

ALUMINIUM - BACK SURFACE FIELD: BOW INVESTIGATION AND ELIMINATION

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ABSTRACT: This paper is one part of a small series [1, 2] of contributions to this conference dealing with the fundamental properties and the limitations of the alloyed aluminium back surface field (BSF). In this work, the bowing that results with a screen printed and fired Al BSF is investigated. It was found that a plastic deformation of the rear contact after firing plays an important role in bow formation. Based on this finding, a simple procedure was developed with which the bow of a finished solar cell can be totally eliminated. This is achieved by cooling the cell after firing to between -20°C and -50°C , depending on cell geometry and used paste. After heating up to room temperature, the bow is removed and there is no evidence of either mechanical or electrical damage to the cell.

Keywords: Back-Surface-Field, Bow, Manufacturing and Processing

1 INTRODUCTION

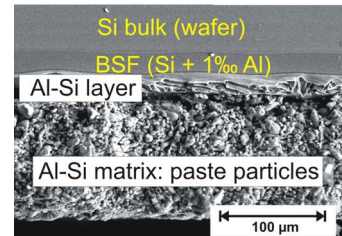
The screen printed alloyed aluminium back surface field (BSF) remains the standard rear passivation and contact for most industrial silicon solar cells, as it was from the beginning of mass production of terrestrial solar cells in the 1970s. In view of the current trend towards larger and thinner wafers, the wafer bow, caused by the strong contraction of the Al rear contact after contact firing, is an increasingly important issue for solar cell process development. The Al BSF technology used in the so-called PECVD-SiN_x firing-through process enables high industrial efficiencies both for multi- and mono-crystalline silicon. Alternatives such as dielectric passivation in combination with local rear contacts are still not competitive for industrial mass production. Therefore, it is important to pursue efforts to optimize the Al BSF. In recent years, some progress on bow reduction was reported by research institutes and paste manufacturers, but no break-through was made. The paste composition was altered, but details were not disclosed. A detailed picture of the mechanical behaviour is still lacking, and the common bimetallic elastic model fails completely to explain the observed bow (it overestimates the bow by a factor of 50). In this work, a close look is taken at the formation of the Al rear contact and most importantly its elastic and plastic behaviour on cooling down after contact firing. With new insights, the failure of the bimetallic calculation can be explained. Going one step further, a process sequence was developed with which the bow of a finished cell can be eliminated completely.

2 GENERAL DESCRIPTION OF BOW

In an industrial solar cell process a thick layer of Al paste is printed onto the rear surface and alloyed with the silicon in the contact firing step. The cell is heated to about 800°C for a few seconds. At this temperature, a liquid phase consisting of approximately 30 atomic-% Si and 70% Al is formed. On cooling down, a Si layer doped with Al is epitaxially grown on the wafer, building up the BSF layer. When the temperature is lowered below the Al-Si eutectic temperature of 577°C , the remaining liquid solidifies. This layer has the eutectic composition (Al + 12 atomic-% Si) and is written as AlSi in the following. The rear side of the cell is now composed of three layers as shown in Figure 1: the BSF (Si doped with 0.1 % Al, not important for bow

considerations), a compact AlSi layer of 2-5 μm thickness and a 30-60 μm thick paste matrix of AlSi particles enclosed by thin oxide shells.

Figure 1: SEM cross-section of a fired Al back contact (Here a double printed Al layer is shown). The volume filling of the matrix is 50-70%.



The temperature averaged linear thermal coefficient of expansion (TCE) of AlSi ($\alpha=23\times 10^{-6}\text{K}^{-1}$) [3] is much higher than that of Si ($\alpha=3.5\times 10^{-6}\text{K}^{-1}$) [4], leading to a stronger contraction of the rear contact and therefore a convex wafer bow. The stress-free lengths L_0 of the Si wafer and the AlSi layer and matrix are equal at the solidification temperature of 577°C and differ by $\approx 1\%$ at room temperature. The layers are in rigid contact, which does not allow for any slippage, and therefore the system can respond to this difference in only three ways:

- *Compression of the Si wafer.* This effect can be neglected to first order because of the stiffness of Si (modulus of elasticity 100-200 GPa, depending on crystal orientation) and the thickness of the wafer. The total modulus of elasticity of a 200 μm thick Si wafer is at least 50 times larger than that of a 40 μm thick AlSi matrix.
- *Wafer bow (convex).* The strain relief due to wafer bow is minimal due to the relatively thin layers: using geometric arguments, this relief can be estimated to be less than 0.02% for a 40 μm thick AlSi matrix on a solar cell of 200 mm thickness with an area of $15\times 15\text{ cm}^2$, assuming a bow of 2 mm.
- *Lengthening of the AlSi layer and matrix.* The remaining difference in L_0 , which is nearly equal to the 1% difference in thermal contraction, is compensated by an elastic and plastic deformation of the AlSi rear contact.

