Inkjet printing of Ag nanoparticle inks for heterojunction solar cell metallization

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Abstract: In the highly competitive photovoltaics market, manufacturers of solar cells and modules are under constant pressure to reduce the manufacturing costs. Next to the silicon wafer the main cost driver of solar cells is the metallization, especially the front-side silver. By replacing the traditional tabbing-stringing cell-to-cell interconnection with the multi-busbar solution Smart Wire Connect Technology (SWCT) from Meyer Burger a significant reduction in Ag consumption can be achieved, because of the relaxed requirements on finger resistance and therefore on finger height. Utilizing 18 wires instead of the traditional 3 busbars allows for a finger resistance as high as 10 Ω/cm; this finger resistance can be achieved with finger heights of only a few micrometer. Fingers with such low height can not effectively be screen-printed because of the inevitable height variation coming from the screen-mesh. In this paper the front-grid fingers are deposited by inkjet printing of a silver (Ag) nanoparticle ink, which allows for improved control of the finger height and therefore further reduction of the Ag consumption to below 10mg per cell. Finger widths as low as 35µm are achieved on heterojunction (HJT) solar cells with indium-tin-oxide (ITO) top layer. The nanometer sized Ag particles allow for effective sintering even at temperatures below 200°C, which is the maximum temperature for curing heterojunction solar cells.

After single cell mini-module assembly with SWCT the module efficiency was 19.7% for an Ag consumption of 18mg (V_{oc}=733mV, I_{sc}=8.86A, FF=72.3%), this module efficiency was comparable to the screen-printed reference. Cells with only 6mg of Ag showed an efficiency of 19.4% (V_{oc}=734mW, I_{sc}=9.00A, FF=69.9%) after SWCT mini-module assembly.

Keywords: Silicon Heterojunction Solar Cells, Metallization, Multi-busbar, Inkjet Printing.

1 Introduction

In the highly competitive photovoltaics market, manufacturers of solar cells and modules are under constant pressure to reduce the manufacturing costs. Next to the silicon wafer the main cost driver of solar cells is the metallization, especially the front-side silver. By replacing the traditional tabbing-stringing cell-to-cell interconnection with a multi-busbar solution like the Smart Wire Connect Technology (SWCT) from Meyer Burger a significant reduction in Ag consumption can be achieved, because of the relaxed requirement on the finger conductivity. In traditional solar modules with a 3 busbar design the unit cell has a finger length of 26mm (in the case of a 156mm solar cell); for solar modules modules with SWCT the busbars are replaced by 18 wires, resulting in a unit cell finger length of ~4mm, thereby substantially reducing the requirement of finger conductivity [1, 2]. Since the finger conductivity is directly related to the cross-section area this relaxed requirement on finger conductivity allows for a significant reduction in the finger height compared to fingers designed for 3 busbar solar cells. When using SWCT the finger height can even be as low as 1µm [3], which results in a substantial reduction in Ag usage. For fingers with such low heights the industry standard screen-print deposition technique is not suitable anymore because of the big finger height variation coming from the screen-mesh, this finger height variation is typically around 5µm [4] To account for this variation in finger height one has to print the fingers significantly higher than theoretically required, normally around 7µm, which result in a minimal Ag consumption of ~40mg for the front-grid [1, 2]. This 40mg of Ag is already an impressive reduction compared to the 350mg typically used for solar cells with a 3 busbar design, but one has to realize that more than 50% of this 40mg of Ag is used for building the peaks, which do not really contribute to the overall finger conductivity; and that this finger height variation of 5µm limits the minimum finger height to values above those theoretically needed. By having better control over the uniformity of the finger height the Ag consumption can be further reduced. Inkjet printing gives an excellent control over the amount of material deposited resulting in very uniform layer thickness and therefore extremely low Ag consumption of <10mg.

In terms of finger width screen-printing has made great improvement in the last few years in reducing the finger width, but currently screen-printing is pushing its technological limits at a finger width of ~45µm. Screen-print solutions for <45µm finger width requires extremely expensive screens with low lifetime, which makes these solutions economically unfeasible. Inkjet printing on the other hands has already shown to be able to achieve finger width <35µm [5] and with the developments of new printheads, going to smaller droplet sizes, the finger width potential is even <20µm.

