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Energy Procedia 43 (2013) 2 – 11
Energy Procedia

4th Workshop on Metallization for Crystalline Silicon Solar Cells

Summary of the 4th Workshop on Metallization for Crystalline Silicon Solar Cells

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Abstract

The 4th Metallization Workshop held in May 2013 in Constance, Germany, enabled experts in metallization for crystalline silicon solar cells to obtain a clear view on the status of the technology, as well as to exchange and generate new ideas and insights. From the contributions on the workshop, it was clear that the traditional metallization technique of screenprinting Ag paste has been improved in a dramatic way over the last two years, accelerating the decrease of Ag consumption per cell while improving solar cell efficiency. This was achieved through enhanced understanding of screenprinted contacts, improving Ag pastes and evolutionary modifications to the screenprinting technique. Alternatives to screenprinting, including electroplating of Ni and Cu contacts, also continue to progress, though not quite at the same impressive rate of improvement as Ag printing.

Selection and peer-review under responsibility of Guy Beaucarne, Gunnar Schubert and Jaap Hoornstra

Keywords: Metallization; silicon solar cells

1. Introduction

The photovoltaic industry is going through very difficult times, as evidenced by bankruptcies and solar exits of major players. To survive in this context, companies have been spending enormous efforts to increase solar cell efficiency and reduce cost. Metallization is a process step that has a direct substantial impact on both aspects, and therefore, not surprisingly, has been a topic of intense research and development. In order to provide a forum for metallization experts to share and discuss those research efforts, the authors started in 2008 a series of workshops that focuses on the metallization of crystalline silicon solar cells. This paper is a contents summary of the fourth

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Selection and peer-review under responsibility of Guy Beaucarne, Gunnar Schubert and Jaap Hoornstra
doi:10.1016/j.egypro.2013.11.082

edition of the workshop, which was held in Constance, Germany on 7 and 8 May 2013, bringing about 170 metallization researchers together for two days. All the presentations referred to are posted on the website www.metallizationworkshop.eu. Some of the authors wrote a paper to complement their oral presentation. Those papers are now available in the present issue of Energy Procedia.

Metallization of crystalline solar cells today is dominated by the screenprinting technology. Most of the talks therefore dealt with this type of metallization, covering the fundamental and material aspects, the process technology and the application. Several talks however dealt with alternatives to screenprinting, looking at the advantages as well as challenges ahead for those technologies to emerge as competitive solutions.

2. Improved understanding of screenprinted contacts

The exact nature of the Ag screenprinted contact and the current path through the different materials under and in the fingers has been a matter of debate for several years. It was shown about a decade ago that Ag crystallites grow into the Si surface during the Ag paste firing, that the density of those crystallites vary according to the surface doping and defects concentration, and that they play a role in providing a good contact between the Si and the bulk Ag in the fingers [1,2]. Two main conduction mechanisms were hypothesized: Via direct interconnection between the silver crystallite and the bulk silver of the finger [2] or via a multi-step tunneling mechanism through an ultra-thin glass layer between the crystallite and the bulk silver [3]. A few years ago, it was pointed out that Ag nano-colloids were present in the glass phase that is formed between the silicon and the bulk Ag during contact firing, emphasizing that the contact was mainly occurring tunneling through the glass via the nanocolloids [4,5]. At the workshop, the results of a recent German research project Mikrosol was presented, which aimed to shed light on the conduction mechanism by imaging and quantifying key microscopic features under screenprinted contacts [6,7]. It was shown that both crystallites as Ag nanocolloids can be found in screenprinted contacts, and that a continuous glass layer correlates with a low contact resistance. However, the results could not yet point at the dominating current paths. Valuable approaches to better understand the fundamental transport mechanisms were presented, such as Kelvin Probe Microscopy, which enables mapping of the local workfunction and energy band alignment on atomic scale [8], and integration of microscopic contact features in device modeling [9].

