SOLDER JOINT DEGRADATION IN HIGH EFFICIENCY ALL BACK CONTACT SOLAR CELLS

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ABSTRACT: Thermal cycling induced degradation in SunPower's high efficiency, all back contact, solar cells was experimentally investigated. The need for long service life in widely varied field conditions makes it important to understand the degradation behavior of photovoltaic modules. Solder joint degradation caused by environmental temperature and irradiance fluctuation is one of the major causes of photovoltaic module performance degradation and failure. This paper investigates the degradation behavior of SnPb63 and SnAg3.5 solder joints in high efficiency, all back contact, photovoltaic modules manufactured by SunPower Corporation. Back contact solar cells interact with solder joints differently than conventional cells. The photovoltaic modules were subjected to two accelerated thermal cycling profiles while the solder joints were individually monitored in-situ. The electrical resistance of individual joints was monitored until the end of joint life, i.e. infinite electrical resistance. Monitoring the electrical resistance of solder joints is the most direct way of detecting individual joint failure. Interconnect design was shown to have a significant effect on solder joint life. The effect of individual solder joint life on module performance for all back contact cells was modeled and results are presented. Another set of photovoltaic modules was thermally cycled and flash tested. Solder alloy was shown to have a significant effect on photovoltaic module series resistance degradation. With the combination of SunPower's robust interconnect design and lead free solder, no degradation was observed after 2000 cycles. This is 10 times the industry standard test duration.
Keywords: PV module, Reliability, Back contact, Performance, Solder Degradation

1 INTRODUCTION

Since the 1980s, photovoltaic (PV) module warranty length has rapidly increased as seen in figure 1 [1]. The current industry goal is to develop PV systems with a 30 year service life by 2020 [2, 3]. This implies a maximum

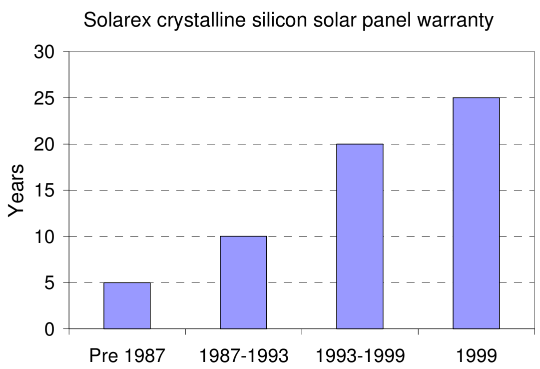

Figure 1: Trend in solar panel warranty length

of 0.5% to 1% module power degradation per year. Actual installed module power annual degradation rates of about 0.5% to 10% have been observed [4, 5]. Worldwide cumulative installed PV power has grown rapidly, 21% to 43% per year, since 1992. In 2005, over 1 GW was installed worldwide. Assuming a 1% annual module power degradation rate, the systems installed in 2005 will lose over 10 MW of output power by the end of their first year in the field. It is clear that minimizing all mechanisms that lead to power degradation is critical. The first step in minimizing these mechanisms is understanding them.

Industry standard certification tests are helpful in determining infant mortality failures and can be a useful tool in identifying especially weak points in solar cell or module design and manufacturing [7, 8]. Currently there are no industry standard methods to determine long term PV module performance in the field. Obviously, 30 year outdoor tests are not feasible for every design iteration. Because of this, accelerated laboratory test to failure (TTF) testing must be performed on identified failure mechanisms to assess their long term effect on module output power. The IEC 61215 thermal cycling test requires that PV modules be subjected to 200 cycles of -40˚C to 85˚C. Modules that experience greater than 5% relative power degradation fail the test.

Several PV module reliability concerns that can affect module power are packaging material degradation, adhesional degradation, interconnect degradation, moisture intrusion and semiconductor device degradation. This work concentrates on interconnect degradation in high efficiency, all back contact, solar cells. Aging behavior of SnPb63 solder is compared to that of SnAg3.5. Also, two interconnect designs were experimentally evaluated for their impact on solder aging behavior.

