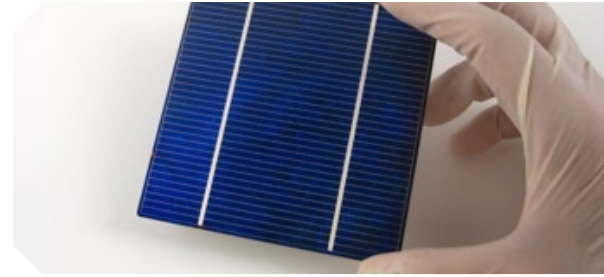


◆ Enabling thin wafers for today's high efficiency silicon solar cells

IL-RTS In-Line Rapid Thermal Shock



ABSTRACT: Reducing consumption of silicon through the use of thin wafers promises to significantly reduce the cost for photovoltaic electricity. To enable thinner wafer usage, the mechanical and electrical properties of the cell must be preserved and ultimately improved upon. Today's optimized solar cell structure applies aluminum to the back side of the silicon wafer to create back surface field or BSF that improves overall cell efficiency.

Because silicon and aluminum have different thermal expansion coefficients, a bow is created in the wafer during the high temperature firing process. Tradeoffs in efficiency, breakage and yield have slowed the industry's natural migration to thinner wafers. While new cell structures show the promise of overcoming these challenges, these new structures are more complex and may not be readily available to existing cell lines.

This paper reports on the optimization of a simple low-temperature process that has successfully removed the bow without degrading cell electrical or mechanical performance and does not require significant materials optimization efforts. We have achieved equivalent cell efficiencies and mechanical properties after bow removal for silicon solar cells below 180 μm , 160 μm , etc. The performance of this simple process will be presented in this paper.

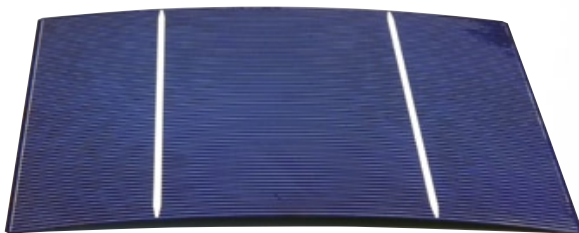
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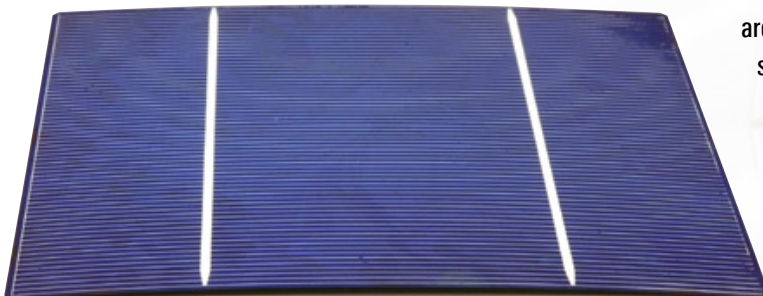
INTRODUCTION

A major challenge for the solar industry is the generation of energy at costs competitive to that of fossil fuel energy. The majority of solar modules in the PV market are manufactured using crystalline silicon solar cells. The crystalline silicon solar cell manufacturing cost per Wp can be lowered by increasing production volumes and yield, by producing higher efficiency silicon solar cells and by reducing silicon usage through reduced wafer thickness [1]. Since the silicon wafer is the largest cost component of finished solar cell, it is widely accepted that reducing the cost of silicon through reduced wafer thicknesses [2-3] will greatly benefit lower solar energy costs.

