BOW REDUCING FACTORS FOR THIN SCREENPRINTED MC-SI SOLAR CELLS WITH AL BSF

A. Schneider, C. Gerhards, P. Fath, E. Bucher[1],
R.J.S. Young[2], J.A. Raby[2], A.F. Carroll[3]
Author for correspondence: A. Schneider
[1]University of Konstanz, Department of Physics, P.O. Box X916, D-78457 Konstanz, Germany
Tel.: +49-7531-88-2082, Fax: +49-7531-88-3895, email: A.Schneider@uni-konstanz.de
[2]DuPont iTechnologies, Coldharbour Lane, Frenchay, Bristol, United Kingdom BS16 1QD
Tel.: +44-1-179-313-227, email: Richard.Young@gbr.DuPont.com
[3]DuPont iTechnologies, 14 Alexander Dr., Research Triangle Park, NC, 27709 USA
Tel.: +1-919-248-5322, email: Alan.F.Carroll@usa.DuPont.com

ABSTRACT

Silicon solar cell costs could be strongly reduced by the use of thinner wafers. However, thin wafers are susceptible to bowing caused by the influence of the metallisations on the front and rear side. Excessively bowed wafers lead to unacceptable yield losses during module construction. Screen printed aluminium paste is the major contributor to bowing which increases with decreasing wafer thickness. One barrier to using thinner wafers is the lack of an aluminium paste that combines good doping conditions for the BSF, good ohmic contact properties with a composition that has low bowing tendencies. In this work, we studied the effect of Al print thickness on electrical and mechanical performance of new aluminium pastes, developed by DuPont, using 200 µm thick 12.5x12.5 cm wafers. The influence of aluminium paste composition, firing conditions and silver front side was also studied.

INTRODUCTION

One key to reducing costs and energy consumption of the solar cell production process is the use of thinner wafers of the order of 200 µm thickness compared to the current industry range of 280-350 µm. The BSF (back surface field) is formed during the firing of a screen printed Al (20-60 µm thick) on the rear side. One of the major material challenges using thinner wafers with Al BSF is the bow of the wafers after firing. Problems during module production with handling and wafer mounting will occur if the bow exceeds a value of 1.4 mm.

The bow is a result of the different thermal coefficients of expansion (TCE) of aluminium and silicon. Bowing is negligible (< 0.5 mm) for 12.5x12.5 cm standard wafers of 330-350 µm thickness increasing dramatically with reducing wafer thickness. Values up to 5.5 mm could be measured for 200 µm thickness standard industrially processed 12.5x12.5 cm cells. In previous work [1], we showed that bow is strongly dependent on the wafer thickness. The experimental results were compared to the theoretical prediction, based on a simple bimetallic strip model [2].

In the present work, we investigated the factors that influence the bow of thin solar cells. The results should give us better understanding of how to reduce the bowing to a minimum so that module production is not affected. Paste composition and consumption were varied over a wide range to enable us to understand their influence on wafer bowing and electrical performance. Furthermore, we investigated the influence of the firing temperature. The influence of the silver front grid on bowing was also investigated.

SOLAR CELL PROCESS

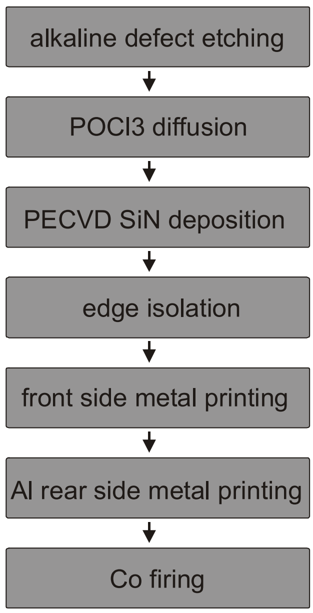

Figure 1 : Applied process sequence; cells were fired for almost all experiments under the same firing conditions to gain comparable results.

The applied process sequence for the solar cells is shown in figure 1. To achieve a wide processing window for the different Al thicknesses a 35 Ω/☐ emitter was used. In addition, we used a 45 Ω/☐ emitter for some cells to look for the yield in short circuit current and efficiency.