Modules in the field can experience temperature swings of about 60˚ C each day [9]. Due to the mismatch of the coefficients of thermal expansion (CTE) of silicon, glass, copper and solder, the solar cells move in relation to the interconnect and solder, causing the solder joints to get mechanically cycled as seen in figure 2. Both local and global CTE mismatch contributes to solder joint degradation [10]. Global mismatch induced degradation is caused by the solder joint being stressed and deforming to accommodate CTE mismatch in surrounding materials, i.e. solar cells, glass and interconnect. Local mismatch induced degradation is caused by the solder material

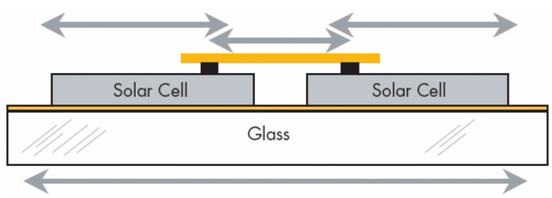

Figure 2: Laminate stack motion in heating

expansion being either restricted or enhanced by the material it is soldered to. As the solder degrades, cracks start to develop, increasing the electrical resistance across the solder joint. Eventually the cracks propagate throughout the entire joint area, resulting in an electrical open. Solder joint degradation has a significant deleterious effect on PV module output power [11].

Modern high current PV modules are especially sensitive because the power loss associated with increasing series resistance (R_s) is I^2R_s [12]. Previous work on solder joint degradation in PV modules has concentrated on conventional cell architecture [13, 14]. Back contact cells have a different geometry and hence a different interaction with solder joints as seen in figure 3.

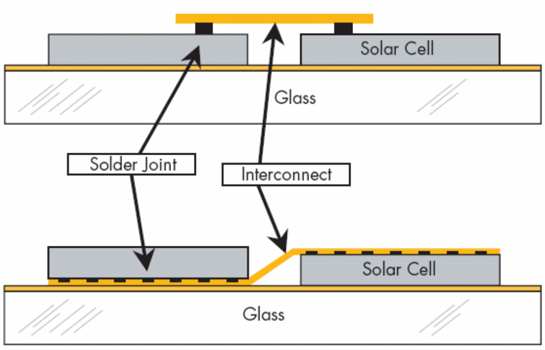

Figure 3: Interconnect geometry
Top: Back contact solar cells
Bottom: Conventional solar cell

When designing PV modules it is essential to consider the role the interconnect will play in initial performance and long term power degradation. The interconnect should be designed to minimize global CTE mismatch induced stress on the solder joint while keeping electrical resistance of the interconnect to a minimum.

2 SOLDER DEGRADATION

When solder is put under stress it deforms or creeps. At temperatures higher than one half of the melting temperature in Kelvin, called the homologous temperature, creep is significant [15]. During thermal cycling the solder joint is almost constantly under shear stress, thus exhibiting creep.

SnPb63 and SnAg3.5 solders contain Pb and Ag_3Sn grains, respectively, suspended in a Sn matrix [16]. The solder interface has a thin brittle intermetallic layer. As the solder is subjected to cyclic thermomechanical stress, it undergoes microstructural coarsening and the intermetallic layer thickens. This microstructural evolution affects creep behavior and promotes crack formation and propagation.

Solder creep is caused by either grain boundary sliding (GBS) or matrix creep (MC). MC is a more damaging creep mechanism and subsequently leads to shorter joint life. The creep mechanism is both temperature and stress dependent [17]. The strain rate, or deformation rate, for a given stress increases with temperature. The creep mechanism has a greater

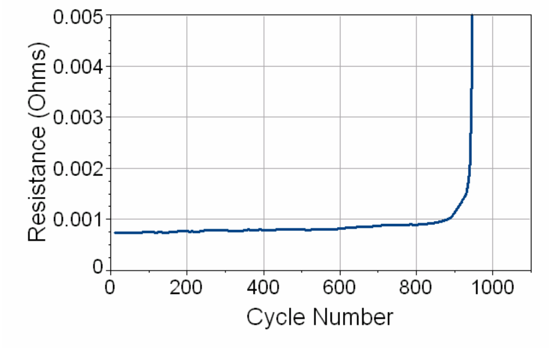

Figure 4: Example of solder joint reaching end of life

temperature dependence in lead free solder, and greater stress dependence in leaded solder. The coarsening of the grains can limit the GBS mechanism and shift the GBS to MC transition point. A common misconception is that lead free solder is either more or less creep resistant than tin lead solder. At low stresses, lead free solder is more creep resistant while at high stresses tin lead solder is more creep resistant [18].