High efficiency silicon (both multi- and mono-crystalline) solar cells utilize a back surface field (BSF) for backside passivation and reflector with 60 ~ 70% reflectivity. This BSF layer is manufactured inexpensively by screen printing aluminum paste and subsequently applying a co-firing process. For most of the crystalline silicon solar cells the screen printed and fired aluminum back surface field has been the standard for backside passivation. However, after the contact firing and cooling required in the metallization process, a solar cell with thickness less than 200 μm will become bowed due to the plastic deformation of the Aluminum Silicon matrix [4]. While the exact manufacturing tolerance specified for wafer bowing varies, solar cells bowed beyond approximately 1.5 mm can reduce yield in the cell line's final test and sort steps as well as in some of the early module production steps. Because of these challenges, it is highly desired to maintain a cell bowing specification as low as possible.



160 μm cell before IL-RTS



160 μm cell after IL-RTS

After the contact firing and cooling required in the metallization process, a solar cell with thickness less than 200 μm will become bowed.

In order to avoid the bowing issues while maintaining high solar cell electrical performance, various technology alternatives are being developed. The first method under development involves the reduction or removal of the backside aluminum by utilizing a dielectric passivation layer along with local rear contacted cell structures. As this process is not yet cost competitive and requires additional process steps, it is not widely used in industrial mass production at this time but shows promise. Secondly, it is widely acknowledged that continuously improving paste formulations have led to higher cell efficiencies. A crucial aspect of these improvements has been the optimization of the paste to the application. One specific target of paste formulation optimization is the introduction and optimization of low bowing pastes for use with thinner wafers. These low bow pastes have successfully reduced the bow formation but can trade off electrical performance as compared to electrical performance optimized pastes. Finally, a thermal de-stressing process has been introduced that applies a very low temperature to the bowed wafer that effectively reduces or eliminates the existing bow in completed solar cells. This process has successfully addressed the wafer bow but concerns regarding electrical performance, mechanical performance and rebowing need to be examined.

As shown in previous work, a bow becomes present after the co-firing process as a result of the different thermal coefficients of the silicon wafer and the fired aluminum back side paste. The amount of bow created is dependent on a number of variables including wafer thickness, paste thickness, paste formulation, firing temperature and firing duration. As with the initial bowing process, wafer debowing is a function of (low cold) temperature, duration at low cold temperature, wafer thickness, paste formulation, paste thickness and the amount of initial bow.

In order for solar cells to be made into solar modules, solar cells are strung together and their busbars are soldered together. The soldering step is a thermal process which raises concerns about the possible rebowing of the wafer. The soldering process can be accomplished using a point of contact conductive "soldering gun", a busbar focused infrared lamp heating mechanism or a multi-cell, "large area" infrared lamp heating mechanism.

The point of contact conductive soldering method does not appear to introduce the thermal stress necessary to generate a rebow in the debowed solar cell. The most challenging soldering process involves the large area infrared heating because it involves heating the entire cell. As reheating of the debowed wafers may cause the wafer to re-bow, the limits of this rebow are explored here.

A thermal de-stressing process has been introduced that applies a very low temperature to the bowed wafer that effectively reduces or eliminates the existing bow in completed solar cells.

The bowing issue becomes more important as market drives toward reduced cost of ownership and utilizes thinner wafers. To support this movement toward thinner wafers, Despatch Industries developed an in-line bow removal tool called the In-line Rapid Thermal Shock or IL-RTS that is based on previous research [4] involving the investigation and reduction of wafer bowing.

This study investigates the following five issues:

1. Bow removal by rapid cooling profile
2. Electrical performance before and after bow removal
3. Adhesion pull strength before and after bow removal
4. Microcrack before and after bow removal
5. Re-bowing observation in relation to time and additional heat treatment of debowed cells

EXPERIMENTAL

The wafers utilized in this experiment were made into solar cells utilizing standard industrial manufacturing processes including acidic texturization, emitter diffusion, PSG etch, SiN_x AR coating, edge isolation, screen printed metallization, drying and co-firing. All materials utilized were commercially available products including the wafers, pastes, chemicals, etc. In particular, the aluminum paste selected was standard, commercially available pastes with no significant optimization completed. In many cases, paste selection and optimization is an important aspect of a lines performance.

