SOLDER JOINT ANALYSIS OF TIN-LEAD AND BISMUTH BASED LEAD FREE PV RIBBONS IN HIGH THROUGHPUT MANUFACTURING

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ABSTRACT: PV module manufacturers increasingly require higher throughput production lines with higher degrees of automation and flexibility. Establishing an electrical connection between solar cells in a module not only defines the final shape and output power of the solar panel, depending on the strategy applied it but also strongly impacts yield and throughput of the entire module factory. There are not too many reports on solder joint analysis in high manufacturing scenario. This paper analyses solder joints and factors affecting solder joints in high throughput manufacturing. Paper also report performance of new lead free solder, EcoSol™ along with standard tin lead ribbon in an automated tabbing machine. We found that under identical conditions, the solder joints in lead and lead free ribbons were comparable and peel strength of >2.5 N/mm on front and back side of the cell obtained. DOE results reveal that the cell metallization play an important role in determining quality of solder joints. Grade A PERC cells yielded higher peel strength compared to p-type c-Si cells due to the smooth surface topology. Similarly, flux having good wetting time performed better. Ribbon alignment was identified as one of the major causes of the weak solder joints. Due to decreased ribbon and bus bar size, this problem might occur frequently. Microscopic investigation yielded, absence of IMC (intermetallic compound) in either of the ribbons due to rapid production speed. Only diffusion of tin into silver matrix was observed. This, however, does not have any effect on peel strength and cohesive failure was evident from fracture surface analysis.

Keywords: Solar cell, soldering, solder joint

1 INTRODUCTION

The PV industry has evolved substantially during the last decade and witnessing continuous advancements with respect to throughput, efficiencies and materials used in the manufacturing of photovoltaic components. The growth is further fueled by the rising demand for energy, support extended by the government, sharp drop in module prices and the growing concern regarding environment [1].

In light of this growth, PV module manufacturers increasingly require higher throughput production lines with higher degrees of automation and flexibility. In the past the focus was on the cell level performance, now it has been shifted to the PV module performance itself. As the number of busbars in the photovoltaic cells increases, the interconnected welding process, becomes a bottleneck in many production lines. Moreover, due to new module designs and equipment, for which providers offer new machines to enable high-throughput production, the knowledge of solder joints becoming crucial and challenging. Establishing an electrical connection between solar cells in a module not only defines the final shape and output power of the solar panel, depending on the strategy applied it also strongly impacts yield and throughput of the entire module factory [2].

There are not too many reports on solder joint analysis in high manufacturing scenario. The effect of shrinking ribbon dimensions and narrower bus bars on reliability of joints is not known. Process parameters such as ribbon misalignment and its impact on peel strength is also not documented. The performance of standard and lead free ribbons in manufacturing conditions has not been studied simultaneously. This paper critically asses the solder joints and factor affecting the same in high throughput environment. Two types of ribbons, viz. tin lead (Sn-Pb) and lead free (Alpha's EcoSol^{TM}) were used for this study. EcoSol ribbon has liquidus temperature of 179^{o}C. It is a non eutectic alloy with Bi content less than 40 wt.%, and performance enhancing additives to improve mechanical and thermal reliability [3]. Besides that, reduced silver (Ag) content in EcoSol makes it attractive in a cost sensitive industry such as PV. These ribbons were soldered on 4 bus bar (BB) c-Si (crystalline silicon) cells. The soldering was achieved in such a way that each busbar of the cell is soldered with lead (Pb) and lead free (EcoSol) ribbon alternatively. P-type and n-type PERC c-Si cells were used for comparison. Experiments were conducted on TeamTechnik machine TT2100, which is automated tabbing and stringing machine with production speed 2100 cells/h. Design of experiments (DOE) approach was used in which parameters such as cell metallization, flux type and volume and processing conditions were varied. The reliability of each process's output was measured by the peel strength of the ribbon that has been soldered to the cell metallization. Nature of the solder joints was investigated by fracture surface analysis and detailed microscopic investigation.

2 APPROACH

The soldering process (cell interconnect) is considered the most critical process in module manufacturing. A key point of a soldering process for photovoltaic (PV) modules is to increase an adhesive strength leading a low resistivity between ribbon and cell [4]. The interconnections provide electrical, mechanical and thermal contact between the solar semiconductor cell and electrodes. The main intention of this work is to assess the quality of solder joint in high throughput environment. A good solder joint is one where the solder wets the surface well and provides good adhesion between the two metals [4]. In the case of solar cells, the two metals of interest are Ag (from the cell busbar) and solder (from the interconnect). The soldering process has been reported as a preliminary source for degradation in PV modules.