Inkjet printed front-grid in combination with SWCT can be used for all common cell types such as the standard Al-BSF, but also for PERC and heterojunction. For heterojunction (HJT) solar cells there is an additional benefit from inkjet printed fingers because the Ag nanoparticles in the ink allow for high conductivity even at low sintering temperatures. Where state-of-the-art screen-print pastes for low temperature curing (<220°C) can only obtain a specific resistivity of 10µΩcm [6] inks with Ag nanoparticles can obtain excellent resistivity values down to 5µΩcm after curing at temperatures <220°C [7]. This effect is a result from the high surface area to volume ratio for the nanometer sized particles [8, 9]. This improved conductivity of Ag nanoparticle inks allow for a further reduction in the finger cross-section and therefore allowing for a reduction in finger width and finger height.

So in terms of Ag consumption, finger width and finger width potential inkjet printing holds the advantage over screen-printing; therefore inkjet printing is the logical choice of metallization technique for the combination with SWCT.

In this paper the current status of inkjet printed fingers for SWCT in term of finger width, Ag usage and resulting mini-module IV-characteristics will be shown. The results shown in this paper are achieved on heterojunction solar cells, but similar investigations are ongoing for Al-BSF and PERC cell types. Next to the cell and mini-module results the developments from R&D towards industrialization will be discussed and we will show a glimpse of the future.

2 Inkjet printed front-grid on heterojunction solar cells

2.1 HJT cell design

In order to show the performance of inkjet printed front-grid metallization a commercially available silver inkjet ink has been printed on heterojunction solar cells. These HJT cells are obtained from the Meyer Burger heterojunction pilot line in Hauterive, Switzerland. Figure 1 shows a schematic representation of the cell design. The base material is 156x156mm n-type doped Cz-Si. After saw damage removal and alkaline based texturisation, to obtain random pyramid texture, the intrinsic and doped amorphous silicon layers are deposited on the cell front- and rearside by plasma-enhanced chemical vapor deposition (PECVD). The front- and rear ITO layer is deposited by physical vapour deposition (PVD). A blanket Ag layer is sputtered to finish the rear-side metallization. The PECVD and PVD processing steps are performed in the industrial HELiA tools. For the front-side metallization a finger pattern is inkjet printed with a silver nanoparticle ink. By replacing the rear blanket Ag layer with an inkjet printed rear-grid pattern bifacial cells can be made. The inkjet printed ink is afterwards cured at temperatures <200°C; this curing step is also used as a post-deposition anneal for the sputtered ITO.

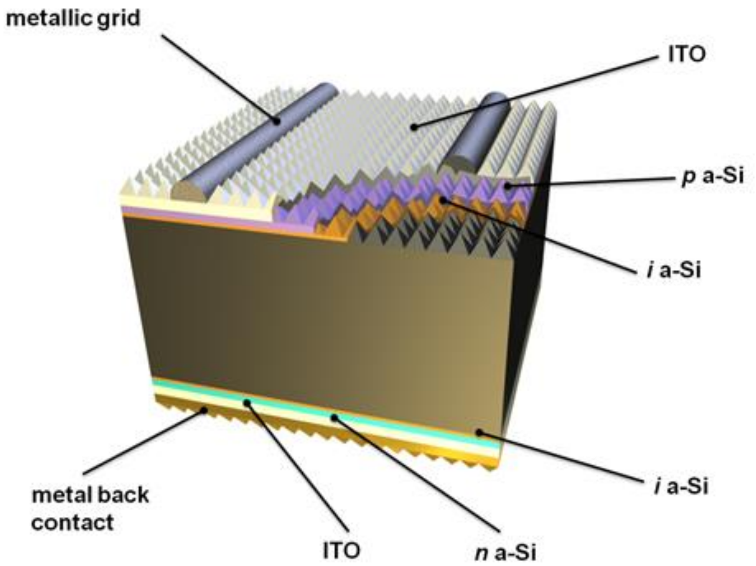

Figure 1; Monofacial Heterojunction solar cell design

SWCT (mini-)module assembly is performed at Meyer Burger; the wires of SWCT consist of a copper (Cu) core surrounded by a thin shell of low temperature solder alloy indium-tin. These wires are incorporated in a PET foil. This PET foil with wires is positioned on the cells with the wires perpendicular to the finger grid of the cell. During lamination the low temperature solder alloy melts and makes contact with the thin Ag fingers on the cells. More details on SWCT module assembly are described in [1].