There are two solder aging behaviors of interest; solder degradation rate and number of cycles to end of joint life. Figure 4 shows an example of a solder joint reaching end of life. The slow increase in electrical resistance is a result of microstructural coarsening and crack formation. Shear stress is inversely proportional to cross sectional area. As the cracks propagate, the solder joint cross sectional area is reduced. After the effective joint area reaches some critical threshold value, it takes about 50 cycles for the joint to become an electrical open. The solder joint in figure 4 reached this critical threshold at about cycle 875.

3 EXPERIMENTAL INVESTIGATION OF SOLDER JOINT DEGRADATION

3.1 Description

Two experiments were performed to evaluate solder degradation behavior. Electrical resistance of individual solder joints was monitored in real time as they were subjected to thermal cycling. Also, another set of PV modules was subjected to thermal cycling and periodically flash tested. The effect of solder alloy

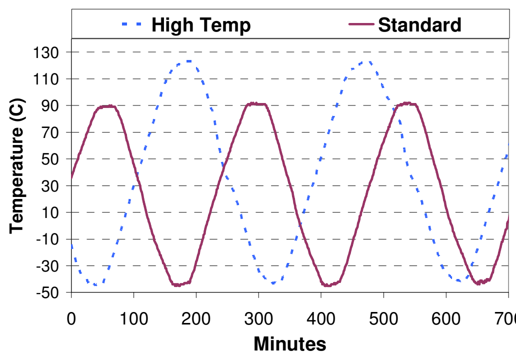

Figure 5: Thermal cycling profiles
High Temp Profile: -40 to 125˚C
Standard Profile: -40 to 90˚C (UL Thermal Cycling test)

on PV module series resistance degradation behavior was evaluated. Both experiments used the same thermal cycling profiles as seen in figure 5.

Two interconnect designs (A and B) which relieved thermomechanical stress on the joints differently were evaluated. PV module construction with conventional cells typically does not use any interconnect stress relief between solder joints.

Because of size restrictions it was not feasible to use full size PV modules. Three cell PV minimodules were used as the test vehicle. Individual solder joints were monitored in-situ as the PV minimodules were subjected to thermal cycling. A four wire resistance measurement of each joint was performed in real time to monitor joint failure as seen in figure 6. This technique is the most direct way of detecting failure of individual joints.

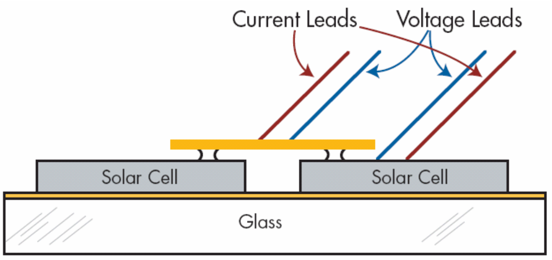

Figure 6: Monitoring setup

Extracting series resistance from dark IV curves requires non-linear curve fitting and is sensitive to semiconductor device degradation [19]. Light IV testing can not be performed in real time and requires removing the samples from the environmental test chamber.

To evaluate the effect of different solder alloys on module series resistance degradation, PV minimodules were thermally cycled and periodically flash tested [20]. PV minimodules were built with SnPb63 and SnAg3.5 using interconnect A. Ten PV minimodules of each solder alloy were built for each profile.

3.2 Results

The results of individual joint monitoring are outlined in table 1. To date about 50% of the SnPb63 joints built with interconnect B have failed. Very few joints built with interconnect A have failed.

Table 1: Individual monitoring results for SnPb63 joints

		Interconnect A	Interconnect B
Profile	**Cycles Completed**	**Joints Failed**	**Joints Failed**
Standard	2300	0.0%	50.0%
High Temp	1130	2.5%	47.5%

Cumulative failure of solder joints built with interconnect B is seen in figure 7. The interconnect design has proven to have a significant impact on solder joint life.

A model was developed in Spice to demonstrate the effect of individual joint failure on PV minimodule series resistance. A two diode equivalent model was used for the solar cell and an equivalent resistor network was used to model the interconnect and solder joints. Measured solder joint resistance values were used as inputs to the model. Steps in the series resistance curves indicate individual joints reaching end of life. One joint reaching end of life has a significant impact on PV minimodule series resistance, as seen in figure 8.

