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Capitalising on the Precisions of Ion Implantation and Ink Jetted Fine Gridline to Create Low-Cost High Efficiency Silicon Solar Cells

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Abstract

This paper reports ink-jetted gridline, production ready, solar cells with ion implanted homogeneous high sheet resistance emitters having efficiency of >19%. The average efficiency of ~18.96% on 80 ohm/square ion implanted emitter with highest efficiency of 19.2% demonstrates the potential of combining the two high precision technologies, inkjet printing and ion implantation. The key attributes of the cells include average open circuit voltage (V_{OC}) of 640 mV, fill factor (FF) of 79.14% and short circuit current density (J_{SC}) of 37.8 mA/cm^2. Worthy of note is that, the front gridlines width and height of 47.6 μm and 43.9 μm resulting in aspect ratio of 0.92 using only 83 mg total Ag, which is, at least 20% Ag less than today's screen printed cells. However, the reference screen-printed cells showed similar average efficiency with the best gridline widths of ~70 μm and height of ~28 μm used >100 mg of Ag. Statistical analysis illustrates that the highest efficiency with the screen-printed contacts is an outlier as the minimum efficiency for the ink-jetted group. This efficiency is very significant because all cells were fabricated on a pilot production line at Shanghai Shengzhou New Energy Co. Ltd, in China.

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Keywords: Ion implant; ion implanter; ion implantation; inkjet printing; ink-jetted gridline; fine gridlines; high sheet resistance

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1. Introduction

Cost reduction in solar cell electricity is not only in producing high efficiency at lower cost but also improving the yield to reduce the efficiency binning or binning. Binning and cost of production can be realised by centering the mean efficiency and eliminating the 25th quartile cells. Thus, better and highly efficient modules of similar performance can be achieved. More so, the associated reliability issues at the system level can be circumvented. To achieve this, the traditional $POCl_3$ emitter and screen-printed metal contacts, which are difficult process steps to control, must be replaced with more precise technologies such as the ion implantations for the emitters and inkjet printing for the front metal contacts. The ion implantation has been adapted for solar cell production recently [1-3] because of the ability to produce precise and uniform single sided junction, eliminate edge isolation and dopant glass removal, and growth of high quality passivation oxide during implantation anneal. The ink-jetted gridline, which is capable of an aspect ratio of $\geqslant 1$ has been demonstrated [4] with excellent uniformity on a wafer and from wafer to wafer. By applying such precise gridline printing to ion implanted emitter, the binning of solar cell efficiency in production can be eliminated or drastically reduced.

Although there is great understanding in using $POCl_3$ to form high sheet resistance emitter, many solar cell companies still use emitter sheet resistance of ≤65 ohm/square in production because of the uncertainty in contact formation due to non-uniformity. That is why the efficiency potential of the high sheet resistance is yet to be realised. Therefore, the recent move by some companies [1] who have switched to ion implanted emitters where precision in peak surface concentration, junction depth and uniformity is guaranteed. This trend is expected to continue until the confidence in creating uniform and reproducible high sheet resistance emitters is achieved. More so, companies are still struggling with screen-printing gridline uncertainties despite the huge investment in new screen technologies. There has been a great effort in developing new screen materials that enables the printing of fine gridlines down to 70 μm in pilot production without losing efficiency. However, such advantage evaporates when it is transferred to manufacturing floor because the non-uniformity in gridline printing kicks in as the number of printed wafers increases. To overcome the short comings of $POCl_3$ and screen-printed contacts, a combination of ion implanted emitters and ink-jetted gridline, which guarantees uniform high sheet resistance emitter (UHSE) formation and gridline widths and heights from wafer to wafer and on the same wafer has been utilised to realise explore some of the potentials of UHSE. In this work a ion implanted emitters having 80 ohm/sq. and Al-BSF are assessed with (i) screen-printed front contacts and (ii) ink jetted gridlines.