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2.2 Inkjet printed fingers

By inkjet printing a commercially available silver nanoparticle ink on the ITO top layer the front-grid fingers are created. By optimizing the printing conditions and adjusting the surface energy of the Ag nanoparticle ink to the surface energy of the ITO finger widths as low as 35µm are obtained, without any pre-treatment necessary. These fingers widths are obtained even on extremely rough surfaces such as pyramid textured cells. Figure 2 shows a scanning electron microscope (SEM) image of an inkjet printed finger with 32µm width and a microscope image of a 35µm finger inkjet printed on top of a pyramid textured HJT cell with ITO top layer.

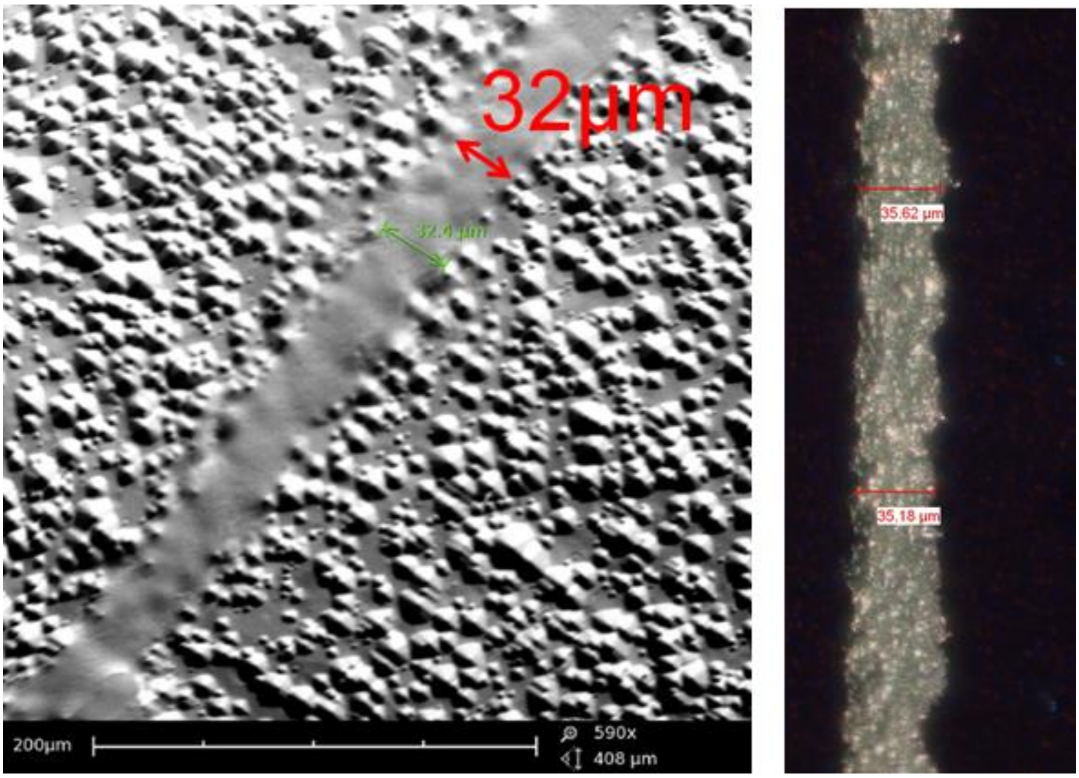

Figure 2: SEM image (left) and microscope (right) of inkjet printed fingers with a width ~32µm on pyramid textured HJT cells