FACTORS THAT INFLUENCE BOW

Bowing will be observed when two or more layers of materials of different temperature expansion coefficients are in contact, in this case silicon and aluminium. Simple models for the deflection are available [2] as shown in the following equation (1)

$$\delta = \frac{3(\alpha_b - \alpha_a)(T_f - T)(t_b + t_a)d^2}{4t_b^{\,2}(4 + 6t_a/t_b + 4(t_a/t_b)^2 + (E_a/E_b)(t_a/t_b)^3 + (E_b/E_a)(t_b/t_a))} \qquad (1)$$

where δ is the deflection (m), t_a is the thickness of the top layer (m), t_b is the thickness of the bottom layer (m), T_f is the firing temperature (°C), T is the measuring temperature (°C), α_a is the TCE for top component (10^{-6} K^{-1}), α_b is the TCE for the bottom component (10^{-6} K^{-1}), E_a is the elastic modulus for the top component (Pa), E_b is the elastic modulus for the bottom component (Pa) and d is the width of the smaller component (m).

In this model, the salient factors for bowing are the relative thickness of the layers, the difference in temperature between the solidification point of one of the phases and the measuring temperature. The influence of the paste is seen through the TCE and elastic modulus of the top component. Another factor affecting the bowing of the real wafer is the effect of the front silver grid. Thus, for the real wafer, the model must be extended to a multilayer system, including the special grid geometry. The theory for a multilayer configuration can be found in [3] and is regarded to be outside the scope of this work.

EXPERIMENTAL RESULTS

For all experiments, 12.5x12.5 cm Baysix wafer of 200 µm thickness were used. The best cell result obtained was an efficiency η=15.1 %, J_{sc}=31.7 mA/cm^2, V_{oc}=616 mV and FF=77.2 % for the 35 Ω/☐ emitter.

Effects of Al deposition thickness

Previous work [1] showed the influence of Al thickness on bow. With lower paste applications we observed that the bow could be reduced by up to 50 % of the largest value. Cell performance was not affected by lower Al thickness, indicating that the BSF was still thick enough.

Dependence of paste composition on bowing and electrical performance

We wanted to investigate the effect of the paste composition over a wide range of fired thickness and the impact on bowing. Two different paste systems were prepared (paste A and B) which were printed to give

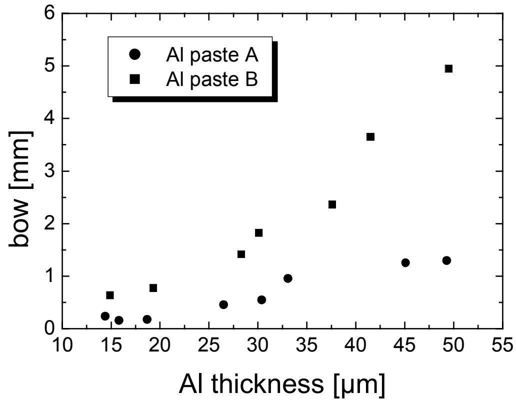

Figure 2: Bow as a function of fired Al thickness for aluminium pastes A and B.

different deposit weights by systematically varying paste rheological parameters. Figure 2 shows the influence of the paste composition on bowing and clearly demonstrates that the composition has a greater impact than the fired thickness.
Figure 3 shows that the open circuit voltage reaches a saturated value above a threshold aluminium thickness, but reduces systematically below a certain value. The same behaviour could be observed for both pastes, with a slight better performance for paste A.

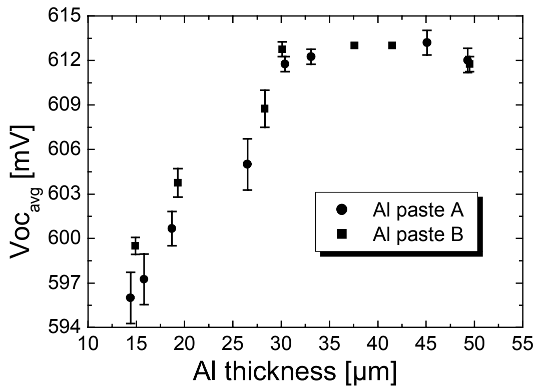

Figure 3: Dependence of V_{oc} on the fired Al thickness. All solar cells were fired with the same firing parameters to reach comparable values.

It is assumed that the behaviour of V_{oc} with decreasing aluminium thickness is caused by the amount of aluminium that is available at the interface influencing the thickness and Al dopant concentration of the epitaxially grown Si layer [4].