2. Ion implantation and Inkjet printing

2.1. IonSolar^{TM}

The fact that the emitter can be tailored according to needs in order to achieve a uniform peak surface dopant concentration and junction depth, and grow passivation oxide without additional steps renders ion implantation a unique technology with huge potential to increase yield and reduce variability in device performance. Suniva Inc. has reported average efficiency of 18.6% [1, 2] with screen-printed contacts in production, which is attributed to uniform emitter and low emitter recombination resulting from in-situ oxide passivation. Although it can be argued that ion implantation is more expensive than $POCl_3$ because the current ion implanter delivers only 1000 wafers per hour, the low throughput can be overcome by using lower dose and energy. A high throughput system designed for 2400 wafers/hour, which will have three rows of wafers passing through the three sections of an ion beam [5], can be cost effective. Although such tool is yet to be in operation, a combination of such high throughput system, and reduced implant annealing time (shorter than $POCl_3$ process), can lead to a more cost effective ion implantation solar cells. By combining a high throughput ion implanter with inkjet printing of >2000 wafers per hour, the two most important process steps in solar cell production will lead to high yield and reduced spread in power output. In this work the *IonSolar*TM implanter designed and built by Kingstone Semiconductor Co Ltd capable of implanting >1600 wafers/hour was used.

Kingstone Semiconductor has developed high throughput and continuous flux ion implanter with mass analyser - *IonSolar*TM. Figure 1 shows the production *IonSolar*TM implanter that was used in this work. The attributes of this design include: (i) continuous implanting and curtain-like beams, which provides three times 156 mm uniformity providing high beam utilisation; (ii) Small footprint of 4.9 m (L) by 3.6-m (W); (iii) collimated beams with precise angle control (iv) beam current up to 60 mA (v) open format design with maintenance platform and easy to service. This architecture can provide a wide range of acceleration energies of 10-25 keV and ion source life of >150 hours. It is capable of implanting > 1400 wafers/hour at 3E15 dose. The uptime of >90% is guaranteed and thus a 40% reduction in the cost of ownership.

Fig. 1. Kingstone Semiconductor Co Ltd IonSolarTM implanter

2.2. Inkjet printing

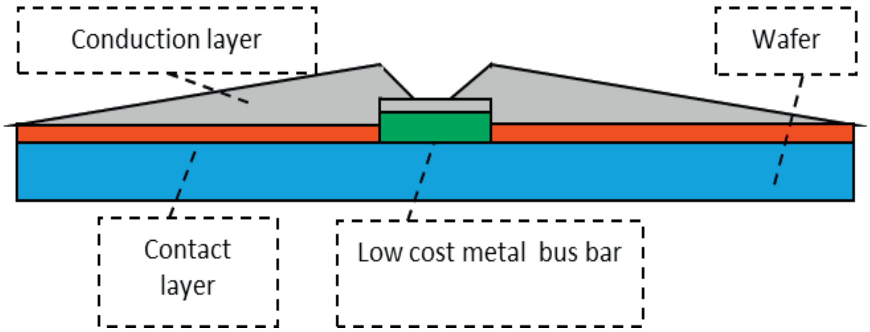

Fig. 2. 3D Inkjet metallisation scheme

Inkjet printing as an alternative metallisation for crystalline silicon solar cell can eliminate the associated variation in gridline width and height and the resulting fill factor and efficiency. Because of the finer gridline attributes of the inkjet printing, the short circuit current can increase and hence the efficiency. The narrow gridlines can improve the efficiency by 0.3% and the uniform deposition for uniform contact can add additional 0.3% in efficiency. At module level, every 0.1% efficiency is worth ~\$0.015 of extra revenue/cell, thus for 100MW line inkjet printing can improve PV manufacturer's revenue and profit of ~\$1M/year. The inkjet printing in this study uses three different inks as illustrated in Fig. 2, the 3D metallisation scheme. The three inks are co-printed in a single printing step, and co-fired like conventional screen-printed cells. Each of the inks can be optimised independently and different materials can also be used to increase performance and reduce the cost of metallisation. As seen in Fig. 3, the SEM micrograph of the ink-jetted gridline, has been structured with 2 materials, a thin contact layer at the bottom and a conductive layer at the top. This unique jetting capability in co-printing multiple inks enables the elimination of trade-off and compromises often taking place in traditional screen-printing paste development. As an example, to improve contact, glass may be added to the contact layer without affecting the resistivity of the donductance layer. Adhesion promoters can be added to the bus bar and its electrical contact can reduce without affecting either the finger contact or finger resistivity. This seperation of layer form and function enables not only performance optimisation but also faster ink development cycles. When an improvement in finger resistivity is targeted, it can be pursued without concern or regards to other key attributes such as adhesion or contact that are rendered by neighbouring layers.

