A Study of Molten Lead-Free Solder Deposited by Inkjet Printing for Interconnections of Thin-Film Solar Cell Modules

Wen-Ming Chen, Chien-Hsun Wang and Weng-Sing Hwang*,
Department of Materials Science and Engineering, National Cheng-Kung University
(No. 1, University Road, Tainan City 701, Taiwan, R.O.C.)
Tel.: +886-6-2757575 ext. 62928; fax: +886-6-234-4393
E-mail address: wshwang@mail.ncku.edu.tw (W. S. Hwang)

ABSTRACT

A joint of lead-free solder deposited by inkjet printing on a thin-film solar cell was investigated in this study. The lead-free solder Sn3.0Ag0.5Cu was applied as the solder joint between the back electrode of a thin-film solar cell and photovoltaic ribbon. A single droplet of molten lead-free solder was ejected from the orifice for each pulse of the bipolar waveform at a suitable amplitude. An array pattern with solder joints was applied on the aluminum back electrode of thin-film solar cell to replace silver conductive adhesives. A high joint strength of 1.95 N/mm was measured for the bonding structures after a reflow process at 245 °C for 75 s. The photovoltaic conversion efficiency of thin-film solar cell was 8.54 %. A solder joint deposited via inkjet printing provides high strength at low cost for the energy technology applications.

Keywords: lead-free solder, inkjet printing, thin-film solar cell

1 INTRODUCTION

The photovoltaic (PV) industry is booming and fast growing over last decade. The main inorganic solar cells are crystalline silicon solar cells, however, due to the high cost of silicon wafers, its cost reduction potential seems be limited, considering the material consumption, cost efficiency, photovoltaic conversion efficiency and module fabrication. Now, the main developments of solar cells are Si-based thin-film solar cell [1,2]. However, most of studies focus on the cell structure to enhance the conversion efficiency rather than improving the solar module packaging. One of the important steps of the solar module process is to connect conductive ribbon and lead current to the junction box. In thin-film solar module fabrication, it needs to connect solar cell and copper ribbon by using silver conductive adhesives, but the high cost of silver conductive adhesives and poor bonding strength limited developments of thin-film solar cell. Sodering is one of the interconnection techniques in modern electronic industry. Previous studies examined the effect and performance of solder-coated ribbon on solar cell [3,4]. Since the inkjet printing technology provides the advantages of direct writing [5] that cause the reduction of material consumption, control precise position and design particular patterns for electronic module application, it is a potential method to fabricate soldering micro-joint in interconnection. This study focused on using a simple and efficient approach and development of innovative connection techniques for thin-film solar cell module fabrication. In order to alter and improve the connection fabricating process, this study attempted to use the drop-on-demand (DOD) inkjet printing method to fabricate uniform array pattern of lead-free solder as joints to connect with copper ribbon.

2 EXPERIMENT METHOD

2.1 Inkjet printing device

The DOD piezoelectric inkjet printing device is constructed with four functional sections: pneumatic, heating, printing and monitoring. The pneumatic control section uses N_2 gas to alter back-pressure of the molten solder reservoir and N_2 shroud-flow to prevent oxidation of molten solder near the print head during printing. The heating section provides heat and maintains temperature for the molten solder reservoir. The printing section consists of a piezoelectric print head that is driven by using a waveform of a given pulse time and voltage. The piezoelectric print head is manufactured by MicroFab Inc. and the diameter of the print-head nozzle orifice in this study is 50 μm. The monitoring section records images, using a CCD camera and a light emitting diode (LED), to observe the evolution of micro-droplet between the print-head nozzle and the substrate.

2.2 Solder material

A commercial lead free solder of Sn3.0 wt%Ag0.5 wt%Cu with 99.99% purity composition was used in this study. The melting point of SnAgCu alloy is about 217 °C. The fluid properties of molten SnAgCu alloys from the previous study reveal that the surface tension is 493 mN/m at 270 °C and viscosity is about 2 mPa s at 240 °C. In addition, the surface tension and viscosity of molten metal decrease as temperature increases. Therefore, in order to obtain the proper fluid properties in the experiment, the ink-reservoir temperature was maintained at 230 °C at all times to provide sufficient superheat of SnAgCu alloy.