For the DOE (Fig. 1), all the experiments were performed on TeamTechnik tabbing and stringing machine. Two spools of each, Sn-Pb and EcoSol were housed in a cabin and tabbing and stringing was done on cells in such a way that each ribbon is bussed alternatively (Table I, Fig. 2). Three strings of each DOE experiments were made (10 x 1 cells).

Table I: Processing parameter details

Process Parameter	Details
Machine	: Automated tabbing & stringing
Fluxing method	: Spray on cell
Soldering method	: IR soldering
Pre-heat temperature	: 170°C
Soldering time	: 800-1500 ms
Soldering temperature	: 195°C-210°C
Peel strength	: Imada peel tester
Peel angle	: 180°
Observation	: Keyence microscope and SEM

Fig. 1 gives a set factors that affect quality of solder joint. We conducted DOE (design of experiment) around those factors to assess effect of each parameter and investigate optimum conditions for soldering and nature of joints formation in production. On material size, there are cell, ribbon and flux are the main players and process side, factors such as soldering time, temperature and ribbon alignment play an important role in determining the quality of a solder joint. In a DOE, each bus bar (BB) of 4 BB solar cell was tabbed with standard tin lead (Sn-Pb) and Ecosol alternatively.

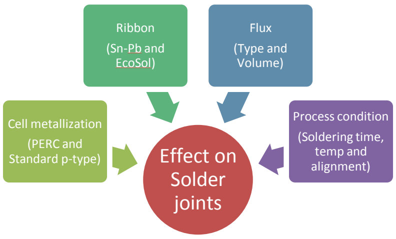

Figure 1: Factors affecting solder joints. Complete DOE was performed around these factors

The findings of this report may help PV professionals in taking some precautions in high speed manufacturing. They can have optimum conditions for tabbing and stringing and will be able to understand effect of ribbon camber and misalignment. In addition, companies may start to think of lead free option seriously.

3 RESULTS AND DISCUSSION

Currently, most PV ribbons used in the solar market are tinned with lead containing solders. However, lead and lead containing alloys are toxic. Disposal and recycling of lead containing modules which have been removed from service is quite difficult [3]. Expected changes in worldwide regulations will require that lead-based solders be replaced with less toxic alternatives. One of the objectives of this study was also to evaluate EcoSol in the production along with standard tin lead ribbon. This has not been done before. Any lead free (Pb-free) alternatives must exhibit acceptable soldering and reliability performance. EcoSol has liquidus of 179^{o}C. This temperature is very close to the standard ribbon (183 and 192^{o}C) and thus the ribbons can be processed at similar conditions to that of standard one. Fig. 2 shows the representative strings containing each bus bar soldered with tin-lead and EcoSol ribbon in an alternate fashion.

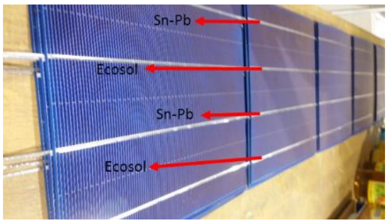

Figure 2: Strings of the soldered cells. Sn-Pb and EcoSol are bussed alternatively on each cell

3.1 Effect of cell metallization and ribbon

In the manufacture of solar cells, long-term reliability is of utmost importance. Peel strength is directly associated with reliability of the PV module. Any weak solder joint can severely affect the power output and module life. The joints are formed between silver and solder therefore, both factors are important. Silver metallization is a key for reliable joints [5]. In an industry's efforts toward reducing the silver consumption, the silver BB designs are getting narrower, BBs are patterned and the amount of silver that is used per cell is also reduced. This also means that there are very less contact points to form solder. In our experiment, n-type PERC cells and p-type c-Si cells were used. PERC type cells are made of telluride based silver paste with efficiency of 21 % and other p-type cells were 17.8 % efficiency. The design of the solder joint involves using appropriate parameters especially flux and soldering temperature. Fig. 3 shows the peel strength data of Sn-Pb and EcoSol ribbon processed at 210°C soldering temperature for 1.2 s. Fig. 3a shows results of n-type PERC cells while Fig. 3b shows p-type c-Si cells. As can be seen from the graphs, the peel strength values in both ribbons are excellent. Typically, on sunny side the values were >2.5 N/mm and on back > 3.0 N/mm. Both ribbons have comparable peel values, EcoSol being slightly less. EcoSol could be processed as same way as Sn-Pb without changing any parameters.