The variables explored in this study include wafer thickness, paste formulation, paste thickness and rebow time and temperature. Accordingly, the firing profiles and the IL-RTS debowing profiles were held constant. Each of these tools and processes can be adjusted to affect the bow and debow performance results.

Silicon wafers were provided by Schott Solar AG in Germany. 156 X 156 mm polycrystalline wafers were utilized with pre-metallization thicknesses of approximately 180 μm , 160 μm , and 140 μm . For

the microcracking observations, 125 X 125 mm monocrystalline solar cells with thickness of 180 μm and 156 X 156 mm polycrystalline solar cells with thickness of 180 μm were utilized.

The aluminum and silver pastes were provided by Ferro Corporation. The baseline paste is a commercially available, high performance paste formulated for 280 μm thick wafers. To compare bow prevention, a commercially available aluminum paste formulated for minimal bowing or 200 μm wafers was provided. By design, no special paste optimization were attempted. In normal operation, paste selection and formula optimization will improve electrical and/or bowing performance. The amount of aluminum paste printed was normally 1.6 ~ 1.7 grams per wafer. In order to understand the bowing sensitivity to the amount of aluminum paste applied, cells with 1.7 ~ 2.0 grams of aluminum paste were processed and compared.

Bow Performance Testing

Bow of solar cells was measured by placing the front side down on a glass plate, measuring the center of two sides of solar cells, four corners of solar cells and averaging them. The finished solar cell bow was measured immediately after the final firing step. The firing was held constant and completed in a Despatch firing furnace. Thermal debowing was accomplished in a Despatch IL-RTS. The thermal process was held constant for all cells and is shown in Figure 1. The fired, bowed cells were cooled to -55°C and heated back to +20°C at a belt speed of 3700 mm/min. Figure 1 shows the temperature profile utilized in the IL-RTS to accomplish the debowing comparisons. The debowed solar cell bow was measured immediately after the IL-RTS debowing step.

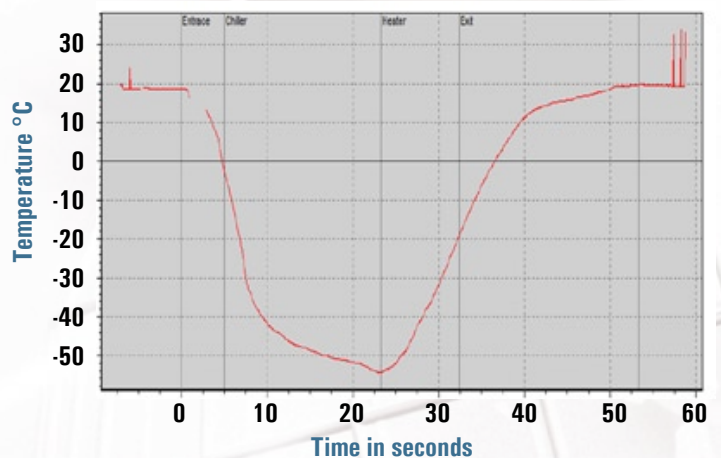


Figure 1: Temperature profile of IL-RTS used to accomplish cell debowing.

This test was designed to compare the bow removal attributes of varying wafer thicknesses using a baseline thermal debowing profile. (The thermal profile can be adjusted to remove more or less bow as desired.)

Electrical characterization

The electrical performance of fired cells was measured by using a Pasan I-V tester before and after bow removal. This test was designed to compare the electrical performance of debowing and bow prevention pastes.

Adhesion pull strength of silver paste

Adhesion pull strength of fired silver pastes was measured by soldering tabbing ribbon on the fired silver paste before and after IL-RTS. This test was conducted to verify the thermal debowing process does not affect the bonding strength of fired silver paste

Microcrack observation

Microcrack evaluation was performed at Schott Solar AG Ag utilizing Electroluminescence (EL) picture. One hundred and one (101) monocrystalline and ninety-four (94) multicrystalline solar cells were analyzed before and after IL-RTS treatment. This test was conducted to verify that additional microcracking did not occur during the thermal debowing process.