2.3 Soldering flux

The thin-film solar cell structure usually deposits aluminum thin-film as back-contact electrode, but the bonding of aluminum is very difficult due to its surface oxide (Al_2O_3). Therefore, it is necessary to coat flux on aluminum back electrode of thin-film solar cell to enhance the wettability of solder. The basic compositions of commercial flux contain Aminoethylethanolamin, Triethanolamine and Ammonium fluoborate. The main composition remove the surface oxide of aluminum was Aminoethylethanolamin (NH_4BF_4). The chemical compositions react with surface oxide by following equations [6,7].

$$NH_4BF_4 \rightarrow NH_3 + HBF_4 \quad (1)$$

$$HBF_4 \rightarrow HF + BF_3 \quad (2)$$

$$Al_2O_3 + 6HF \rightarrow 2AlF_3 + 3H_2O \quad (3)$$

In addition, the rosin was also used to mix with flux due to the high concentration of commercial flux caused the residual on substrate. The mixture ratio of fluxes to rosin was 1: 3 and then maintained at 150 ˚C for 30 minutes to become homogeneous mixture.

2.4 Printing and connection process

The 30mm × 30mm × 4mm sample of amorphous silicon thin-film solar cell (glass/TCO/a-Si/Al) was used in this study. A bipolar pulse waveform with given pulse voltages and times drives the piezoelectric printing head. A schematic diagram of bipolar pulse waveform is shown in Fig. 1.The printing parameters of pulse time were set as 4 μs for t_{rise}, 10 μs for t_{dwell}, 2 μs for t_{fall}, 4 μs for t_{echo} and 6 μs for $t_{finalrise}$. The parameters of pulse voltage were set as V_1 of -5 V, V_{DC} of -31 V and V_2 of -57 V. In addition, because the surface tension of molten solder is 493 mN/m, a positive pressure was maintained in inkjet reservoir in order to fill the molten solder into the squeeze tube. The reservoir pressure was 2.5kPa in this experiment. The single droplet of molten lead-free solder was ejected from the orifice for each bipolar pulse waveform at suitable amplitude and deposited on aluminum back electrode coated with flux. Under the effective area with width of 5mm and length of 30mm, the interval between deposited droplets of lead-free solder was 100 μm for each one and formed an array pattern. Subsequently, copper ribbons(purity≧99.90%) with the thickness of 0.1mm and width of 5m covered on the aluminum back electrode with coated flux. During reflow process with reflow profile of 245 ˚C for 75 seconds of the time above liquidus, the droplets of lead-free solder were re-melted to connect aluminum back electrode and copper ribbon. A schematic illustration of connection of thin film solar cell module is shown in Fig. 2.

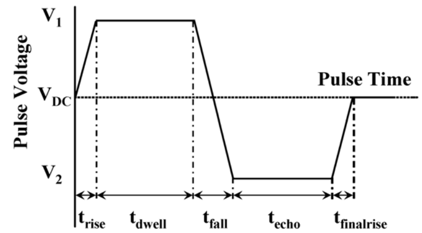

Figure 1: A schematic diagram of bipolar pulse waveform.

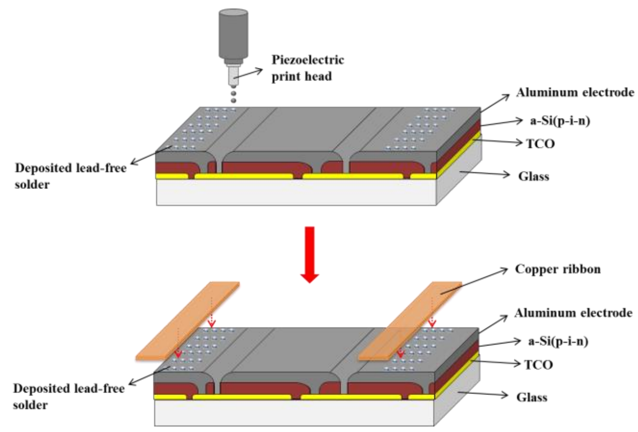

Figure 2: A schematic illustration of connection of thin film solar cell module.