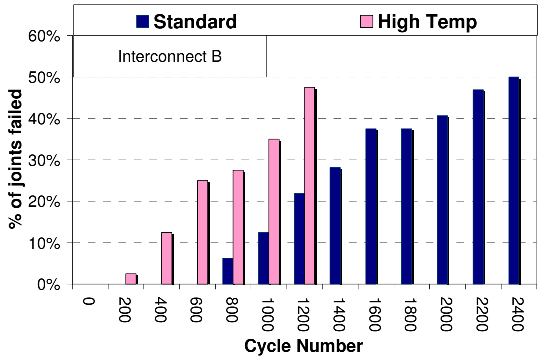

Figure 7: Joints failed with interconnect B

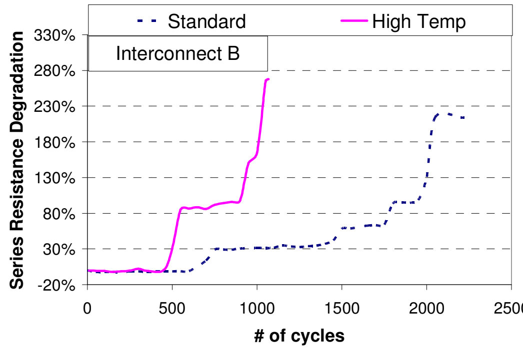

Figure 8: PV minimodule modeling results

Flash test results from thermally cycled PV minimodules are shown in figures 9 and 10. All of these PV minimodules were built with the more robust interconnect A. Each data set is the average degradation of ten minimodules.

In both thermal profiles, thermal cycling induced higher increases in the series resistance of SnPb63 minimodules compared to SnAg3.5 minimodules. No degradation of the PV minimodules built with SnAg3.5 was observed after about 2000 cycles. This is 10 times the duration of industry standard certification tests. As expected, the SnAg3.5 solder is more sensitive to high temperature. Nevertheless, even at 125˚C the SnAg3.5 minimodules retain their performance significantly better than the SnPb63 minimodules.

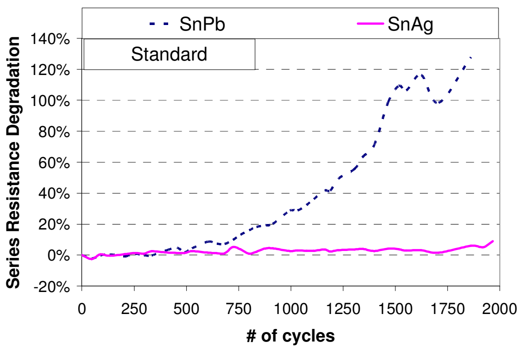

Figure 9: Standard profile flash test results with interconnect A

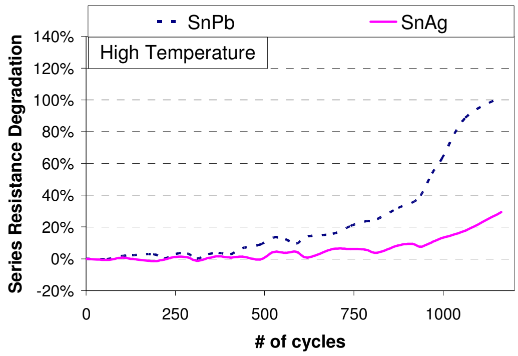

Figure 10: High temp profile flash test results with interconnect A

4 CONCLUSION

The current industry goal is to achieve 30 year service life PV systems with allowable PV module performance degradation of 0.5% to 1% per year. As PV modules age in the field, they undergo daily thermal cycling induced by environmental factors. Thermomechanical fatigue of solder joints has a significant deleterious effect on PV module performance. Interconnect design and solder alloy play a significant role in the performance degradation rate.

Two interconnect designs were evaluated for thermal cycling induced solder degradation in high efficiency, all back contact PV modules. Interconnect design proved to have a significant impact on solder joint life. SunPower has developed a robust interconnect design that is resistant to thermal cycling induced degradation. Standard and high temperature profiles were used in this study. After 2300 cycles in the standard profile, no solder joints built with the robust interconnect have reached end of life as compared to about 50% of the joints built with the other interconnect. Similarly, in the high temp profile, only 2.5% of the robust interconnect joints failed as compared to about 50% of the joints built with the other interconnect.