Rebowing

After firing and thermal debowing, the bow was remeasured (per previously described methodology) after specified time intervals and after application of a simulated wide area soldering thermal profile. The time interval for bow measurement were 15 days, 20 days and 30 days. The fired, debowed cells were processed through the thermal profile shown in Figure 2. This profile simulates a “worst case” thermal process associated with some module manufacturing soldering steps. The temperature profile shows the wafer reached a the temperature of 250°C for 5 sec with a maximum temperature of 266°C.

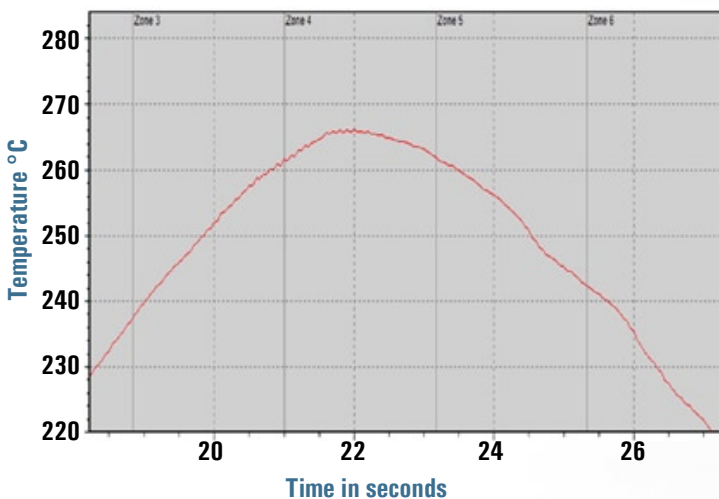


Figure 2: Temperature profile used to simulate worst case soldering process.

This test was designed to determine the re-bowing effects of time and additional heating steps on previously de-bowed solar cells.

IL-RTS demonstrated bow removal of 65.7% - 75.4% for 140 μm, 160 μm, and 180 μm wafers by cooling wafers to -55°C and warming to +20°C. Additional debowing can be achieved by optimizing the IL-RTS thermal profile

RESULTS AND DISCUSSION

Solar Cell Bowing Performance

Bowing results using post-firing, bow removal thermal process

The results in Figure 3 shows that the inline thermal de-stressing process removed a bow up to 5.6 mm (65.7%) for 140 μm wafers, 4.8 mm (71.3%) for 160 μm wafers, and 3.1 mm (75.4%) for 180 μm wafers by cooling wafers to -55°C and warming to +20°C with a belt speed of 3700 mm/min.

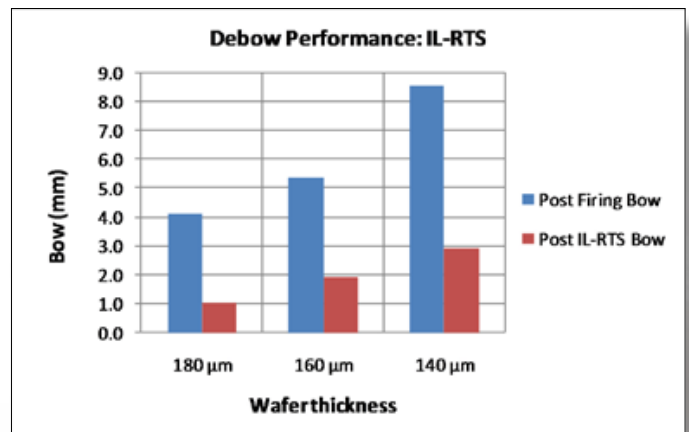


Figure 3: Amount of bow measured before and after IL-RTS for three thicknesses of solar cells.