Just as for conduction mechanisms, the *formation* mechanism of the microscopic contact features during the firing treatment is also not yet completely understood. Some contributions at the Workshop however enhanced the current understanding of the phenomena at play. The dissolution of Ag into the molten glass frit as Ag^+ ions and the transport of those ions through the glass phase appear to be key factors. It was shown that the concentration of Ag crystallites at the Si surface is controlled by the partial pressure of oxygen in the firing ambient [10]. A mechanism was proposed in which Ag reacts with O_2 in the ambient to create Ag^+ ions and O^{2-} ions. Those ions are transported in the molten glass and react with SiN and Si at the surface to form the Ag colloids and crystallites.

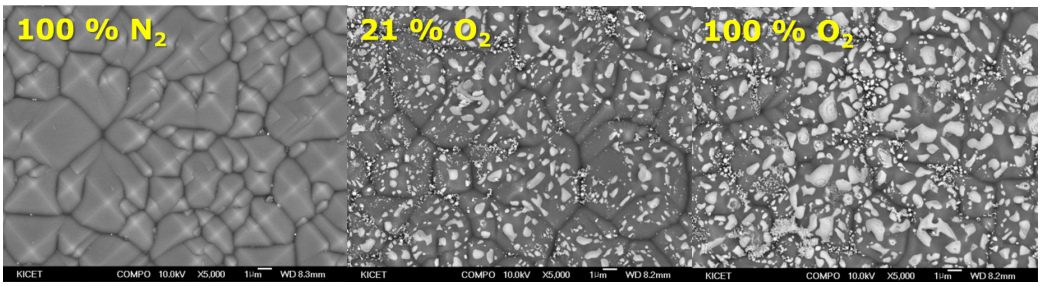

Fig. 1. Scanning Electron Microscopy top view of Si surface after etch revealing Ag crystallite presence, as a function of the oxygen partial pressure in the firing ambient (reproduced with permission from [10])

The way the Ag phase and the glass frit phase densify as a function of temperature was also identified as a key factor in determining the morphology of the contact. Firing optimum is obtained at a temperature where the densification of silver and of the glass is the same. This allows Ag transport in the glass and avoids glass to be trapped in porosity [11].

3. Improvement of screenprinting technology for front side metallization

Apart from fundamental studies of screen printed contacts, many presentations dealt with technological improvements in screen printing metallization. Recent progress in this field has in fact been astounding. Whereas the ITRPV roadmap published in March 2013 predicted an average Ag consumption of 150 mg/cell in 2013 going down to 100 mg in 2015 [12] – which was a huge reduction compared to 2012 and may have seemed very aggressive to anyone – several presentations indicated that best practice in the industry is already around 125 mg/cell and that the advanced processes in the lab already reach about 90 mg Ag/cell (including rear solder pads) while hitting high cell efficiency [13,14,15]. The Ag consumption reduction has been much faster than originally thought. Various strategies are being applied to achieve this drastic reduction.

A first factor is related to the pastes themselves. Recent pastes show much less porosity after firing than earlier paste, resulting in a more conductive material and therefore enabling a somewhat reduced Ag lay-down for the same performance.

Another strategy that is very effective in reducing Ag consumption is to modify the pattern for the front busbars, which account for a very large fraction of the Ag use on the front side for traditional H-patterns (up to 50 %). Instead of printing a continuous busbar, some areas of the busbar area are not printed (see Figure 2 [13], but also Figure 3 in [15]; [14]). The (various) designs of these segmented busbars are such that possible additional resistive losses related to the non-continuous nature of the busbars and soldering issues are minimized. Segmented busbars are already implemented in some production lines.