3 CONVENTIONAL STRATEGIES FOR BOW REDUCTION

To reduce or eliminate the wafer bow, the residual stress at room temperature in the AlSi layer and paste matrix must be reduced. Several methods have been trialled, as detailed below.

- *Use less aluminium.* The easiest way to reduce the wafer bow is by reducing the amount of printed Al. There is not much room for improvement with this method, as the standard amount (6-7 mg/cm² Al using a screen with 200 mesh per inch) is close to the minimum needed to achieve a closed BSF. An Al reduction of 25% results in a strongly increased rear surface recombination velocity due to the presence of unalloyed areas [1].

- *Remove AlSi after firing.* A modified processing scheme, including removal of the AlSi in HCl and a subsequent deposition of a back surface reflector (optional) and a local metal contact on the rear, is a possibility to combine a bow reduction with a slight efficiency increase. An introduction into industrial production lines, however, is unlikely because of the increased process complexity and the resulting large amount of HCl slurry, which has to be disposed or filtered for reuse.

- *Reduce TCE of AlSi-matrix.* By adding components to the Al paste with a very low TCE the average TCE of the system can be slightly decreased [5]. Only a minor effect can be expected as the amount of Al and its thermal contraction can not be reduced with this method.

- *Weaken particle interconnections.* The thermal contraction of the AlSi matrix is an average of the individual components, independent of the matrix structure. On the other hand, the mechanical properties of the system are strongly influenced by its structure, i.e. by the strength of the particle interconnections (see Figure 2). By weakening these interconnections, the maximum tensile stress in the AlSi-matrix and thereby the bow can be reduced. This approach has been used empirically to produce low bow pastes. The interconnections can be weakened by changing the composition or amount of the glass frit, using additives or modifying the firing conditions [6]. Modifications of this kind, however, usually also result in a reduction of the rear surface passivation quality.

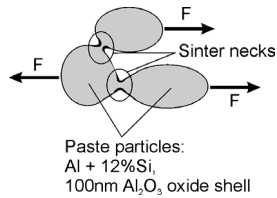


Figure 2: Lateral strain forces acting on AlSi particles on cooling down due to the mismatch of the TCEs. The mechanical properties of the paste matrix are determined by the size and shape of the particles, by the structure and geometry of the matrix and by the interconnections (sinter necks).

- *Interruptions in the AlSi rear contact.* This approach is not very efficient for bow reduction, because the bow is a local property of the system as long as no slip occurs. The local thermal contraction and the resulting stresses and strains result in a local curvature. The total curvature (i.e. bow) is simply the sum of these local curvatures.

4 DETAILED MODEL

A bowed solar cell can be approximately modelled as a bimetallic strip, bending in only one dimension. If only elastic deformation would occur, the resulting bow could be calculated using the following equation [7]:

$$\delta = \frac{3/4L^2(\alpha_{Al} - \alpha_{Si})(577^\circ C - 20^\circ C)(d_{Al} + d_{Si})}{d_{Al}^2 \left(4 + 6 \frac{d_{Si}}{d_{Al}} + 4 \left(\frac{d_{Si}}{d_{Al}} \right)^2 + \frac{E_{Si}}{E_{Al}} \left(\frac{d_{Si}}{d_{Al}} \right)^3 + \frac{E_{Al}}{E_{Si}} \frac{d_{Al}}{d_{Si}} \right)} \quad (1)$$

(δ : bow (height difference between cell centre and edges), L : solar cell length, α_x : TCE, d_x : layer thickness, E_x : modulus of elasticity).