Table shows amount of reduction.

180 μm	3.01 mm	75%
160 μm	4.17 mm	64%
140 μm	5.66 mm	66%

Given the constant thermal distressing profile utilized in this test, the consistent percentages of reduced bow across wafer thicknesses indicate a strong ability to adjust the desired results for a given wafer thickness, paste type and thermal profile.

Bowing results for varying thicknesses of aluminum paste

Table 2 compares the bowing difference of 2 thicknesses of high performance aluminum paste. The chart shows that paste thickness does affect the bow severity.

Paste thickness	Test 1	Test 2	Increase
Paste amount (gr)	1.59	1.79	12.58
Bow average (mm)	6.53	8.41	28.82

Table 2: Results of bowing test using variable thickness of aluminum paste on backside

Bowing results using low bow pastes to prevent bow

The results in Figure 4 shows that the low-bow formulated aluminum paste successfully prevented a bow up to 5.0 mm (61%) for 140 μm wafers, 2.9 mm (57%) for 160 μm wafers, and 3.0 mm (70%) for 180 μm wafers as compared to the 280 μm high bow paste.

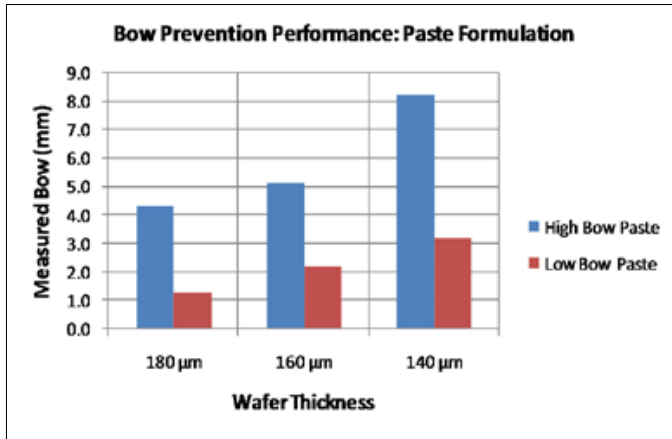


Figure 4: This chart compares the bow-prevention performance of a 200 μm optimized, ("low-bow") paste versus "high bow" paste.

180 μm	3.0 mm	70%
160 μm	2.9 mm	57%
140 μm	5.0 mm	61%

The table shows the amount of reduction.

This test confirms that commercially available 200 μm optimized "low-bow" formulated aluminum paste formulated does prevent or minimize wafer bowing.

The electrical performance of solar cells is not affected by IL-RTS treatment. However, the use of low-bow aluminum paste resulted in 3% loss of efficiency.

Electrical Performance Comparison

Electrical results using post-firing, bow removal process

Electrical performance of fired cells was measured before and after the thermal IL-RTS treatment. If damage to the cell were to occur in the interface between silver paste and silicon, the series resistance should increase and efficiency should decrease. Efficiency measurements from Figure 5A and Figure 5B showed 144 cells increased in measured efficiency after IL-RTS treatment 50 cells decreased in measured efficiency while 1 remained unchanged. Series resistance measurements from Figure 6A and 6B showed 139 cells increased in measured series resistance after IL-RTS treatment, 55 cells decreased in measured series resistance while 1 remained unchanged. As the differences are within the measurement tolerances, the results indicate that there was no change in cell efficiency or series resistances attributable to the IL-RTS debowing process.

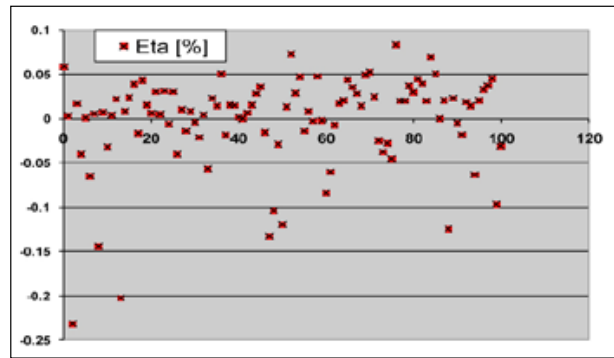


Figure 5A: This chart shows that efficiency difference of 101 fired mono solar cells before and after IL-RTS treatment. Positive values indicate an increase. Negative values indicate a decrease.