Two solder alloys were evaluated for thermal cycling induced degradation with the robust interconnect. SnAg3.5 solder was shown to be more resistant than SnPb63 to degradation. No increase in series resistance was observed in the SnAg3.5 minimodules after almost 2000 cycles in the standard profile as compared to a 120% increase in the SnPb63 minimodules. This is ten times the industry standard thermal cycling test duration. Similarly, after about 1200 cycles in the high temp profile, the series resistance of the SnAg3.5 minimodules has increased roughly 30% as compared to 100% for minimodules using SnPb63. Although the high temperature had a more significant effect on SnAg3.5 than on SnPb63, the SnAg3.5 solder still outperformed the SnPb63 by about 70%.

4 References

[1] J. Wohlgemuth, DOE Solar Program Review Meeting, Denver, CO., March, 2003. pp.179-182.

[2] T. J. McMahon, G. J. Jorgensen, R. L. Hulstrom, D. L. King, M. A. Quintana, NCPV Program Review Meeting, Denver, CO., April, 2000.

[3] R. L. Hulstrom, DOE Solar Energy Technologies Program Review Meeting, Denver, CO., October, 2004.

[4] M. A. Quintana, D. L. King, T. J. McMahon, C. R. Osterwald, Proceedings 29th IEEE Photovoltaic Specialists Conference, May, 2002, pp. 1436-1439.

[5] A. L. Rosenthal, M. G. Thomas, S. J. Durand, Proceedings 23rd IEEE Photovoltaic Specialists Conference, May, 1993, pp. 1289-1291.

[6] Trends in Photovoltaic Applications, Survey Report of Selected IEA Countries Between 1992 and 2005: Report IEA-PVPS T1-15:2006.

[7] UL standard 1703, Standards for Safety, Flat-Plate Photovoltaic Modules and Panels, Underwriters Laboratories, Northbrook, IL, 1993.

[8] IEC 61215, Crystalline silicon terrestrial PV-modules—design qualification and type approval, Geneva, Switzerland, 1993.

[9] D. L. King, W. E. Boyson, J. A. Kratochvil, Sandia Report SAND20043535, August, Sandia National Laboratories, Albuquerque, NM, 2004.

[10] J. P. Clech, Proceedings Surface Mount International Conference, Sept, 1996, pp. 136-151.

[11] E. E. Van Dyk, E. L. Meyer, Renewable energy, 29, 2004, pp. 333-344.

[12] A. G. Aberle, S. R. Wenham, M. A. Green, Proceedings 23rd IEEE Photovoltaics Specialists Conference, May, 1993, pp.133-138.

[13] G. Cuddalorepatta, G. Dasgupta, S. Sealing, J. Moyer, T. Tolliver, J. Lomann, Proceedings 11th International Symposium on Advanced Packaging Materials: Process, Properties and Interface, March, 2006, pp. 16-21.

[14] G. Cuddalorepatta, G. Dasgupta, S. Sealing, J. Moyer, T. Tolliver, J. Lomann, Proceedings Thermal and Thermomechanical Phenomena in Electronics Systems, May, 2006, pp. 1232-1239.

[15] J. K. Tien, B. C. Hendrix, A. I. Attarwala, IEEE Transactions on Components, Hybrids, and Manufacturing Technology, 12, 1989, pp. 502-505.

[16] I Dutta, Journal of Electronic Materials, 32, 2003, pp. 201–207.

[17] J. P. Clech, Proceedings SMTA International Conference, Sept, 2004, pp. 776-802.

[18] D. Xie, M. Arra, H. Pan, D. Shangguan, D. Geiger, S. Yi, Proceedings of the Telecomm Hardware Solutions Conference, May, 2002, pp.83-88.

[19] D. L. King, J. A. Hansen, Proceedings 26th IEEE Photovoltaics Specialists Conference, Sept, 1997, pp.1125-1128.

[20] R. A Sinton, D. DeCeuster, K. Wilson, L. R. Barbosa, 20th European Photovoltaic Energy Conference, June, 2000.