Technology development of fine-line crystalline silicon solar cells

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ABSTRACT

Development of fine-line crystalline silicon solar cells is a potential direction for application of high-efficiency and low-cost solar cells in the industry. Fine-line mask-free metallization offers huge potential to increase cell efficiency by reducing metal shadowing losses and surface recombination losses. At China Sunergy, three promising approaches for fine-line crystalline silicon solar cells are currently undergoing research, including processes such as laser doping selective emitter (LDSE) technology, inkjet or aerosol jet printing of metal paste and upgraded screen-printing technology. This paper presents the basic investigations of these three manufacturing technologies, singling out the technology that presents the most potential for further application.

Introduction

Reducing the cost per Wp is the industrial goal of solar cell manufacturers. Achieving this goal requires increasing the solar cells' efficiency while lowering the cost of production [1]. Metallization technology, commonly regarded as the technology with the most potential to satisfy these requirements, can be used to increase the cells' efficiency during the cell processing stage. Cell efficiency can be greatly improved by reducing the metallized area and implementing surface recombination [2]. As a result, fine-line printing has, along with sheet resistance, become one of the main research directions in standard industrial solar cell production. This process is very easily carried out in the lab [3], but due to complex processing and ultra-high cost, it is not suitable for industrial mass production.

> "Cell efficiency can be greatly improved by reducing the metallized area and implementing surface recombination."

Based on lab development of solar cells, the two-step metallization concept seems to hold most promise [4]. In this process, the first step sees the creation of a narrow metallization line named the *seed layer* on the silicon surface. This seed layer should have a good mechanical and electrical contact to the silicon surface. Three techniques currently in use for seed layer formation include normal screen-printing of silver paste (NSP) [2], inkjet or aerosol jet printing of metal paste [5,6], and laser doping selective emitter (LDSE) combined with subsequent self-aligned nickel electroless plating [7]. NSP is the simplest and most cost-effective method of seed layer formation, using conventional silver paste and fine-line screen to achieve fine-line printing with a width greater than 40µm.

Compared to NSP, the LDSE technology requires more complicated processing steps. A phosphorous dopant source (phosphoric acid) is applied to the substrate before laser treatment. The heavy diffusion area is formed for selective emitter solar cells via local melting of silicon beneath the antireflection coating (ARC). During the laser doping process, the high-power laser removes the ARC and exposes silicon for nickel seed layer formation. The formation of the seed layer for LDSE is through plating Ni after laser doping

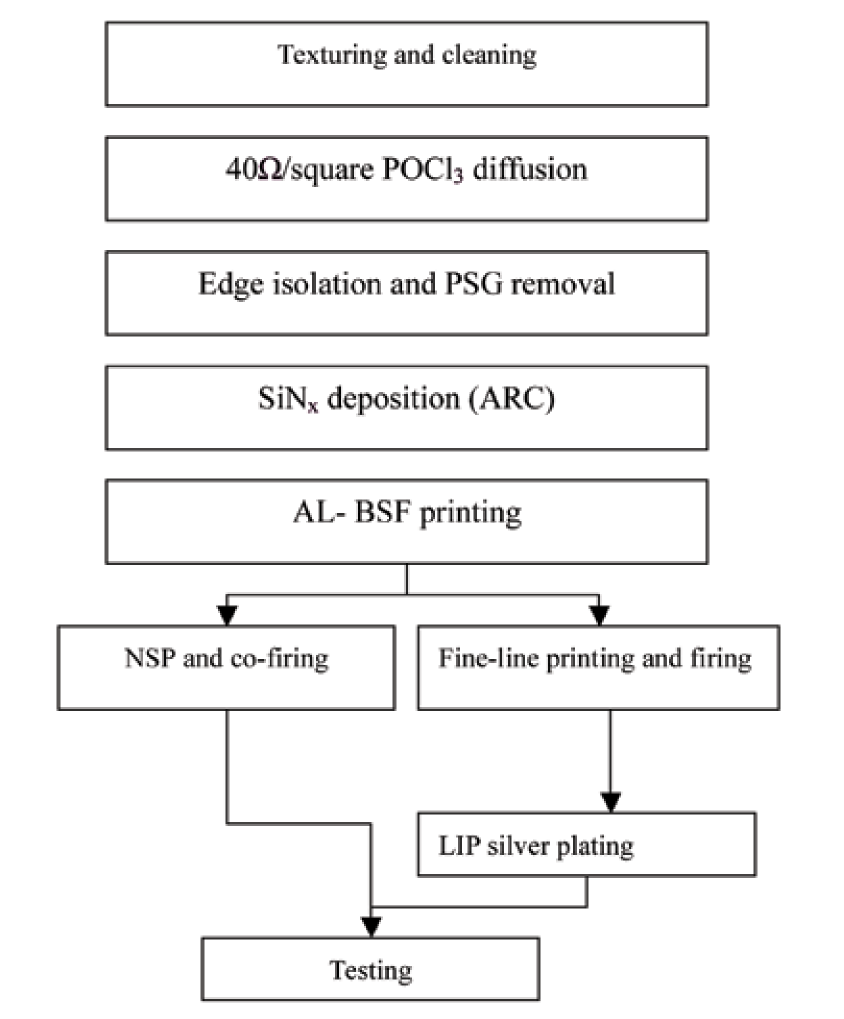

Figure 1. Typical processing flowchart of industrial crystalline silicon solar cells.