Influence of paste composition and firing temperature on performance

The composition of thick film pastes are broadly defined in terms of metal and inorganic powders that are dispersed in an organic vehicle with a rheology designed for screen printing. The fired properties of the thick film are designed to meet the fit and function. To achieve this objective, the designer will control chemistry and physical parameters such as powder morphology or particle size distribution. To examine the influence of the composition of the Al paste on bowing several Al pastes with systematic compositional changes were designed by DuPont, the end members of this system we call in this work D and E and have the same Al content. The solar cells were fired under two different firing conditions: To assess the impact of firing, the standard belt speed and a slower belt speed were employed to reach different wafer firing temperatures.

Figure 4 shows the influence of the systematic composition variation on bowing. The extent of bowing is lower for the higher belt speed, which is seen to increase with compositional change from D to E.

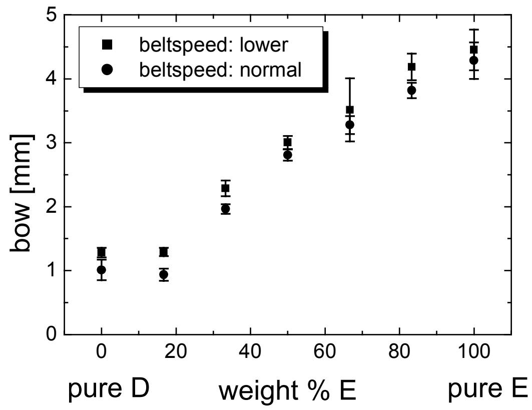

Figure 4: Bow variation as a function of D-E blend composition for two different firing profiles.

These changes are expected and are due to the change in the elastic modulus and the TCE of the thick film, which are, both impacted by the firing profile. In future work, we will demonstrate the level of control that can be achieved with these parameters and the subsequent impact on bowing for thin wafers.

Cell performance decreases with a non-linear characteristic with composition changes from D to E. As shown in figure 5, the V_{oc} decreases by about 1 %. We observe degradation of the series resistance as the system becomes richer in E, which is due to poor contact behaviour of the Al rear side paste E. There appears to be some correlation in changes in the V_{oc} and bow with composition change which will be the subject of future work.

Bowing has a linear correlation with the difference between measurement temperature and firing temperature as described in (1). In this work, we investigated the influence of firing temperature and belt speed on bowing; the data is shown in Figure 6. The temperature and belt speed, which were varied over a broad range, are normalized: A value of 1 relates to the standard firing regime where good cell results were obtained.

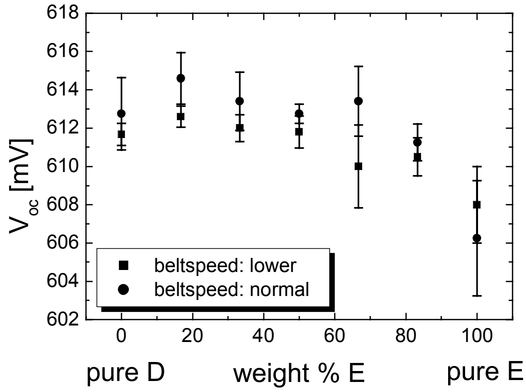

Figure 5: Open circuit voltage variation as a function of D-E blend composition for two different firing profiles.

The firing process window for 35 Ω/□ emitter solar cells is much broader than for more shallow emitter cells. This fact can be exploited to reduce the bow by adjusting the firing temperature to the lowest value following a firing process optimisation but still within the process window. Clearly, in this case, the manufacturer would be compromising between bow and cell performance to achieve the lowest cost per W_p. In comparison to the standard firing parameters we were able to reduce bow by 15 % using the lowest firing parameters. Our results showed that the temperature of the firing zone has a much larger effect on bowing than the furnace belt speed.

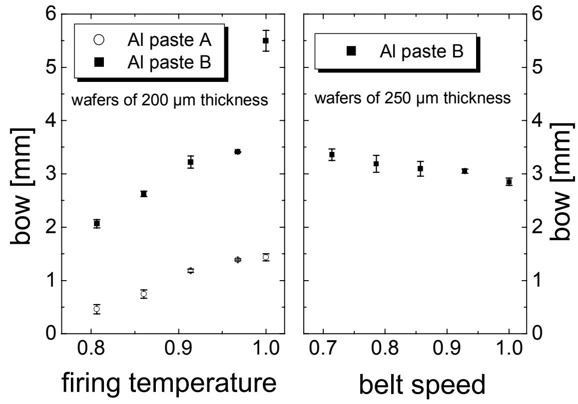

Figure 6: Bow in dependence of firing temperature and belt speed. Temperature and belt speed are normalized.