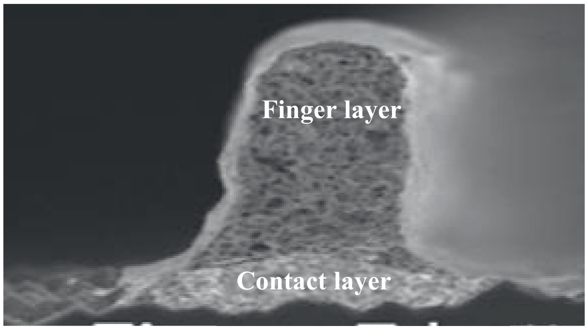

Fig. 3. SEM micrograph ink-jetted gridline

In addition, the nature of digital print enables a creative and precise devolment method. The conductive ink is rendered by some 50 jetted layers, the contact layer by some 20 layers. However, these numbers are programable and may be instantly changed from wafer to wafer. In other words, digitial metallisation enabled us to add and remove layers as we desired. Each inkjetted layer addes ~1.1 mg of material to the cell, optimisation can be done at resolution of 1.1 mg with high degree of uniformity with a resolution never possible before. This unique feature enabled precise recipes for glass, by means of adding or removing contact layers we were able to add or remove glass and immediately affect the contact formation. We were able to resolve paste to firing conditions conflicts and much more. The precision provided by digitisation enables a vast field of print to firing optimisation that was only intially tested in this paper. In fact, following the experiment described in this paper, further optimisation has continiously yielded better results and a clear demonstration of further potential improvement. Therefore, the 3D capabile digital printer enables a dramtic reduction in Ag consumption to below 70 mg on a 6" cells. Every 10 mg of silver paste cost ~\$0.015, a saving of some 80 mg per cell delivers a \$0.12 saving per cell. Multiplied by a 100-MW line this saving comes at ~$2.6 M/year. These savings are rather dramatic when one considers the effect on cell producers' economics. Combined paste saving and efficiency digital print enables upward of $0.15 delivering an effective metallisation cost reduction of ~60%. Since inkjet printing is contactless, thinner wafers can be processed with certainty and high yield because of lower breakage. The attributes of the pilot production inkjet printer used in this work is given elsewhere [4].

3. Device fabrication – ion implanted emitters with screen-printed and ink jetted gridlines

In this work, the Al-BSF solar cell is fabricated on Cz mono crystalline 156-mm 2.6 ohm-cm wafer using the following process sequence: (i) texturing – alkaline (ii) ion implant using 2.8E15 dose at 15 keV (front side only) (iii) ion implant anneal and in-situ thermal oxide growth; (iv) PECVD silicon nitride deposition (v) Ag back soldering pad print/dry; (vi) Al back print/dry (vii) Ag front print/dry or inkjet printing/no dry and (viii) contact co-firing. After contact co-firing the cells were measured after calibrating the solar simulator with a reference cell traceable to Fraunhofer Institute for Solar Energy Systems (ISE).

