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Ultrasonic Tinning of Al Pads for Silver- and Lead-Free Cell Interconnection

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Abstract. Polysilicon on oxide back junction solar cells offer a high efficiency potential with significantly reduced silver consumption by using an aluminum front grid. The cell interconnection typically requires additional silver pads for soldering. Ultrasonic tinning of aluminum generates silver-free tin solder pads which can further decrease the silver consumption. Here, we demonstrate ultrasonic tinning on front side Al pads of polysilicon on oxide back junction solar cells solar cells for a silver-free cell interconnection. We report low damage to the passivation layers with local losses in implied open circuit voltage of 5 mV to 15 mV. On cell level, this results in small open circuit voltage losses of 1 mV to 1.5 mV, or 0.2 %. Single cell mini module fabrication shows moderate cell-to-module losses of 1.3 % to 2 %, reaching up to 20.8 % module efficiency.

Keywords: Ultrasonic Tinning, Silver-Free, Cell Interconnection

1. Introduction

In 2024, over 27 % of the annual silver supply has been consumed by the photovoltaic (PV) sector [1] while the absolute supply has been constant over the last decade [2]. The consumption of silver is a major concern towards the goal of world-wide 100 % renewable energy production. Also, it is a significant cost factor accounting for 5 % to 15 % of the whole module price [3]. Current crystalline silicon PV technologies often use silver contacts for both polarities on the solar cells. Aluminum is an established material for solar cell metallization [4, 5]. It can also contact poly silicon layers [6, 7]. One drawback of aluminum is the formation of a highly stable native oxide when exposed to air. As a result, it cannot be contacted by the standard soldering process and typically requires additional silver solder pads. This increases both the silver consumption and the series resistance due to the high resistivity of the silver-aluminum alloy formed at the overlap of the two metals [8, 9].

Ultrasonic (US) soldering is a technique which allows to break up the native oxide on Al to form a contact between the solder and the pure metal. It can be applied to aluminum metallization on solar cells to generate silver-free structures that are solderable using standard processes [10]. We call the application on aluminum US tinning to avoid a mix up with the wire soldering for the cell interconnection. Its potential has been shown in the past on passivated emitter and rear contact (PERC) solar cells with full area rear metallization [11] and in the recent time on bifacial PERC+ solar cells with busbar structures on the rear side [12]. US tinning is highly compatible with the standard stringing process that uses solder coated copper wires by replacing the Ag pad printing by US tinning of aluminum.

We present our work on US tinning of Al structures on the front side of solar cells on the example polysilicon on oxide (POLO) back junction (BJ) cells. Transferring the technology to the front side leads to additional challenges. To avoid shading, the size of the Al structures for tinning are much smaller on the front side compared to the rear side metallization which poses higher demands on the tinning process to achieve loss-free and stable interconnection. We report local losses in implied open circuit voltage (iV_{OC}) of 5 mV to 15 mV resulting in low open circuit voltage (V_{OC}) losses on cell level of 0.2 %. The fabrication of single cell mini module demonstrates considerate cell-to-module losses of 1.3 % to 2 % absolute using US tinning and lead-free interconnects.

2. Ultrasonic tinning process, cells and modules

We use a handheld US soldering station by MBR Electronics providing an US power ranging from 4 W to 14 W. The iron tip temperature is adjustable between 150°C and 480°C. The station features a 0.75 × 1 mm^2 sonotrode operating at 60 kHz. We use a lead- and silver-free Sn90Zn10 composite for tinning. Adding Zn to the tin based solder can improve the strength of the contact to Al [13]. Due to the solder tip's low heating power, the solar cell is preheated to 180°C to prevent premature solder solidification during processing.

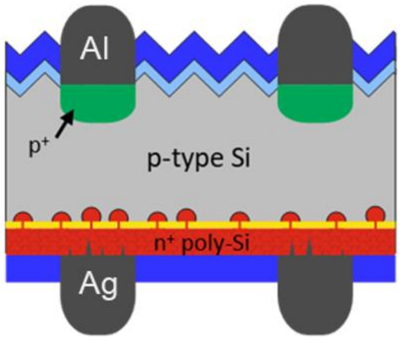

Figure 1. *Schematic of POLO BJ solar cell with Al front grid.*

We demonstrate the transfer of the US tinning process from rear to front side on POLO BJ solar cells. This cell structure offers a lean process flow with high efficiency potential [14] and allows also Ag-free solar cells [6]. They have lower silver consumption compared to other high-efficiency cell concepts. *Figure 1* shows the cell schematic. The polarities are reversed from PERC to POLO BJ and the Al metallization has moved to the front side.