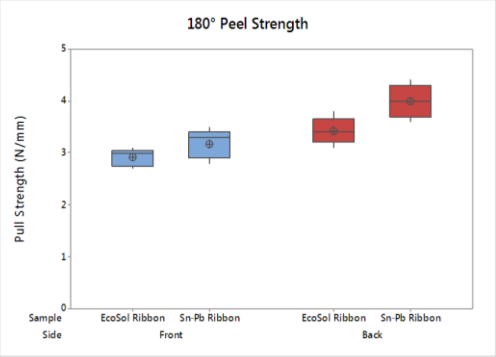

Figure 3a: Peel strength data of n-type PERC cell

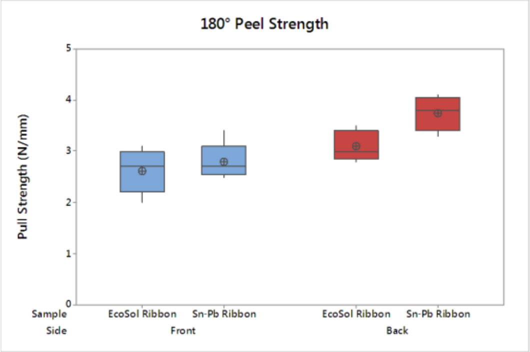

Figure 3b: Peel strength data of p-type c-Si cell

Close examination revealed, PERC cells give slightly better peel strength values and data is less scattered. Fig. 4a and 4b illustrate the result of the busbar profile from the cells used for the busbar profile experiment. As can be seen in the Fig. 4a PERC cell is smooth without much variation while in p-type cell (Fig. 4b), the edges are very high and there is a low lying saddle in the middle of the busbar with significant height variations. The difference between the highest (edge) and the lowest point in the middle of the busbar is in some places higher than 12 µm. The peaks at the edges will keep the ribbon off from the major part of the surface [6]. The consequence is an increase of thermal contact resistance between the busbar and the ribbon. In case of low quality cells where the variations are high and paste is not printed smoothly, impact is significant and this is the main reason for the failure mode. To evaluate effect of metallization further, some cells were oxidized and soldered under similar conditions. In all those cases non wetting or very less peel strength observed.

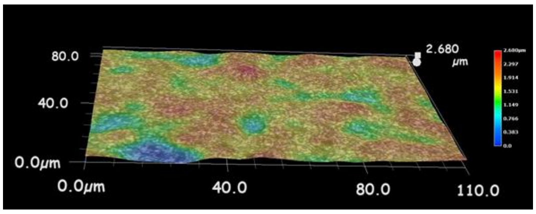

Figure 4a: Surface topology of bus bars of n type PERC cell

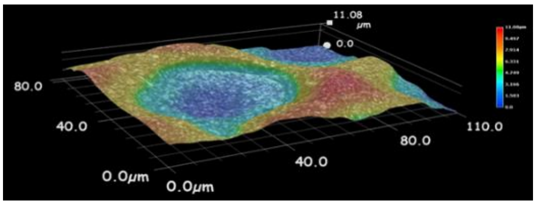

Figure 4b: Surface topology of bus bars of p-type cSi cell

3.2 Effect of flux

Due to higher throughput, the soldering time for tabbing and stringing has reduced and flux hass to wet the surface, remove the oxide and prepare surface for a good joint in such a short time span [7]. In full production run, only about 1-1.5 seconds are available for peak soldering. Many equipment have preheating zones, which sometime causes flux to evaporate making it less reactive.

Three fluxes, with solid content 1.1, 1.4 and 1.65 wt % were used for the study. The flux amount to be sprayed was adjusted by means of the cell conveyor speed. Slower the speed, more the flux volume per cell. The flux application at TeamTechnik takes place on both sides in one pass. Therefore, the specified amount applies to one cell (top and bottom side). Under controlled conditions and on dummy wafer, the flux amount was measured when sprayed at different speeds. Typically, 1000 mm/s is the desired speed so that TeamTechnik’s Tabber and Stringer type 2100 is able to run 2100 cells/h. This translated to a calculated flux amount of 75 µl per cell. In addition, speeds of 900 mm/s = 84 µl and 700 mm/s = 109 µl were also tested.

