. 1. (a) Measured viscosities of Galinstan, the carrier vehicle and the Galinstan paste, (b) yield stresses of the carrier vehicle and Galinstan paste, and photographic images of Galinstan in (c) and the carrier vehicle in (d).

interconnection, which is imperatively demanded for the fabrication of photovoltaic modules with thin silicon solar cells.

Here, we propose a novel means to interconnect solar cells with metal ribbons without the development of thermomechanical stress and compare the efficiencies of the unit modules—one fabricated using a conventional soldering method and the other using the thermomechanical-stress-free method with a highly conductive liquid metal, *i.e.*, Galinstan [19].

2. Experimental

Although this study intended to investigate the ability of a liquid metal to produce a thermomechanical-stress-free interconnection for thin solar cells with metal ribbons for future photovoltaic modules, commercially available standard Al BSF mono-crystalline silicon solar cells (nominal thickness of 180 µm) with three segmented busbars on the front side and three dashed-line busbars on the rear side were used for these experiments, as thin silicon solar cells less than 180 µm are not yet commercially available. The electric parameters of 20 solar cells before interconnection are provided in Table S1 (Supporting Information). Solder-alloy-coated metal ribbons (ETP-Cu Sn60Pb40, KOS Ltd.) were interconnected with the front and rear busbars of a solar cell using either conventional soldering or the thermomechanical-stress-free interconnection method proposed in this study. For conventional soldering, a soldering iron (FX-888D, Hakko Corp.) with a replaceable hot-knife tip was used. Notably, the set temperature of the used soldering iron does not represent the real soldering temperature at the soldering tip and metal ribbon because of the use of a replaceable soldering tip, the position of the temperature sensor, and the rate of heat transfer. No pre-heating was performed before soldering, which might also increase the set temperature of the solder iron. In accordance with our experiments, the required minimum set temperature for soldering was at least 375 °C. Therefore, for smooth soldering at a speed of at least 1.5 cm/s with the minimized occurrence of wafer cracks, the solder iron was set at 450 °C to quickly melt and join the solder alloy on the metal ribbon with the fluxed silver busbar of the solar cell.

For the thermomechanical-stress-free interconnection, a carrier vehicle was first prepared by dissolving ethyl cellulose (CAS No. 9004-57-3, Sigma-Aldrich Corp.) with a surfactant (Zephrym™ PD 2246, Croda International Plc.) and a rheological modifier (Thixatrol® Max, Elememtis Specialties, Inc.) in the solvent mixture of 2-(2-butoxyethoxy)ethyl acetate (CAS No. 124-17-4, Samchun Pure Chemical Co., Ltd.) and α-terpineol (CAS No. 98-55-5, Kanto Chemical Co., Inc.). The liquid metal used as an interconnecting material was the ternary eutectic system of gallium (68.5 wt%), indium (21.5 wt%), and tin (10 wt %), *i.e.*, Galinstan (Changsha Santech Materials Co., Ltd.). Galinstan is a non-toxic liquid metal alloy with a nominal melting temperature, electrical conductivity, and surface tension of -19 °C, 2.3×10^6 S/m, and 534.6 mN/m under a nitrogen atmosphere at 28 °C, respectively [20]. Galinstan was mixed with the carrier vehicle using a planetary centrifugal mixer (ARE-310, Thinky Corp.). The detailed preparation procedure of the developed Galinstan paste is described in Fig. S1 (Supporting Information). The mixed form of Galinstan and the carrier vehicle, *i.e.*, the Galinstan paste, was manually dispensed *via* syringe on the solar cell busbars. For the temporary bonding of the solar cell busbars and metal ribbons, a transparent UV curable adhesive (UV-8800, Skycares Co.) was used and cured with a generic hand-held UV LED lamp. The unit modules were finally completed using a vacuum laminator (480–1222 S, Nisshinbo Mechatronics, Inc.) with 9 min of pre-annealing at 110 °C in vacuum, followed by 5 min of hot pressing at 150 °C under the pressure of 760 mmHg. The detailed temporal parameters of temperature and pressure for the hot pressing are shown in Fig. S2 (Supporting Information).

The rheological properties of Galinstan, the carrier vehicle and their mixture were characterized using an HAAKE Mars Rheometer (Thermo Fisher Scientific, Inc.) at 23 °C. Electrical characterization was conducted using a probe station (MST 4000 A, MS Tech Co., Ltd.) and a source metre (Model 2410, Keithley Instruments Inc.). The efficiencies of the unit modules were measured with a solar cell I-V test system (K3000, McScience, Inc.). The electroluminescent (EL) and thermal