The front metal grid of the investigated cells of M2 wafer size consists of Al fingers and 12 busbars (BB), the latter measuring 180 µm in width, with twelve Al pads per busbar. The pads measure 1 mm in width and vary in length (1 mm, 1.5 mm or 2 mm, see *Figure 2a*)). US tinning is applied to these pads to create a solderable surface. The solar cell precursors have a non-metallized rear side, enabling unobstructed visual inspection of the cell via rear side photoluminescence (PL) imaging. The finalized solar cells feature a 9BB Ag grid, screen printed on the rear side. The busbars of this grid are offset to the front busbars, allowing rear side PL imaging. We analyze their current-voltage (*I*-*V*) characteristics before and after US tinning as well as post light soaking to assess process induced damage.

We fabricate mini modules using another batch of solar cells with a 12BB Al metal grid on the front side and 1×1 mm^2 pads (see *Figure 2b*). These cells feature a standard 12BB Ag grid on the rear side. Each module contains a single half-cell. For cell interconnection we use round copper wires with a diameter of 325 µm coated with 10 µm to 15 µm of lead-free SnAg solder. The modules have a 3 mm thick front glass, UV transparent polyolefin (POE) as encapsulant on the sunny side and non-UV-transparent POE on to the rear side. On the rear side the modules are finalized with a transparent backsheet.

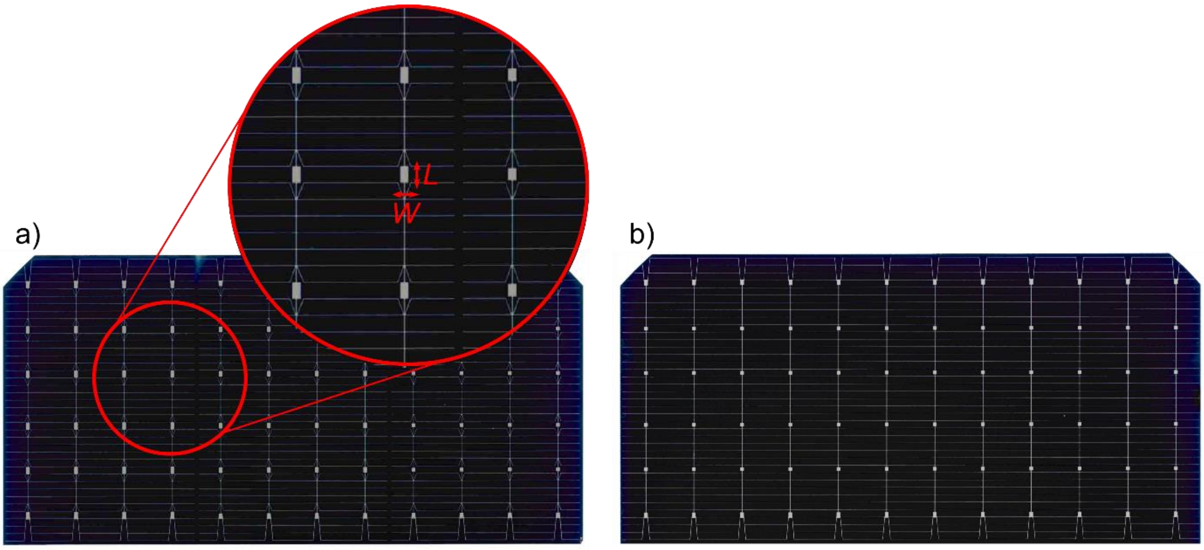

Figure 2. *Photo of the front side of POLO BJ half-cells with Al metal grid. US tinning is applied to the Al pads. The cells for PL imaging and I-V characterization have a width W = 1 mm and varying length L = 1.0, 1.5, 2.0 mm (see magnification) and are shown in a). The half-cell in b) has a pad size of W = 1 mm and L = 1 mm and is used for module fabrication.*

3. Results

During the US tinning process sound waves are coupled into the solar cell metallization, which can potentially damage the surface passivation. We perform photoconductance-calibrated and spatially resolved photoluminescence imaging (PCPLI) [15] to calculate the local open circuit voltage losses caused by the US tinning. For calibration we use unmetallized samples processed similarly to the metallized samples. Recording the PCPLI images from the rear side of cell precursors without metallization ensures that the damaged areas are visible during the analysis.