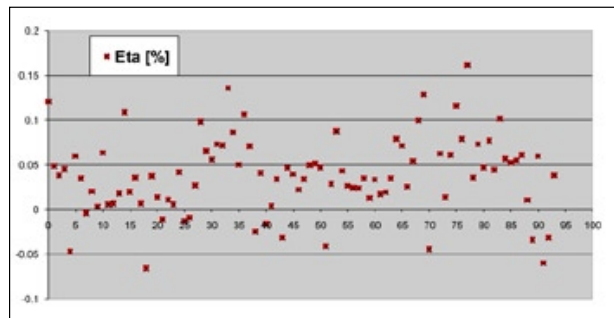


Figure 5B: This chart shows that efficiency difference of 94 fired polycrystalline solar cells before and after IL-RTS treatment. Positive values indicate an increase. Negative values indicate a decrease.

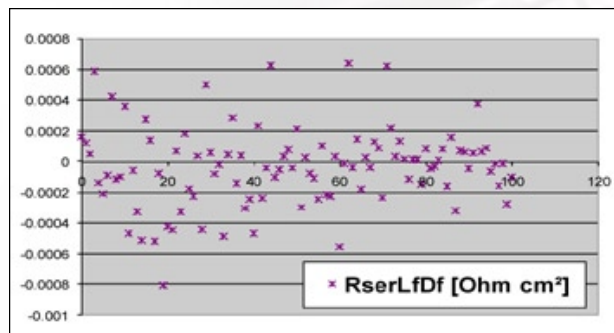


Figure 6A: This chart shows that series resistance difference of 101 fired mono solar cells before and after IL-RTS treatment. Positive values indicate an increase. Negative values indicate a decrease.

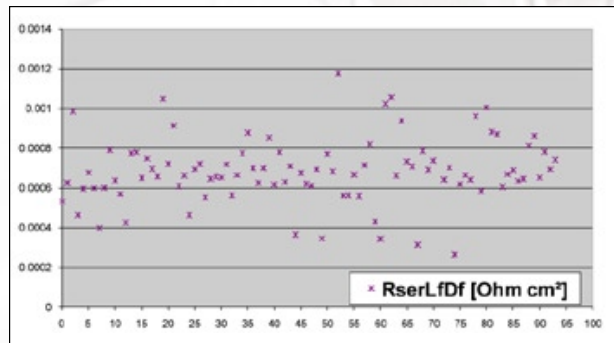


Figure 6B: This chart shows that series resistance difference of 94 fired polycrystalline solar cells before and after IL-RTS treatment. Positive values indicate an increase. Negative values indicate a decrease.

Electrical results of high performance, 280 μm paste compared to 200 μm bow optimized paste

Table 4 compares the efficiency of high performance, 280 μm aluminum pastes to a commercially available 200 μm bow optimized aluminum paste. The results demonstrate one of the challenges faced in formulating high performance aluminum pastes for mass production cell manufacturing at thinner wafer thicknesses. The 280 μm optimized paste showed a 3% improvement in electrical performance but a much higher bowing result on sub 200 μm thick wafers.

Paste Formulation	Wafer Thickness (μm)			Relative Cell Efficiency
	180	160	140	
Commercial "200 μm " Paste Bow	1.3 mm	2.2 mm	3.2 mm	100%
Commercial "280 μm " Paste Bow	4.3 mm	5.1 mm	8.2 mm	103%

Table 4: This compares the amount of bow and efficiency for commercial "200 μm " optimized and high performance "280 μm " aluminum pastes.