A bow calculation using this equation fits to measurements only if a very “soft” AlSi matrix is assumed, with a modulus of elasticity about 1/50 of the literature value [8]. Motivated by this discrepancy, the temperature dependent material properties and the behaviour of the system during cool down were studied. Figure 3b shows in detail the calculated tensile stress of an AlSi rear contact based on the values of the TCEs and the modulus of elasticity E , if a fully elastic behaviour is assumed. $E(T)$ of Al is shown in Figure 3a; Al-12%Si is known to have only a slightly higher E [8]. The straight line in Figure 3b should be compared with the literature values of the ultimate tensile stress (UTS) of Al-12%Si (triangles). From this it can be seen that soon after cooling down from the solidification temperature (577°C) the stress in the AlSi contact is no longer determined by $\sigma = \epsilon \times E$ (Hooke’s law; ϵ : strain) but by $\sigma = \text{UTS}$. In other words, during cool down the elastic limit of the AlSi is exceeded and most of the elongation is a plastic and thereby permanent deformation of the AlSi. Figure 3c shows that the elastic component, assuming a compact structure of the AlSi, constitutes only 1/10 of the room temperature strain. In reality, the paste matrix is softer and the elastic part is greater, in the range of 0.2 to 0.5 % strain.

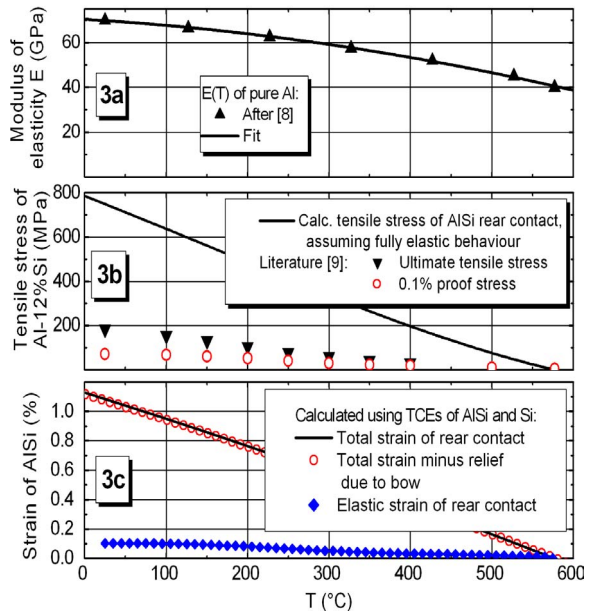


Figure 3a-c: Temperature dependence of some relevant material properties.

In Figure 4, the bow model is explained with a schematic stress-strain diagram of the AlSi matrix. At 577°C the system is stress free. On cooling down, the AlSi layers contract more than the silicon wafer, leading to a strain of the AlSi layers and a resulting stress, determined by the modulus of elasticity. Once the elastic limit is reached (estimated to occur between 400°C and 300°C), a plastic flow of the AlSi matrix sets in. The stress in the rear contact is now limited by the tensile

stress, with only a small temperature dependent increase (see Figure 3b; this effect is neglected in Figure 4). Note that a constant stress means a constant bow.

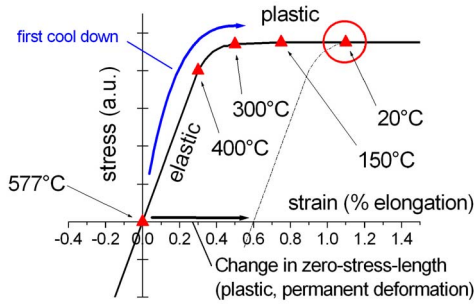


Figure 4: Schematic stress-strain diagram of the AlSi rear contact on cooling down after contact firing.

Based on the model described above, equation 1 was modified to include plastic deformation and simplified by neglecting insignificant terms:

$$\delta = \frac{3}{4} L^2 \frac{d_{Al}}{d_{Si}^2} \frac{\sigma_{Al,yield,eff}}{E_{Si}} \quad (2)$$

In Figure 5 a one-parameter-fit (σ) of equation 2 to experimental values of bow measurements with solar cells of different thicknesses is shown, yielding an effective tensile strength of the AlSi matrix $\sigma_{Al,yield,eff} = 15$ MPa (referring to the whole cross-section of 40 μ m thickness). This is between 10% and 20% of the literature value for a plastic flow tensile stress of a compact AlSi layer. The difference can be explained by the 50% volume filling and by the fact that the particle interconnections are the weakest part of the structure.