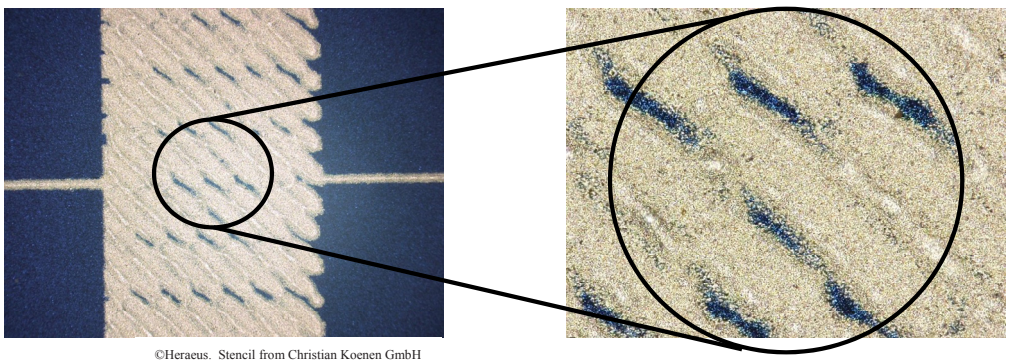

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Fig.2 : Top view of a cell with segmented busbars (reproduced with permission from [13])

Furthermore, there is also progress in screen and pastes enabling fine line printing. Screens using ultra-fine mesh enable extremely narrow lines below 50 μm in width [16]. Such screens for fine-line printing require modified Ag paste formulations in terms of rheology (sufficient shear thinning to flow through very small mesh openings) and composition (ensure good contact and adhesion in spite of small contact area, for instance through glass frit tuning) [16,17,18]. It was pointed out that single print fine-line printing may lead to poor finger adhesion and to finger breaks. A possible solution to that is to apply a double print approach, where the fingers are formed by two very narrow prints on top of each other [19,20].

Another promising approach to achieve narrow fingers and low Ag consumption is to use stencils rather than screens. Stencils have continuous openings instead of the small mesh openings of screens, and enable narrow, high aspect ratio prints with a single print. A separate print is however required to apply the busbars ('dual printing'). The presentations at the workshop showed that this strategy is particularly successful in reducing Ag consumption while enhancing efficiency [21,14,5].

Finally, optimizing the front grid design is often the most efficient way of reducing Ag consumption. Whereas previously, the grid was often optimized only to determine the number of fingers and finger spacing for optimal efficiency, now optimizations are carried out varying several additional factors such as the finger thickness, the finger width and the number of busbars, and not only to maximize performance but often to minimize paste consumption [22,23,14,15]. Even if the outcome often may seem unattainable because the fingers are too narrow or the module structure impractical, these calculations are important because they point at what might be achievable as metallization and module assembly technology progresses and provide insight into the inefficiencies of existing designs. Although analytical models are often adequate, numerical software tools can be convenient, particularly for more complex metallization designs [24,25].

Apart from the focus on Ag reduction, adaptation of metallization pastes to new cell structures is also an important topic. In particular, B-doped emitter for cells made on n-type wafers are more difficult to contact by screen printing than traditional P-doped emitters on p-type wafers. Introducing some Al in the Ag paste was shown to be an effective way to reduce contact resistance, though detrimental effects such as increased line resistance and recombination losses need to be controlled [26]. Combining adapted paste composition and stencil printing in a dual sequence enables very low Ag consumption and high efficiency on this type of cells [21].

4. Novel pastes and printing techniques

For solar cell manufacturers, a process that reduces cost and increases performance but requiring only a relatively minor departure from the present technology is appealing. An example of such an evolution is to switch from screenprinting to dispensing. While the basic chemistry of the Ag paste and the general process flow remains, it was shown that very narrow (< 30 μm) and high aspect ratio lines could be achieved by this technique, leading to an efficiency gain of 0.2 % compared to screen printing [27].

Another evolutionary change would be to keep the screen printing and firing-through technologies, but replace the Ag in high temperature pastes by another, lower cost metal. At the workshop, a study of pastes made with Ni and Zn was presented [28,29]. It was concluded that the present used paste system, containing Ag and glass frit, has quite unique properties which are difficult to duplicate with another system.

5. New module structures for further drastic Ag reduction

A new topic in the 4th Workshop was the introduction of novel interconnection technologies and their relation to cell metallization. This topic fits in the general trend towards Ag consumption reduction as the new structures potentially allow removing the busbars altogether, and in some cases reducing the finger thickness.