4. Results and discussion

4.1. Open circuit voltage (V_{OC}), short circuit current (J_{SC}), fill factor (FF) and Efficiency

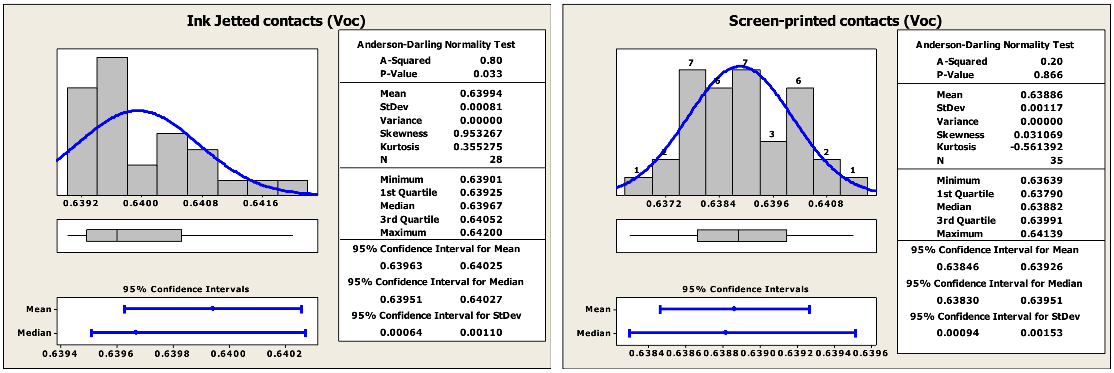

Fig. 4. V_{OC} for cells with (a) ink-jetted and (b) screen-printed contacts

Figures 4a and 4b compare the V_{OC} for the silicon solar cells having ink-jetted and screen-printed gridlines, respectively. The mean V_{OC} for the cells with ink-jetted gridlines is 639.9 mV compares to 638.9 mV for the screen-printed counterparts. The maximum V_{OC} for cells with ink-jetted and screen-printed contacts are 642 mV and 639 mV, respectively. The standard deviation of 0.0008 for ink-jetted and 0.00117 for screen printed cells attest to the superior tight distribution in ink-jetted gridlines, which is highly reproducible and very uniform within a gridline and the entire wafer.

In Figs. 5a and 5b, J_{SC} for the two set of cells are shown with mean values of 37.73 mA/cm^2 and 37.217 mA/cm^2, respectively, for ink-jetted and screen-printed. A J_{SC} difference of 0.515 mA/cm^2 results from lower shading loss due to finer ink-jetted gridlines. As shown in Fig. 6a, the height versus width of the ink-jetted gridlines, the finger width ranges from 44 to 48 µm and height from 32 to ~49 µm; with aspect ratio of 0.74 to 1.09 depending on the number of layers as depicted in Fig. 6b. In this work, the number of layers printed was 60, which corresponds to aspect ratio of 0.92. A maximum J_{SC} of 38.01 mA/cm^2 for the ink-jetted cell was noted compared to screen-printed cell of 37.60 mA/cm^2.

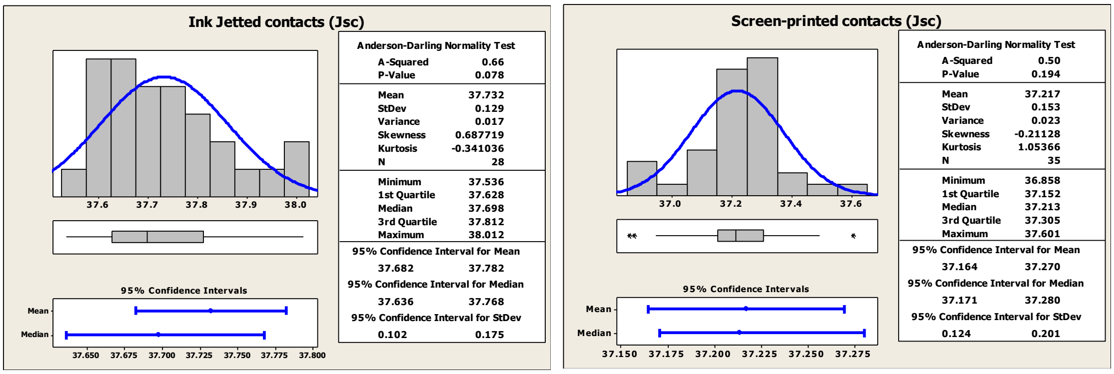

Fig. 5. J_{SC} for cells with (a) ink jetted gridlines; (b) screen-printed gridlines