Sample	V_{oc} (V)	I_{sc} (A)	R_s (Ω)	R_{sh} (Ω)	FF	Eff	I_{rev2} (A)
A	0.624	5.60	0.0171	85	68.5	0.1554	0.289
B	0.625	5.52	0.0042	55	78.1	0.1740	0.971
C	0.625	5.65	0.0045	95	79.1	0.1804	0.263

* All measurements performed in-house on reference cells provided by the Fraunhofer Institute.

Table 1. I-V performance of screen-printed cells with: 40μm finger design before (A) and after (B) Ag plating, and cells with a 100μm finger design (C).

Group	SHR (Ω/square)	Number of fingers	Thickness of finger (μm)	Finger width before LIP (μm)*
A	80	82	6.6	50
B	60	82	6.6	50
C	60	96	7.8	50
D	60	110	5.4	50
E	60	69	6.6	50

*Average increased width after LIP is about 20μm.

Table 2. Experimental parameters of all samples before LIP treatment.

[8,9]. The line width of Ni plating depends on the laser power and wavelength, among other factors, but is normally greater than 15μm. Inkjet and aerosol jet printing offer a non-contact printing of the seed layer via deposition of nano-sized silver ink directly onto the substrate using a nozzle. The finest line width is smaller than 15μm. After sintering, the contact is thickened by light-induced electroplating (LIP) of silver, similar to the LDSE process.

After formation of the seed layer, the line is thickened by silver electroplating to increase the line conductivity, a process known as the *growth* step. The LIP process, one approach to plating, was used in recent tests to increase the conductivity of screen-printed solar cells, resulting in impressive efficiency increments [10].

Experiments conducted for this paper used this same technique for thickening seed layers. Furthermore, the contacts of different fine lines were investigated in detail. Optimized sheet resistance and finger numbers were also applied according to different formation processes of seed layers.

Experimental details

Typical Cz-silicon wafers with a base resistivity of 1-3Ωcm and about 200μm thickness were used in these experiments. For reference purposes, a standard industrial process was chosen for the fine-line screen-printing of the cells as shown in Fig. 1. Detailed processing steps include $POCl_3$ source diffusion in a tube furnace with uniform sheet resistances (SHR) of about 40Ω/square, followed by PSG removal by HF etching prior to SiN_x deposition. Frontal silver contact was formed using a 100µm finger-width standard screen following the AL-BSF metallization process step. A seed layer is conducted by reducing the fingers' width down to 50µm and increasing the amount of fingers to 80.

During the LDSE process, the seed layer was formed by laser doping of phosphoric acid and self-aligned nickel plating. In this paper, however, different surface morphologies and cell parameters are compared according to different laser parameters from several laser suppliers.

In the case of inkjet batches, most of the processing steps are the same as those used within the processing of typical industrial crystalline silicon solar cells. After AL-BSF printing and drying, the seed layer is applied by inkjet printing, yielding an average finger width of about 50µm. The thickness can be adjusted by applying various different printing conditions, but the typical thickness of a single layer is about 0.6µm. The I-V