2.3 HJT SWCT mini-module results

To investigate the dependence of the finger height on the IV-characteristics single cell SWCT mini-module are assembled from HJT cells with finger heights of ~1µm; ~2µm and ~3µm. Table 1 shows the mini-module IV-characteristics; all mini-modules had an output above 4.4W corresponding to an mini-module efficiency of 18.5%. The highest mini-module efficiency of 19.7% was obtained for a cell with ~3µm finger height, corresponding to 18mg of Ag for the full front-grid. For a finger height of ~1µm the best mini-module has an efficiency of 19.4%; with an extremely low Ag usage of 6mg. Together with these SWCT mini-modules with inkjet printed metallization a reference module with screen-printed front-grid was manufactured; this screen-print reference module showed a similar performance as the modules with inkjet printed metallization, but for the screen-printed module the Ag consumption was ~40mg. Both the screen-printed and inkjet printed fingers had a width ~50µm; for screen-printing this is close to the technical limitation of ~45µm while inkjet printing fingers have the short term potential to go to widths <35µm and even <20µm in the mid-term.

		Ag [mg]	Pmax [W]	Efficiency [%]	Isc [A]	Voc [mV]	FF [%]
Finger height ~1µm	Average	6	4.53	19.0	8.94	735	69.0
	Best module	6	4.62	19.4	9.00	734	69.9
Finger height ~2µm	Average	12	4.65	19.5	8.92	736	70.9
	Best module	12	4.66	19.5	8.93	737	70.8
Finger height ~3µm	Average	18	4.66	19.5	8.87	734	71.5
	Best module	18	4.70	19.7	8.86	733	72.3
Screen print reference		40	4.69	19.7	8.97	724	72.3

Table 1: Single cell SWCT mini-modules made from 6inch HJT cells with inkjet printed fingers of ~1µm to ~3µm finger height compared to a reference SWCT module with screen-printed fingers.

For these investigations a finger grid pattern with interrupted fingers is inkjet printed; this design of interrupted fingers allows for a quick and easy investigation into the contacting between the fingers and the wires from SWCT by photoluminescence (PL) imaging of the modules. If there is bad contact between the interrupted finger and the SWCT-wire this area will show as a dark spot. PL imaging of the SWCT mini-modules shows that the performance is limited by non-optimal contacting at the wafer edges; see Figure 3. By improving the contacts at these edges it is expected that the fill factor and therefore the module efficiency will further improve.

Taking these improvements in Isc and Fill Factor into account, combined with the excellent Voc values of >730mV, mini-module efficiencies above 20.5% are possible, even with extremely low Ag consumptions below 10mg.

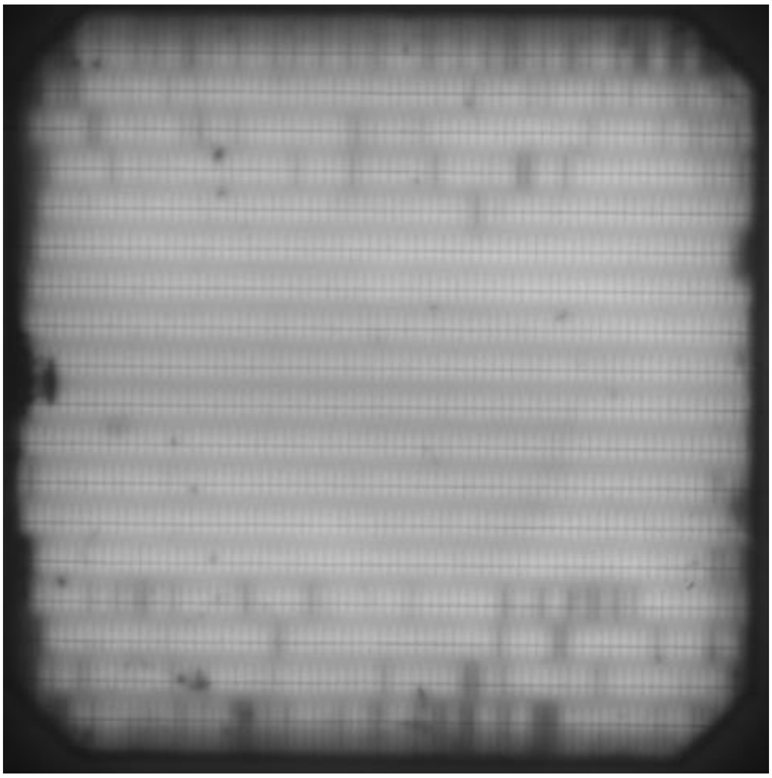

Figure 3: EL image of the SWCT mini-module made from a 6inch HJT cell with inkjet printed fingers; the fingers on the upper and lower edges show sub-optimal finger to wire contacting while the fingers in the middle are fully contacted.