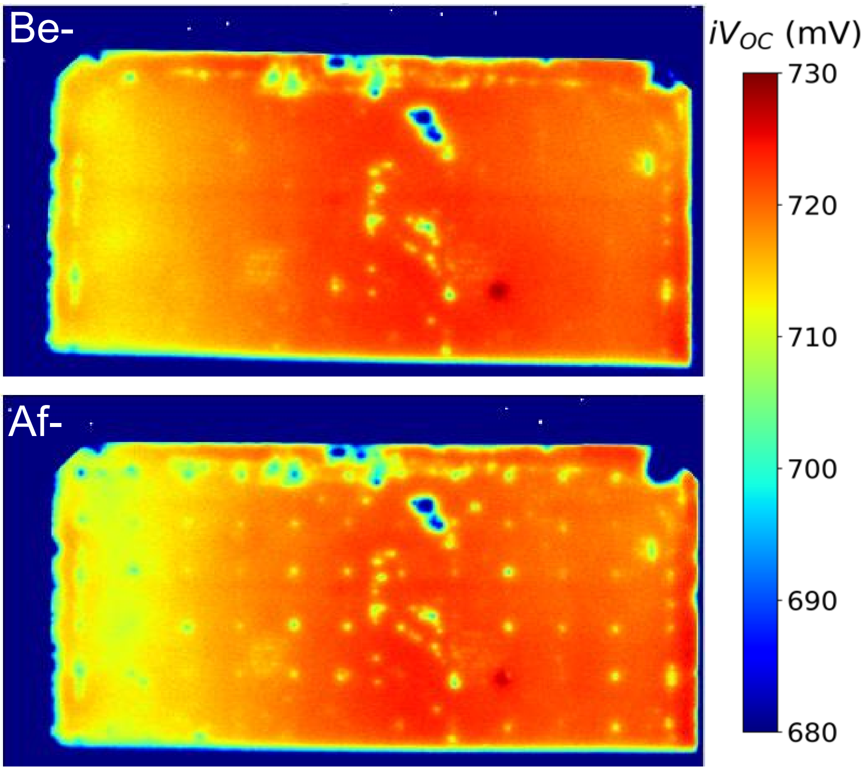

Figure 3. *Implied open circuit voltage iV_{OC} of a POLO BJ half-cell before and after US tinning process.*

Figure 3 shows the spatially resolved iV_{OC} mapping before and after US tinning at the maximum power of 14 W with a set temperature of 370°C of the US soldering tip. We detect local reductions in iV_{OC} of 5 mV to 15 mV. The damaged areas account for 3 % to 10 % of the whole cell area. The rather high deviation is not correlated to the size of the Al pads but stems from the manual handling of the US tinning process. The limited precision leads to the application of US power not only on the designated Al pad but also on unmetallized cell areas resulting in higher damage to the passivation layers. We estimate an overall reduction in iV_{OC} of 0.5 mV to 2 mV on cell level from the iV_{OC} mapping.

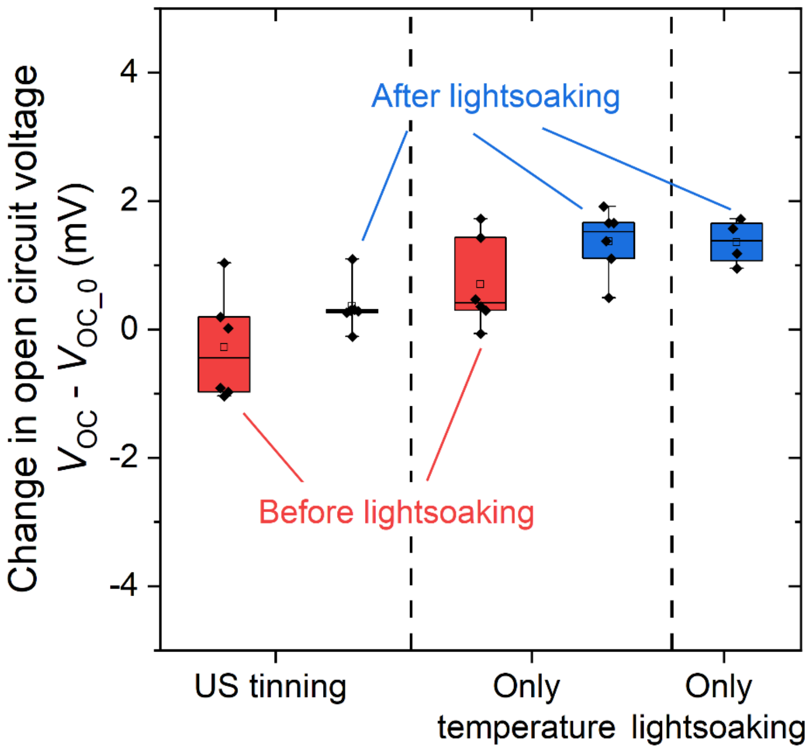

Figure 4. *Change in open circuit voltage after US tinning and light soaking. Three groups are compared: cells with applied US tinning, cells annealed at 180°C for 10 minutes and only light soaked cells.*