Adhesion pull strength before and after IL-RTS treatment

The maximum adhesion pull strength test results are presented in Table 5. While the results of the tests show slightly better results after the thermal de-bowing process, the measurements are considered within testing error. This indicates that thermal treatment by IL-RTS did not affect the interface between fired silver paste and silicon.

Sample	1	2	3
Before (grams)	347	331	353
After (grams)	358	358	389

Table 5. Maximum adhesion pull strength in grams before and after IL-RTS treatment

Electroluminescence micro-crack observation before and after IL-RTS treatment

One hundred and one (101) mono-crystalline solar cells and ninety-four (94) polycrystalline solar cells were evaluated to determine micro-cracks performance resulting from the thermal de-bow process. Sample Electroluminescence pictures are shown in Figure 7A and Figure 7B.

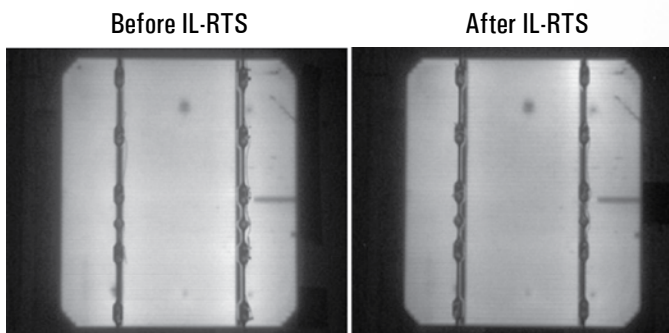


Figure 7A. Electroluminescence pictures of a mono-crystalline solar cell before and after IL-RTS thermal debowing treatment showing no discernable difference in micro-cracking performance.

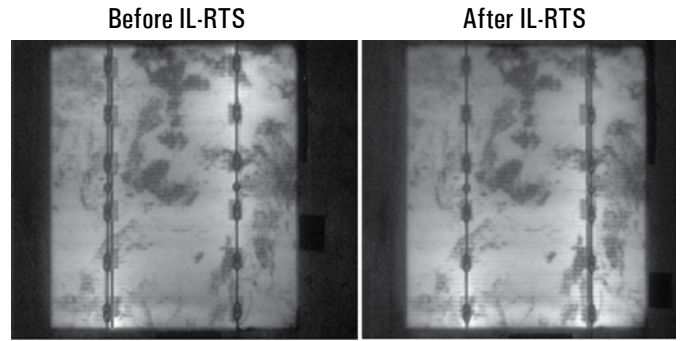


Figure 7B. Electroluminescence pictures of a multi-crystalline solar cell before and after IL-RTS thermal debowing treatment showing no discernable difference in micro-cracking performance.

The cells passed the electroluminescence microcracking evaluation by showing no discernable difference in micro-cracking before and after IL-RTS thermal debowing treatment.

Rebow Performance

Time Dependence

Figure 8 shows the amount of bow at extended times after IL-RTS treatment. The amount of bow increase was 20.6 % and 17.2% for 140 μm wafer, 19.1% and 17.3% for 160 μm wafer, and 48.2% 129.1% for 180 μm wafer on 15th and 20th day respectively after IL-RTS treatment. The amount of bow increase leveled off at 15th day with 140 μm and 160 μm thick wafers. However, the amount of bow increase for 180 μm continues up to 20th day.