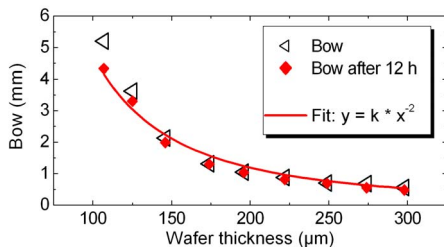


Figure 5: Bow of solar cells with different thicknesses. (Al rear contact: 7 mg/cm², 42 μ m). After 12 hours some relaxation can be observed. A one-parameter-fit of formula (2) to these results yields $\sigma_{Al,yield,eff}$.

4 NOVEL TECHNIQUE FOR BOW REDUCTION

As shown in Figure 4, the AlSi rear contact is strained by about 1.1% at room temperature, of which approx. 0.4% is elastic strain. This means that the rear contact of every standard industrial solar cell undergoes a plastic lengthening of about 0.7% after firing. Now, if it is possible to let this plastic flow proceed by another 0.4%, the whole strain (of 1.1%) will be compensated by a plastic deformation. No elastic deformation will remain, which means that the stress and therefore the bow will vanish. How can the AlSi-matrix be permanently lengthened, preferably by another 0.4%? This can be achieved by:

- *Waiting:* Usually some creep of the strained AlSi can be observed over hours and days, which helps in reducing the wafer bow but is not very efficient.

- *Mechanical means:* The AlSi rear contact can be stretched mechanically by pushing the wafer centre until a flat wafer or even a concave bow is reached. As already mentioned in section 2, only a negligible lengthening can be obtained due to geometrical limitations.

- *Cooling down below room temperature.* This conclusion is the central statement of this paper.

The cooling bow reduction method is illustrated in Figure 6. If the wafer is cooled below room temperature, the plastic flow proceeds, while the tensile stress and therefore the bow remain roughly the same. At some temperature (for example, -50° C) the zero-stress-length of the AlSi matrix has been increased by plastic flow by another 0.4%. When the solar cell is heated to room temperature, the AlSi expands more than the silicon wafer and the elastic part of the strain (0.4%) is removed.

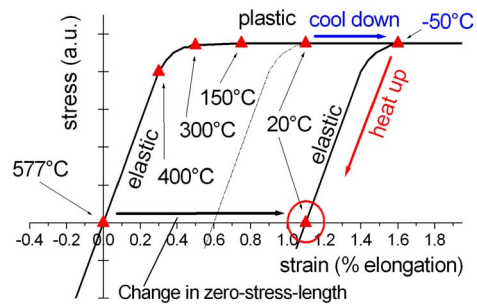


Figure 6: Extension of Fig. 4 to include the bow elimination procedure by cooling below 20° C.

6 EXPERIMENTS

Three application examples are described in the following to demonstrate the effect of temperature on bowed wafers. Solar cells with a large bow were prepared for better visualization. Printing and firing of 12 mg/cm² of fritted Al paste resulted in a 12 mm bow on 100 μ m thick cells of 15 x 15 cm² area.

6.1 Cool to -196° C using liquid nitrogen (LN₂)

In LN₂ a solar cell can be cooled to T=-196° C within seconds. As expected, only a minor increase in the bow was observed. On reheating to room temperature, the expansion of the AlSi matrix removes the elastic strain. As the lengthening of L_0 at T=-196° C is more than the elastic strain at room temperature (i.e. a plastic flow of more than 0.4% occurred between 20° C and -196° C), the final L_0 of the AlSi system is greater than the L_0 of the Si wafer, which results in a *concave* bow at 20° C.

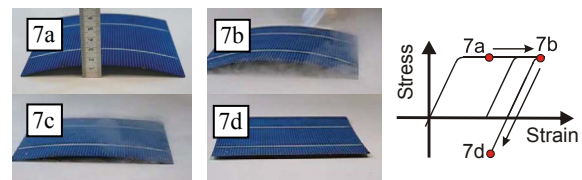


Figure 7: Part a shows a cell with a 12 mm bow at room temperature. In part b the cell is seen immediately after removal from liquid nitrogen. The bow is approximately unchanged. On heating, the bow is reduced (part c) and finally, at room temperature, a permanent concave bow appears (part d), indicating that the applied cooling temperature was too low.

6.2 Eliminate concave bow by heating

Due to the (within limits) symmetric stress-strain curve, a concave bow can be removed by heating until a compressive plastic flow of the AlSi sets in. Figure 8 shows the application of a heat gun resulting in temperatures of 200-300° C. At this temperature, the compressive elastic limit is exceeded, leading to a concave bow of over 10 mm and a compressive plastic flow, i.e. a shortening of the L_0 of AlSi.