Additionally, we measure the *I-V* curve of solar cells using a LOANA system by pv-tools. We compare three groups. US tinning is applied to the first group of cells. The second group is annealed for 10 minutes at 180°C. The annealing emulates the same heating step that the cells undergo during the US tinning process. The long process time is a result of the manual process. We expect much faster process times for an automatized process. These two groups are first measured after US tinning and tempering, respectively. A second measurement is performed after light soaking at 0.3 suns for 72 hours. A third group of cells, which have only undergone light soaking, is measured as well. The changes in open circuit voltage V_{OC} relative to the initial values are shown in *Figure 4*. After US tinning the V_{OC} decreases by 0.5 mV on average. The median V_{OC} of the tempered cells (group 2) slightly increases by 0.4 mV. Light soaking of the US tinned cells increases the V_{OC} by 0.8 mV to +0.3 mV relative to the initial V_{OC}, whereas light soaking of all cells that had not been subjected to US tinning (i.e.: group 2 and group 3) increases the voltage by 1.2 mV to a 1.5 mV gain compared to the initial V_{OC}, regardless of whether they had been annealed or not. This indicates that US tinning is responsible for a median decrease in open circuit voltage of POLO BJ solar cells by 1.2 mV which is a relative loss of 0.2 %. We consider these losses acceptable at the current quality of the manual tinning process.

Table I. *I-V data of modules and corresponding cells fabricated using US tinning on the front side Al grid.*

	V_{OC} of cell (mV)	V_{OC} of module (mV)	J_{SC} (mA/cm^2)	Fill factor *FF* (%)	Efficiency η (%)
Average of cells			38.7	80.5	22.2
Module 1	715.9	714.1	37.2	78.2	20.8
Module 2	718.9	714.1	37.4	75.5	20.2
Module 3	719.3	715.6	37.3	75.5	20.3
Module 4	717.1	715.3	37.1	78.4	20.6

We fabricate three mini modules using US tinning on 1×1 mm^2 pads of a pure Al front grid. The *I-V* Parameters of the initial cells before US tinning and the modules are shown in Table 1. The modules are measured using a module flasher. The efficiency is normalized to the active cell area.

We observe moderate cell-to-module losses of 1.4 % to 2.0 % absolute reaching module efficiencies of 20.8 %. The hand soldering of the interconnects led to a few cell cracks in module 2 and 3, causing the higher loss in V_{OC}. The behavior of module 1 is as expected with 1 mV V_{OC} reduction due to the US tinning process. The additional losses stem from voltage drop of the interconnects and cross-connectors. The latter affects single cell modules much more than modules with multiple cells [16]. The soldering of the lead-free coated round copper interconnects is still not optimized yet, leading to excessive cell cracks. We are positive that the cell cracks can be mitigated in the future.

4. Conclusion and Outlook

In summary, we report on our US tinning process on Al pads on the front side of POLO BJ solar cells. The process enables silver-free metal grids on the sunny side of the solar cells. US tinning induces local damage beneath and around the tinned areas and a reduction in iV_{OC}. Nevertheless, on cell level, the damage averages to only 1 mV to 1.5 mV loss in open circuit voltage. Future automation of the US tinning will enable higher precision in positioning and tip-to-cell distance control. Automation will also reduce the process times. All this should allow the reduction in the expected voltage loss by the US tinning process to less than 0.5 mV.

We demonstrate the interconnection of solar cells with a screen-printed, full Al grid on the front side. The cell-to-module losses are acceptable, with the highest module efficiency reaching 20.8 %. Using lead-free solder for US tinning and soldering during cell stringing shows that the process is also suitable for lead-free PV modules. POLO BJ solar cells featuring Al metallization on both sides [6] highlight the potential of US tinning to achieve efficient modules without the need for silver metallization.

Underlying and related material

All relevant raw data were submitted with the article and can be asked directly to the authors.

Author contributions

M. Brinkmann, main author: conceptualization, investigation, visualization, writing – original draft; H. Schulte-Huxel: conceptualization, writing – review and editing, project administration, supervision, funding acquisition; C. Hollemann: conceptualization, writing – review and editing, project administration, funding acquisition; B. Min: resources, writing – review and editing; S. Junge: resources, writing – review and editing; R. Brendel: conceptualization, writing – review and editing, supervision, funding acquisition;

Competing interests

The authors declare that they have no competing interests.

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