The results were better with lower speed of cells but this in turn may create more contamination in the nozzle and other parts of the machine. Both, the flux selection and volume therefore, need to be carefully selected. Higher solid flux had a better wetting time and wetting force. For any lead free solder, wetting time and force matter a lot because Bi based alloys have low wetting capability than Pb based alloys. Higher solid % flux yielded better peel strength compared to other fluxes, however, the contamination was less with 1.1 % solid flux. Both, Sn-Pb and EcoSol could be soldered with standard flux. EcoSol does not require higher activator fluxes. Flux selection has a significant effect of increasing overall adhesion values and reducing effective soldering temperature. Use of an optimum flux and soldering condition will improve the quality of the solder joint so that failure mode is changed from non-wetting to optimum failure in fracture surfce analysis.

3.3 Effect of processing conditions

Processing conditions are important in determining the quality of solder joints. Effect of soldering time and temperature investigated. Typically, higher soldering time and temperature yielded better peel strength results. One of the important factors observed was the ribbon misalignment. As described above, as the ribbons and BBs are getting narrower, ribbons are becoming more like a wire and problems such as camber are becoming evident. Even in automated machine, the ribbon misalignment could not be avoided. We observed that even for slightest misalignment, the peel strength reduced by upto 40 % (Fig. 5 and Fig. 6). This problem possibly can be solved by making proper adjustments in machine and taking either of the one surfaces (ribbon or BB) wider than other. Slightly wider ribbon than the busbar has been preferred to increase the ribbon cross-section in order to enhance the module power output. Increasing ribbon thickness to increase the ribbon cross-section is in most cases not applicable. The thermo-mechanically induced cell stress in thicker ribbon is by far higher compared to the width of the ribbon [6].

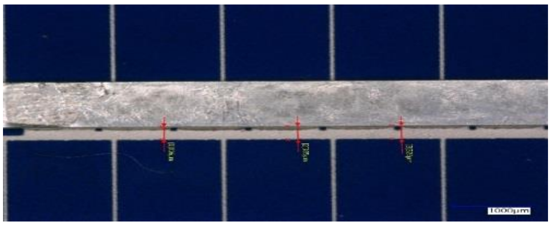

Figure 5: Misalignment during tabbing. This gives reduction in peel strength by upto 35 %

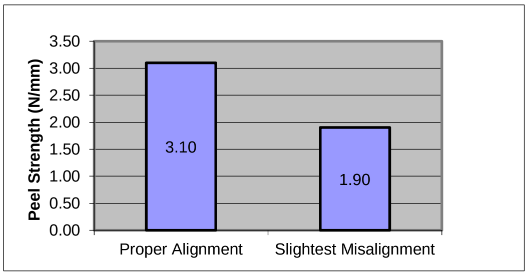

Figure 6: Peel strength comparision between properly aligned ribbon and misaligned ribbon over bus-bar

3.4 Fractured surface and microscopic investigation

Soldering defect usually won't be evident initially as they are more of long term concern. In high throughput manufacturing, under optimized conditions, peel strength was satisfactory in both Sn-Pb and EcoSol ribbons. However, peel strength is localized phenomenon and not distributed across the BB. In addition, BB is patterned and achieving peel strength per standard, EN50461 (>1 N/mm) is relatively easy. Analysis of fractured surface and failure mode is therefore, must be made to assess reliability of the solder joints. In theory, failure of the solder bond may occur at three different locations [3]: (1) at the Cu interconnect/solder interface; (2) at the Ag busbar/solder interface; or (3) within the solder itself. Failures at the Ag/ solder interface, as well as within the solder itself appear to be the dominant modes. Our fractured surface analysis of cell and ribbon showed cohesive failures. In both case, silver from the BB transferred to the ribbon, however silicon cracking was not observed on front side in any case. In EcoSol, at some areas, bulk failure of the solder was observed. Cohesive failure can be seen in both cases (Fig. 7a and Fig. 7b).

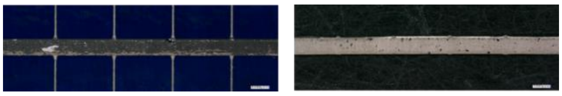

Figure 7a. Fractured surface analysis of peel ribbon (Sn-Pb soldered surface and ribbon)

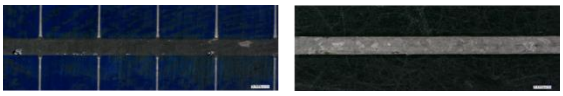

Figure 7b. Fractured surface analysis of peel ribbon (EcoSol peel off soldered surface and ribbon surface)

Characterization by metallographic sample preparation and scanning electron microscopy did not reveal any intermetallic layer, although the samples showed good mechanical peel strength indicating good bonding (Fig. 8a and Fig. 8b). After mechanical polishing and ion milling the samples were imaged and analyzed using FESEM (Field emission scanning electron microscopy) and EDS (Energy dispersive X-ray spectroscopy). A systematic analysis of the cross-sections was carried out to verify the presence of bond formation and identify the intermetallic phase. Using these combined techniques of mechanical etching and surface smears removal, and high resolution imaging helped visualizing the various particles in the solder matrix, which were identified using EDS mapping.