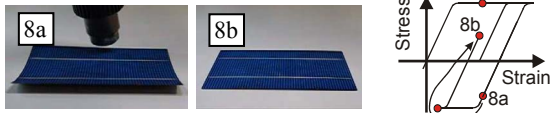


Figure 8: A concave bow can be removed by applying heat and making use of a compressive plastic flow of the AlSi matrix.

6.3 Eliminate convex bow with an appropriate cooling

By choosing the appropriate temperature (depending on the thickness of the wafer and the Al and the thermo-mechanical properties of the AlSi matrix), the bow can be totally eliminated in a single cool-down/return-to-room-temperature cycle. In the example shown in Figure 9, a wafer with a 6 mm bow was chosen. Using a cooling spray, a temperature of nearly -50° C was reached within seconds. Again, no significant change in bow was observed at this stage. After returning to 20° C, the stress is relieved and the bow is eliminated.

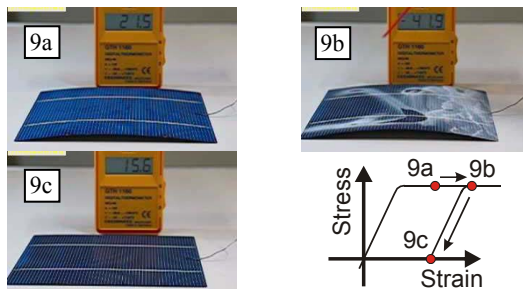


Figure 9: A 6 mm bow is totally and permanently removed by cooling to -50° C for a few seconds using a cooling spray.

7 FURTHER ISSUES

- *No cell damage due to thermal stress has been observed so far*, neither visible nor electrical, even after many cooling/heating cycles. This most important issue should be verified on a large number of cells in an industrial environment. From theoretical considerations, damage is unlikely, because the stresses during cooling and heating do not exceed those that already occur during cool down after firing. A degradation of the front contact due to an embrittlement of glass frit components is possible but has not yet been observed.

- *The effect is stable on a long time scale.* As it is caused by an elimination of the residual stresses, no creeping is expected to occur. Of course, the bow of a thin wafer will vary elastically when the ambient temperature is changed.

- *The bow can be made to range from convex to concave* by adjusting the cooling or heating maximum temperature, which could be useful for special applications.

- *The effect is reversible.* This was shown in section 6 and can be explained using the symmetric hysteresis curve in the stress-strain diagram.

- *A transfer of this procedure into industrial production lines seems to be easy.* Due to the large ratio of surface to volume, solar cells can be effectively cooled by radiative heat transfer in an environment with cool walls. A simulation shown in Figure 10 suggests that the target temperature of -20° C to -50° C can be easily reached within 2 min using a conveyor belt apparatus.

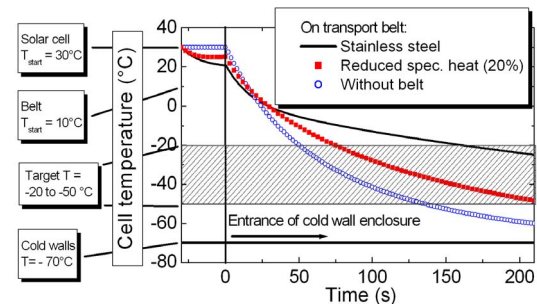


Figure 10: Simulation of solar cell cooling in a closed environment with walls at $T = -70^{\circ}\text{C}$. Only radiative heat exchange is taken into account.

8 SUMMARY AND CONCLUSIONS

A new model to semi-quantitatively explain the bow of solar cells with an alloyed Al rear contact was introduced, emphasizing the importance of a plastic deformation of the AlSi paste matrix. Based on this understanding, a procedure was developed to permanently eliminate the wafer bow of finished solar cells. In order to eliminate the bow, the cell must be cooled to an appropriate temperature, typically between -20° C and -50° C, for a few seconds. After returning to room temperature, the bow vanishes. No evidence of either mechanical or electrical (IV data) damage of cells was observed. This novel technique would be very easy to implement in industrial production lines and a patent application [10] has been filed. Solving the bow problem by applying this technique will help in developing highly efficient Al pastes without making compromises concerning low bow properties.

Acknowledgements

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