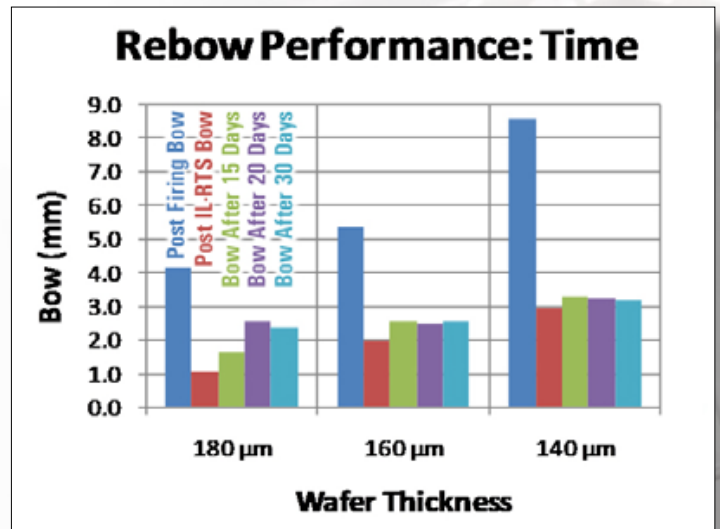


Figure 8. This shows amount of bow at a extended time after IL-RTS treatment.

Temperature Dependence

Figure 9 shows the re-bowing result of de-bowed solar cells after heating at 250°C for 5 seconds with maximum temperature of 266°C. This profile simulates soldering in a tabber stringer process. However the time duration is shorter than 5 seconds in the industrial process.

The percentage of rebow is 77.5% for 140 μm thick wafer, 96.0% for 160 μm thick wafer, and 111.6% for 180 μm thick wafer. Rebowl becomes bigger for thicker wafers. Even though there is a rebow upon heating the amount of bow of rebowed wafer is still lower than the bow after metallization process, that is, 39.1% for 140 μm thick wafer, 29.4% for 160 μm thick wafer, and 47.7% for 180 μm thick wafer.

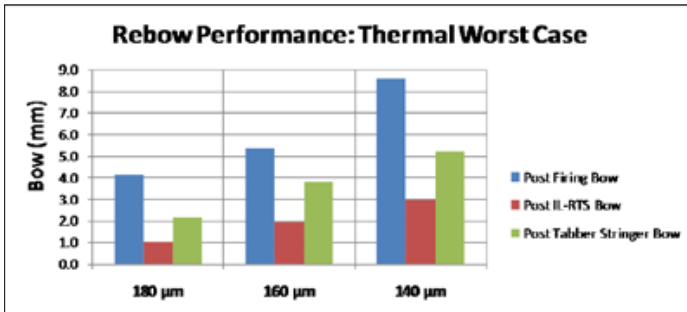


Figure 9. The rebow affect of debowed solar cells after heating at 250°C for 5 seconds simulating a worst case tabber stringer soldering process.

CONCLUSION

IL-RTS enables usage of thin wafers with high bow aluminum paste with good electrical performance. When this bow removal tool is used, solar cell manufacturers will have more choices in aluminum paste selection and have less breakage issues in handling wafers after firing and during module making. The combination of 200 μm optimized pastes and IL-RTS can also extend the life of current paste formulations as the cell manufacturer moves to thinner wafers. IL-RTS demonstrated bow removal of 65.7% - 75.4% for 140 μm, 160 μm, and 180 μm wafers by cooling wafers to -55 C and warming to +20°C. Additional debowing can be achieved by optimizing the IL-RTS thermal profile.

Electrical performance of solar cells is not affected by IL-RTS treatment.

De-bowed solar cells may re-bow upon wide area heating at the soldering temperature of tabbing ribbon in module making. Even though there is a rebow upon heating, the ultimate debow is still significantly lower than the bow after metallization process, that is, 39.1% for 140 μm thick wafer, 29.4% for 160 μm thick wafer, and 47.7% for 180 μm thick wafer.

Bow removal with the IL-RTS allows solar cell manufacturers to process the cells after firing without handling problems and damage.

Acknowledgements

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The Despatch IL-RTS enables usage of thin wafers with high bow aluminum paste with good electrical performance. When this bow removal tool is used, solar cell manufacturers will have more choices in aluminum paste selection and have less breakage issues in handling wafers after firing and during module making.

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