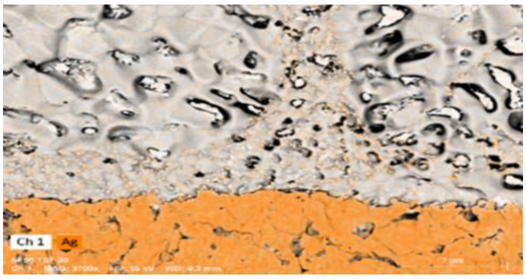

Figure 8a. FESEM and EDS mapping of Sn-Pb solder joint

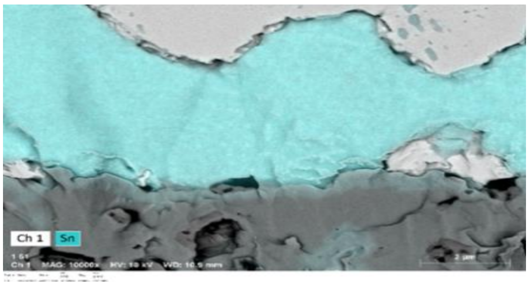

Figure 8b. FESEM and EDS mapping of EcoSol solder joint. Elemental distribution and Sn-Ag interdiffusion. No evidence of IMC compounds.

Despite the absence of a visible layer between the Ag busbar and the PV ribbon, EDS mapping was used to verify the elemental distribution of the soldered area. Fig. 8a shows that Ag particles diffused into the solder region. A further spot scan on the Ag rich region observed in the EDS mapping showed presence of Sn, Pb and Ag. Thus, we can assume that the Ag particles dispersed into the solder are starting to combine with Sn. However, due to the very short duration of heating during soldering, the time and temperature were not enough to ensure the formation of an actual intermetallic phase. Imaging of another area of the same sample confirmed these observations. Similarly, the cross-section analysis of EcoSol did not show presence of intermetallics formation, but EDS mapping of the Ag busbar/solder interface showed presence of a thin layer containing Sn and Ag. This was also confirmed by additional individual EDS mapping (Fig. 8b). An area scan determined that this thin layer has 85 wt.% Ag and 11.6 wt.% Sn. From the Ag-Sn phase diagram, we conclude that this layer was Ag and Sn in solid solution, and not the eutectic Ag_3Sn phase. Although we did not see formation of a clear intermetallic compound, we observed several areas with Ag-Sn inter-diffusion. This data is interesting and points out the situation in high throughput manufacturing. One could see nucleation sites but IMC layer is not formed. Although, in some instances, the IMC compounds can be noticeable under the microscope, observed IMC thickness is very thin and irregular in those cases. In absence of IMC, the strength of the bond can be realized by reduced surface tension, element interdiffusion and consequent disappearance of the metallization layer.

4 CONCLUSION

Solder joint analysis of standard tin lead and lead free, EcoSol in high throughput manufacturing is reported. Under identical conditions, the solder joints in lead and lead free ribbons were comparable and peel strength of >2.5 N/mm on front and >3.5 N/mm on the back side of the cell obtained. DOE results reveal that the cell metallization play an important role in determining quality of solder joints. Grade A PERC cells yielded higher peel strength compared to p-type c-Si cells due to the smooth surface topology. Similarly, flux having good wetting time performed better. Ribbon alignment was identified as one of the major causes of the weak solder joints. Due to decreased ribbon and bus bar size, this problem might occur frequently. Ribbon wider than BB can be suggested to alleviate this problem. Microscopic investigation yielded, absence of IMC in either of the ribbons due to rapid production speed. Only diffusion of tin into silver matrix was observed. This, however, do not have any effect on peel strength and cohesive failure was evident from fracture surface analysis. This study thus compare standard and EcoSol ribbons and further confirms lead free alternative can be used as an effective replacement to Pb containing ribbons. It looks possible to use lead free alternative as a “drop in” to the existing manufacturing set up.

4.1 Acknowledgement

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