3 Industrialisation

In process developments project the step from R&D to production usually takes a long time and a lot of efforts because the processes in R&D equipment can not easily be up-scaled to mass-production equipment. For inkjet printing, however, this step from lab to fab can quickly be done because the R&D equipment uses exactly the same printheads as the production equipment, therefore the recipes developed on the R&D equipment can directly be copied to the mass-production equipment. The mass-production equipment simply uses a higher amount of printheads and high-speed wafer and cassette handling.

3.1 PiXDRO JETx mass-production inkjet printer

For the process of inkjet printed front-grid fingers for heterojunction solar cell metallization the same mass-production inkjet printing equipment (PiXDRO JETx) is used as the systems installed at a high-efficiency module manufacturer, see figure 4. These PiXDRO JETx systems are in full production with a yield >99.9% at the specified throughput for the customer specific process.

Figure 4: PiXDRO JETx mass-production inkjet printer.

4 Outlook

Mass-production equipment usually has a depreciation time of 5 to 7 years, therefore it is crucial that the techniques used in this equipment are not only state-of-the-art at the moment of installation, but also can be upgraded or improved so that they remain state-of-the-art in the future. In the field of inkjet printing the printhead manufacturers are constantly improving their printheads in term of higher nozzle density (more nozzles per printhead), higher jetting frequency (allowing faster print speeds), improved printhead lifetime and smaller droplet size.

For the process of inkjet printed fingers for solar cell metallization one of the main factors influencing the finger width is the droplet size; smaller droplets result in smaller finger width.

Figure 5 shows an inkjet printed finger of 18µm wide; this finger is inkjet printed with a printhead for a droplet size of ~1pl; industrial 1pl printheads are currently being developed and will become available as an upgrade for the current JETx mass-production inkjet printers, allowing the cell manufacturers to further improve their cell performance.

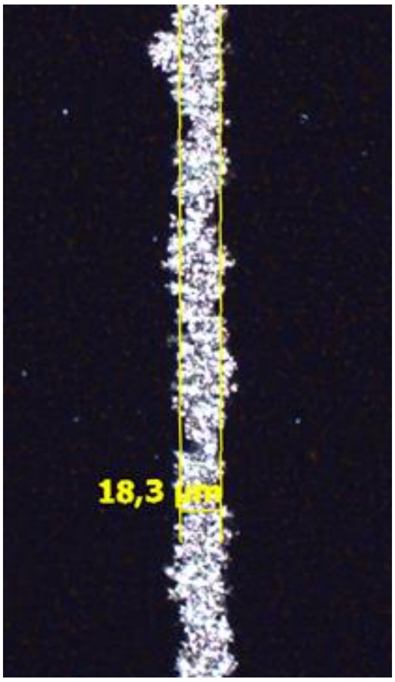

Figure 5: Inkjet printed finger of 18um, printed with a printhead with 1pl droplet volume. Picture courtesy of Fraunhofer ISE.

5 Conclusions

The Smart Wire Connect Technology (SWCT) multi-busbar solution from Meyer Burger offers a cost effective way of reducing the silver consumption during solar cell metallization, especially when combined with inkjet printing of a silver nanoparticle ink to deposit the finger grid. This process of inkjet printed metallization can be used for all cell types, like standard Al-BSF or PERC, but also for heterojunction (HJT) solar cells. Finger widths on pyramid textured HJT cells are currently around 35µm, for next-generation printheads, with smaller droplet size, the finger width can even be as low as 18µm.

Single cell SWCT mini-modules made from HJT cells with inkjet printed front-grid fingers show a module efficiency of 19.4% with an extremely low Ag consumption of 6mg. This module efficiency is comparable to the screen-printed reference, showing that the process of inkjet printed metallization is already on-par with screen-printing in terms of module efficiency, but with a much lower Ag consumption. Since inkjet printing technology still has much room for further improvements while screen-printing is close to its technological limits, inkjet printing is the logical choice as the deposition process for solar cell metallization of busbarless solar cells.

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