This temperature adjustment becomes more difficult for a 45 Ω/□ emitter, where bow reduction is found to be in the range of 5-10 %. For more shallow emitters the small processing window prevents an adjustment of firing parameters using the front side conductor employed in these experiments.

Some cells were processed with a 45 Ω/□ emitter to examine the yield in short circuit current. The best celll result was an efficiency η=15.1 %, J_{sc}=32.2 mA/cm^2, V_{oc}=617 mV and a fill factor FF=75.7 %.

Effect of front side metallisation on bowing

We have investigated the impact of the Al paste on bowing, however, it is also important to assess the impact of the front side metallisation on bowing as we might expect that it would counter the bending stress from the Al leading to lower bow.

To investigate this influence on bowing, a front side test structure was designed whereby we varied the percentage area from 0 % (no metallisation) to 100 % coverage, i.e. the metallisation was a plane. The print thickness remained constant; the coverage area was altered by using tape on the screen that could be progressively removed to leave more open area. The cells were processed with a standard print of aluminium and fired under identical conditions.

We know that the firing conditions are not in equilibrium, therefore, we can see from how the Al fires (colour), that wafers with a low coverage of front side metallisation demands less energy to achieve temperature compared with a 100 % coverage (the silver paste will consume energy due to its thermal mass and because there is considerable energy consumed during the sintering process).

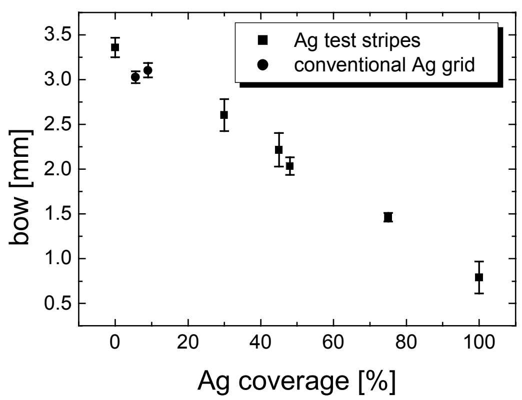

Figure 7: Dependence of bowing for different front side silver coverage ratios. The cells had a standard printed aluminium rear side. Conventional silver front paste was used.

Thus, the data that is reported in Figure 7 represents wafers that are in essence under fired at high silver coverage compared with the standard grid. We could compensate for firing by measuring the wafer temperature and modifying the firing profile, however, in the context of this work, we did not make the compensation.

Figure 7 shows a linear correlation between the bow and the paste area based on normalising the weight at 100 % coverage. The gradient will be a function of the elastic moduli, the TCE, the sintered stress and thickness of the metallisation. Clearly, for low bowing Al paste systems, it may be possible to design the silver conductor (or other fired printed material) to counter and perhaps eliminate bowing in thin wafers.

CONCLUSIONS

In this work, we investigated the effect of aluminium paste composition and firing profile on the electrical performance and bowing tendency for thin wafers.

We demonstrated that there are several possibilities to reduce the bow by using lower print weights, composition design and firing profile in agreement with the expected simple deflection model for 2 layers. More significantly, this work indicates that paste compositions exist that provides low bow performance enabling manufacturers to use 200 µm thick wafers.

There is evidence that bowing can be managed by adjusting the firing conditions where the process window is broad enough for firing the front side metallisation and emitter configuration (e.g. for 35 Ω/□ emitters). The influence of the silver front grid (as currently designed) plays a negligible role in reducing bow due the small surface area occupied.

A multilayer deflection model should be used to model bowing of Solar cells. Future work will, therefore, investigate the influence on bowing by the front side grid and rear side using finite element modelling techniques. Clearly, it will be important to investigate bowing in other cell geometries where the metallisations have migrated to the rear side as in rear contact cells.

ACKNOWLEDGEMENTS

The authors like to thank M. Keil and A. Davies for technical assistance in solar cell processing. The help of T. Pernau and B. Fischer during solar cell characterisation and F. Huster for the help with bowing calculations is also gratefully acknowledged.

REFERENCES

[1] A. Schneider, R.J.S. Young, *Proceedings of the 17th EC PVSEC*, Munich, D, 2001

[2] Roark and Young, *Formula for Stress and Strain*, 5th edition, McGraw Hill (1975), p. 113

[3] Tsung-Yu Pan, *Transactions of the ASME*, 30, **112**, (1990)

[4] J. del Alamo, J. Eguren and A. Luque, *Solid State Electronics* **24**, (1981), p. 415