3 RESULTS AND DISCUSSION

The evolution of molten lead-free solder ejected from the nozzle of piezoelectric print head is shown in Fig. 3. The images of time evolution of single droplet were recorded by the CCD camera. The jetting molten solder formed a liquid thread from the nozzle. Then, the liquid thread necked and pinched off as a droplet. The formation of droplet was a stable single micro-droplet and it was sure that no satellite droplet formation occurred. The formation of satellite droplet affected the quality of inkjet printing on the aluminum back electrode. The array pattern on back electrode of thin film solar cell with each solder joint diameter of 46 μm and 100-μm spacing is shown in Fig. 4.

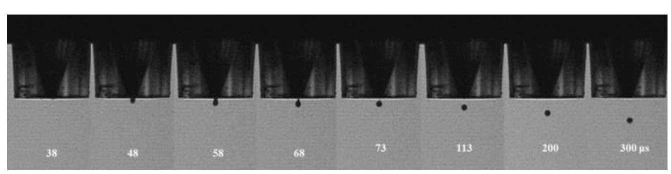

Figure 3: Time evolution of single droplet formation.

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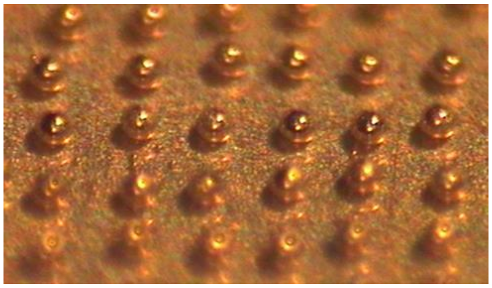


Figure 4: Photograph of array pattern on back electrode of thin film solar cell with 100-µm spacing.

3.1 Peel strength

The peel strength test is used to compare the quality of bonding strength between silver conductive adhesives and soldering. Fig. 5 shows the curve of peel strength and observed clearly that the peel strength of silver conductive adhesives was poorer than soldering. The average peel strength of soldering was 1.95 N/mm and that of silver conductive adhesives was 0.77 N/mm in this study. The peel strength of silver conductive adhesives which was compared from the literature also revealed that it was poorer than soldering [8,9]. The bonding of SnAgCu alloy is much better than the silver based conductive adhesives. The main reason of poor peel strength for silver conductive adhesives was the composition of silver particles and epoxy resin, which formed pores and cracks on the bonding interface between silver conductive adhesives and aluminum electrode. In addition, the SEM images of thin film solar cell before soldering and after soldering are shown in Fig. 6 and show no pore between SnAgCu alloy and aluminum electrode. It was speculated that using solder flux enhanced the wettability and solderability between solder and metal electrode, so it resulted in good mechanical properties.