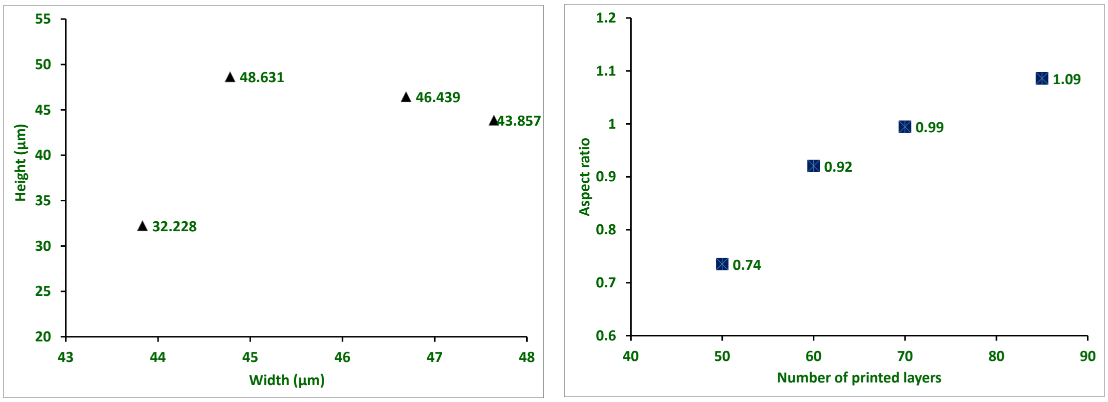

Fig. 6. (a) Height versus width and (b) aspect ratio versus number of ink jetted layers at 86 gridlines

Figure 7 shows the mean FF values of 79.513% and 78.506%, respectively, for cells with screen-printed and ink-jetted contacts. The FF difference between the two contacting technologies is due to emitter resistance component, which dominates the ink-jetted technology as a result of using the same number of gridlines (86 lines) to be consistent with screen-printed counterparts. For an 80 ohm/sq. emitter, the highest FF can be achieved with 112 front gridlines having the dimensions shown in Fig. 6a. This is under investigation to maximise the FF and hence the efficiency of ion implanted and ink-jetted solar cell. It should be noted that the J_{SC} is not expected to increase with 112 lines. However, by maintaining the ~38 mA/cm^2 and a gain in FF, the improvement in efficiency can be realised.

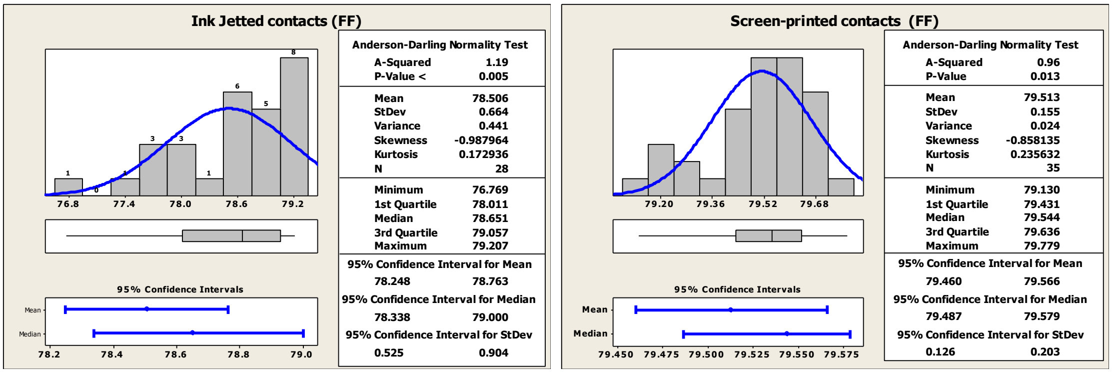

Fig. 7. FF for cells with (a) ink-jetted and (b) screen-printed gridlines

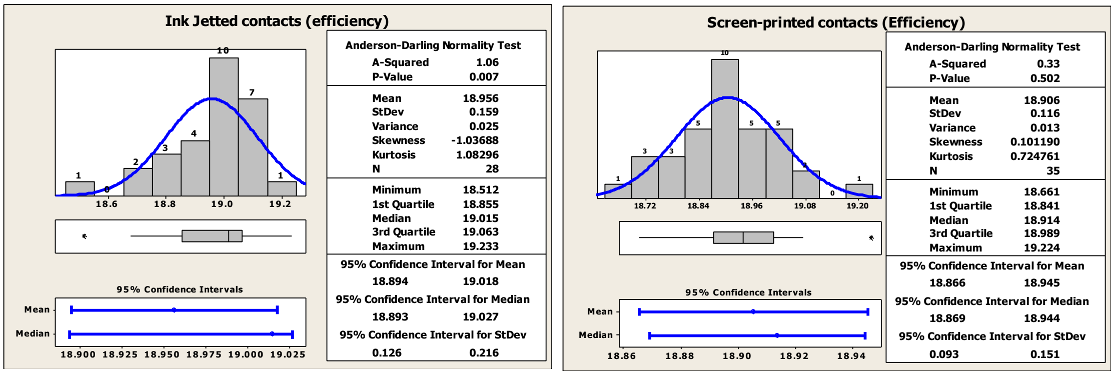

Fig. 8. Efficiency for cells with (a) ink-jetted and (b) screen-printed gridlines