A first approach is to attach interconnection ribbons by conductive adhesives and conductive films instead of soldering them to the busbars. Such scheme is particularly appealing for cells without busbars (lower Ag consumption), for thin cells (no soldering-induced thermal stress) and for temperature-sensitive cells (for instance heterojunction cells). It was shown on full size modules that conductive films can provide adequate connection and durability in accelerated ageing tests, but some challenges remained when tested with busbar-less and pad-less cells [30].

The second module concept that was discussed is the multiwire or 'multibusbar' concept, which involves interconnecting the cells with many (> 15) narrow Cu wires. Two slightly different approaches were presented, which differ in how the wires are attached to the cells. The first one involves soldering the wires to each finger

with conventional solder. The cells in this approach are not completely busbar-free as it still requires small solder pads at the intersections between the fingers and the wires. However, because of the very short finger length, very low Ag laydown for the fingers is sufficient to provide adequate line resistance (68 mg) [22,23]. In the other approach, the connection between the fingers and the wires is obtained during lamination through the use of low temperature solder [31]. This multiwire technology enables the use of completely busbar-less cells and also leads to very low Ag consumption. An example was given of a heterojunction cell with 20.3 % efficiency and a front Ag consumption of only 40 mg, achieved despite the fact that a low temperature Ag paste was used (with a factor 3 higher resistivity than high temperature Ag). Moreover, it was indicated that the low impact of finger resistance on the overall cell performance for this type of interconnection enables the use of other low temperature pastes (with lower Ag content) for the fingers, potentially further reducing the metallization cost.

6. Cu metallization

The ultimate end point of the Ag reduction trend is to achieve cells that do not use Ag at all. Cu is the obvious replacement material for Ag as bulk Cu is almost as conductive as Ag and has a much lower cost, but the implementation of Cu metallization poses various challenges. Several approaches to Cu metallization were presented and discussed at the workshop.

An important technology option is the Ni/Cu plating metallization, where a thin layer of Ni is deposited on bare Si and annealed to form Ni silicide, onto which Cu is grown by an electrochemical process. The Ni silicide provides a good contact to the Si and also acts as a diffusion barrier for the Cu. Although this technology is often viewed as the main long term contender to replace Ag paste screen printing, and in spite of the significant progress achieved over the last two years in this field such as the commercial launch of industrial plating tools for solar cell metallization and simplified processes reaching high efficiency [32,33], there were fewer presentations on this topic at the 4th Workshop than at the 3rd. Some important topics nevertheless were touched upon such as the challenge to create uniform thin Ni silicide layers in laser ablated openings in SiNx [34] and the compatibility of plated Cu metallization with emerging back-contact module structures [35]. The power of Ni/Cu plated contact was also nicely illustrated by the achievement of extremely narrow (< 10 µm) but high aspect ratio contacts obtained by a masked plating approach, enabling currents above 40.1 mA/cm^2 for small area silicon heterojunction cells [36]. Finally, an innovative local plating technology called Localized ElectroChemical Deposition by Dynamic Liquid Drop/Dynamic Liquid Meniscus (Fig. 3) was introduced for use in solar cell metallization. This technique combines electrochemical processes with a special flow dynamics design to achieve the deposition of narrow contacts at a high speed with very low electrolyte drag-out and without pre-patterning [37,38].

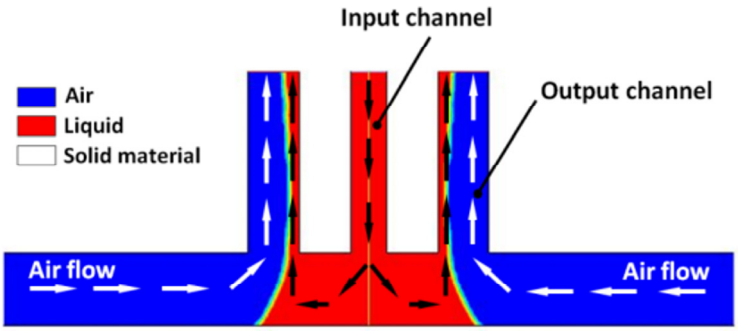

Fig. 3 : Principle of the Dynamic Liquid Meniscus technique (reproduced with permission from [37])

Other approaches to Cu metallization, presently investigated in the PV research community but at an earlier stage of development, also came up at the Workshop, such as cold spray deposition [39] and screenprintable Cu pastes [8,40].