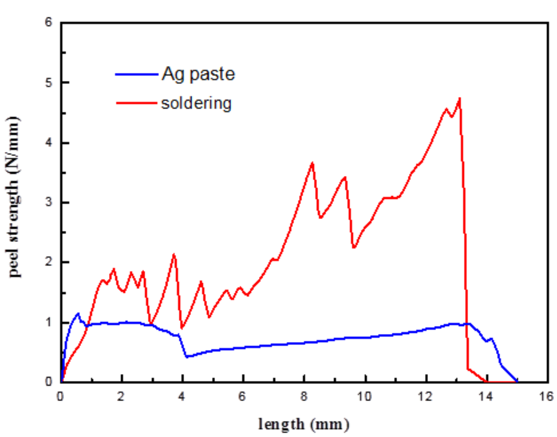
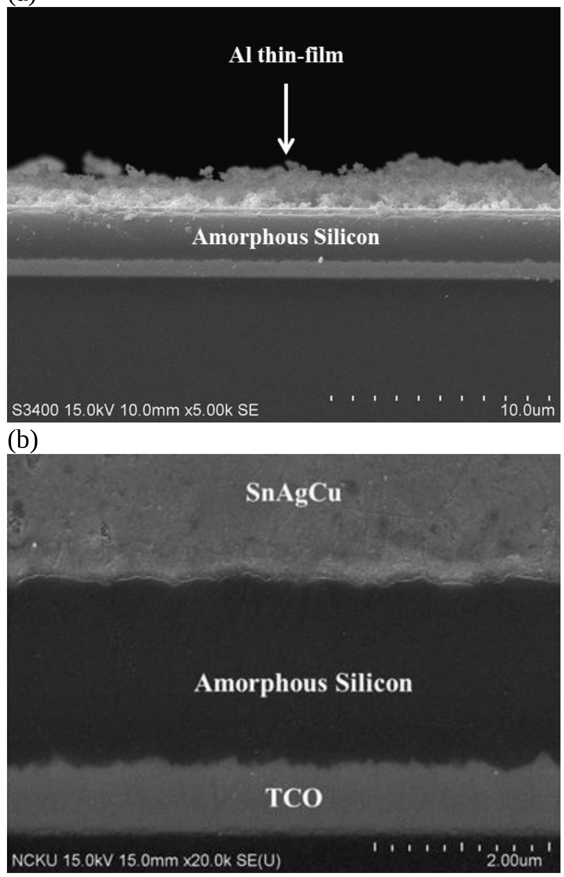


Figure 5: Peel strength with different bonding techniques.

(a)



(b)

Figure 6: SEM images of thin-film solar cell (a) before soldering. (b) after soldering.

3.2 Electrical characteristics

I-V curves of thin-film solar cell before soldering and after soldering are shown in Fig. 7. The electrical variations of solar cell are tabulated in Table 1. The maximum power (P_{max}) of solar cell changed from 52.25 mW to 51.25 mW. Fill factor (FF) of solar cell changed from 0.699 to 0.696 and the photovoltaic conversion efficiency (η) changed from 8.745 % to 8.542 %. Although the degradation of photovoltaic conversion efficiency was 2.32%, it was accepted for solar cell module package and was in the standard range. The change of power loss may be caused by using the SnAgCu alloy as the connection of copper ribbon and aluminum electrode, which increased the contact resistance. Therefore, it is possible to use SnAgCu solder as joints to connect copper ribbon and aluminum electrode by inkjet printing, and the bonding technique cause less electrical power loss. The bonding technique provides a choice for thin-film solar cell module package.

Table 1: The electrical variations of thin-film solar cell.

Thin-film solar cell	**Before soldering**	**After soldering**	**Change %**
P_{max} (mW)	52.47 mW	51.25 mW	-2.33 %
FF	0.699	0.696	-0.43 %
η (%)	8.745 %	8.542 %	-2.32 %

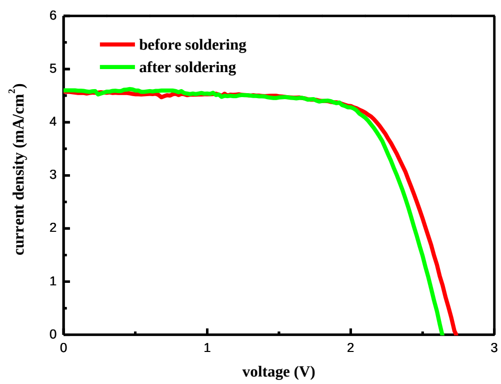


Figure 7: I-V curves of thin-film solar cell before soldering and after soldering .

4 CONCLUSIONS

The main purpose of this study was to alter and replace silver conductive adhesives for the connection copper ribbon and back aluminum electrode in the fabrication of solar cell modules. In this study, the printable SnAgCu solder was successfully as joint connecting between copper ribbon and aluminum back electrode for thin-film solar cell. A high peel strength of 1.95 N/mm was obtained for the bonding structures after a reflow process at 245 ˚C for 75 s. The photovoltaic conversion efficiency of thin-film solar cell was 8.542 %. The bonding technique by inkjet printing provides a choice for thin-film solar cell module package.

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