Figure 8 gives the efficiency of the cells with ink-jetted and screen-printed contacts. Average efficiency of 18.956% for ink-jetted contacted cells compared to the 18.906% for their screen-printed counterparts. Best efficiency of ~19.2% was measured for cells contacted with the two metallisation technologies. The lowest cell efficiency in the ink-jetted category is shown as an outlier in Fig. 8a, as well as the highest efficiency in the screen-printed group. This is because majority of the cells in the ink-jetted category are close are 19% or close to 19%. As seen in Fig. 7, the average FF for the screen-printed cells is higher than the ink-jetted cells, while in Fig. 4, the average J_{SC} for the ink-jetted cells is higher than the other cells. The difference in these two parameters compensates each and leads to only 0.26% efficiency difference between cells using the two metallisation technologies.

4.2. Internal Quantum Efficiency (EQE)

The light-current-voltage measurement showed ~0.5 mA/cm^2 difference in J_{SC} between the ink-jetted and screen-printed cells, and is confirmed by the IQE for the cells shown in Fig. 9 (Note: The spectral

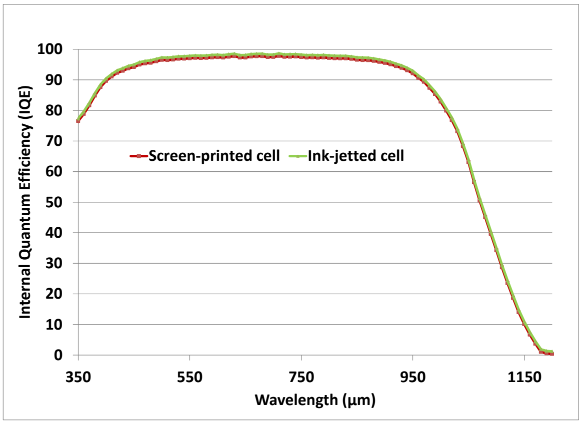

Fig. 9. Internal Quantum Efficiency (EQE) for best cells with ink-jetted and screen-printed gridlines

response measurements was carried out with large beam to account for the grid shading). Figure 9 shows the loss of J_{SC} in the short wavelength response, which indicates a non-optimised emitter with high front surface phosphorus concentration, which could cause absorption and the loss of photons in the blue region. With optimised implant dose, energy and implant anneal, the J_{SC} will increase by >0.5 mA/cm^2, V_{OC} by ~5 mV and hence ~0.41% in absolute efficiency improvement. By optimising the inks for the ink-jetted technology, FF of >80% is anticipated, which will add another 0.24% improvement in the efficiency. The long wavelength response are identical for the two set of cells as seen in Fig. 9 with the mean V_{OC} very close to each other.

5. Conclusion

Ion implantation, a highly precise method of tailoring the emitter with the desired dopant surface concentration and junction depth, to attain the desired J_{SC} and V_{OC} with in-situ passivated thermal oxide was investigated in conjunction with screen-printed and ink-jetted metallisation. The emitter is still under optimisation as seen in the IQE, the loss in blue response due to poor light absorption and the corresponding losses in J_{SC}. Despite the losses in the blue response, the best ink-jetted cell showed a J_{SC} value of ~38 mA/cm^2, which suggests that with optimised phosphorus surface concentration additional 0.5 mA/cm^2 can be realised and increase the efficiency by ~0.25 % in absolute value. Also, with improved ink for the ink-jetted gridlines, FF of 80% can be achieved, which will lead to >19.5% efficient cells combining ion implanted emitters with ink-jetted gridlines. Although the screen-printed cells showed similar average efficiencies, the amount of Ag used per cell, despite the best printing as at least 20% higher than the ink-jetted counterparts. Therefore, inkjet printing can provide higher efficiency at lower cost because it can be tailored to use less Ag. In addition, we have only began to explore the possibilities in digital metallisation leaving us a multitude of further optimisation steps on both device performance as well as metal consumption. The significance of this work is that, the cells were fabricated in production line at Shanghai Zhengzhou New Energy Development Co. Ltd.

Acknowledgements

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