7. Rear side metallization

Although most presentations focused on front side metallization, there were important contributions on rear side metallization aspects.

The conventional rear structure consists of a highly p^+ doped region (the so-called Back Surface Field or BSF) obtained through a Si-Al alloying process during the contact firing step. In a detailed study, it was explained how BSFs can be improved through incorporation of B in the Al-pastes, leading to additional B-doping of the BSF region and a better BSF performance [41,42]. This approach has probably already been implemented in state-of-the-art Al-pastes used in the industry and might partly account for the large V_{oc} improvement in Al-BSF cells observed in the last few years. Another contribution shared some additional insights in the Al-BSF formation process, showing that the Al particle size in the paste plays a critical role in how the Si atoms dissolved in Al during the firing process are distributed in the final Al electrode. This has strong impact on the resistivity of fired Al [43,44]. To study surface recombination at Al-BSF rear structures, Photoluminescence Lifetime Imaging, a lifetime mapping technology that has emerged over the last few years as an essential tool in solar cell development, can be very useful to give information on which conditions give better BSFs [45,46]. However, uncertainties about the measurements, in particular due to the unknown reflectance at the Si/Al interface, prevent accurate quantitative conclusions so far.

Part of the rear side metallization also contains Ag, namely the rear busbars or solder pads. Here, just as for the front, the trend is towards Ag content reduction. While two strategies, namely reducing the thickness of the busbars and solder pads, and adding Al to the Ag paste, have been widely implemented in production, there remain possibilities to reduce the amount of Ag further. A contribution at the workshop showed an alternative paste that contained less than 40 % while still providing adequate solderability and peel strength and allowing for high cell efficiencies [47,48].

An alternative rear metallization to screenprinted Al is Physical Vapor Deposition (PVD) Al, which might give an advantage in terms of performance and material cost for new solar cell generations. An issue with PVD Al is that blanket layers are deposited (on the whole rear surface) and Al cannot be soldered. A solution is to include an additional PVD layer of a solderable material. A study showed that Al/Ni:Si/thin Ag stack can provide sufficient solderability and peel strength, but also indicated that, for PERC solar cells, the adhesion may strongly depend on the type of dielectric stack used [49]. For those cells with PVD metallization, separate tests are needed for each passivation system envisaged.

8. Debate and survey

During the workshop, a ‘debate market place’ was organized, where discussions were held in small groups on hot topics in solar cell metallization. These debates provided a lot of opportunities to exchange views and to learn from the participants’ insights. The outcome of the discussion was summarized in a set of slides, which are available on the website [50].

At the end of the workshop, a questionnaire was again distributed to all participants to probe the participants’ satisfaction with the workshop, but also to survey the metallization experts’ view on the developments in the industry over the coming years. The outcome of the survey, and a comparison with previous results, can be found under [51].

9. Conclusions

The 4th Metallization Workshop brought together experts from the PV industry to present and discuss the latest developments in the field. The main conclusion is that screen printing Ag metallization continues to show strong improvement on cell level, with a faster Ag reduction than anticipated. Although fewer spectacular results were presented on Cu plating, it remains on the experts' roadmap for the future.

Acknowledgements

We are grateful to the presenters for their contributions at the 4th Metallization Workshop. We also thank the participants for their active involvement, in particular those who moderated the debates. Our gratitude also goes to the sponsors for making this workshop again possible. Finally, we would like to thank all members of the Scientific Committee for their involvement in ensuring a high scientific quality of the workshop: Pietro Altermatt, Guy Beaucarne, Aba Ebong, Stefan Glunz, Giso Hahn, Jaap Hoornstra, Jörg Horzel, Sara Olibet, Richard Russell and Gunnar Schubert.

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