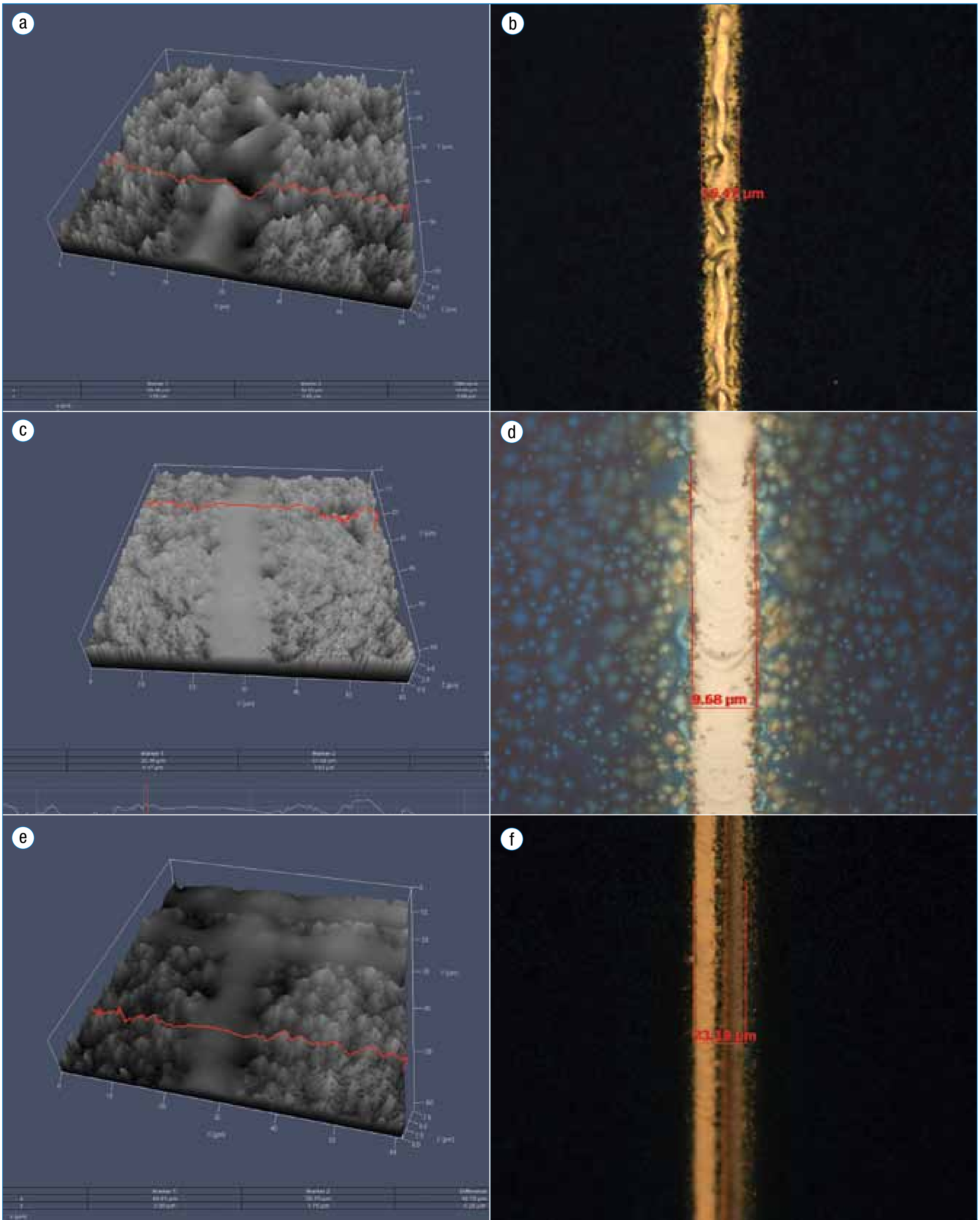

Figure 2. Laser-scanning microscopy images of fingers after laser scribing. A green laser (wavelength 532nm) was used for a and b; images c, d, e and f were created using a UV laser (wavelength 355nm).

performance of cells with different sheet resistance, finger numbers and finger thickness are investigated in the following section.

Results and discussion

Fine-line screen-printing

Screen-printing has already established itself as one of the most important processing steps in mass production of silicon solar cells today. The apparent contradiction between decreasing shading loss and achieving higher conductivity becomes obvious when manufacturing higher efficiency silicon solar cells. We attempted to use narrower finger design to realize fine-line printing, and continued to investigate the feasibility of 'normal' printing with 100µm finger width. Table 1 shows the I-V results for three samples: the fine-line pattern before plating (40µm finger width); the same fine-line pattern after plating (40µm finger width); and the reference pattern (100µm finger width). The V_{oc} remains constant for fine-line samples before and after plating (sample A and sample B). The decreased I_{sc} is a result of the increase in finger width from about 55µm to 75µm, while a higher fill factor (FF) arises from the increased conductivity brought about by decreasing R_s from 17.1mΩ to 4.2mΩ. Although an efficiency gain of about 2% was obtained through plating, the rate of finger breakage increased as a result of the narrowed fine-line design. Compared to the normal screen-printed sample C, a lag of 0.5% in the cell's efficiency is encountered. Optimized patterning, including finger numbers and finger width, need be redesigned to remedy this issue, for which further investigations are underway.

LDSE and nickel plating

Laser technology is widely used in the manufacture of PV solar cells. Most of the research carried out on this topic focuses on laser doping, cutting, ablation, and so on [11-13]. Combining selective emitter technology with lasers is proving to be potentially one of most promising directions for attaining the goal of higher efficiency solar cells. Lasers are often used to heavily dope below metal-contacted areas to form selective emitter structures. Typical processes involve adding the laser treatment directly after the ARC deposition.

> "Combining selective emitter technology with lasers is proving to be potentially one of most promising directions for attaining the goal of higher efficiency solar cells."

There are three types of lasers used in mass production: the IR laser, the UV laser and the green laser, which have wavelengths of 1064nm, 355nm and 532nm respectively. Different laser parameters will affect the laser doping profile and surfaces can be damaged by the laser's heating effect [14]. For LDSE samples, wafers with a resistivity of 1-3Ωcm were used. A 60Ω/square emitter was formed after diffusion in a tube furnace at a temperature of about 850°C. The heavy diffusion area was formed using 5% phosphoric acid under the metal-contacted area.

The laser-doped area of the wafers processed using the green laser yielded a coarse surface, depicted in Fig. 2a. The finger width of the wafers was 16µm (Fig. 2b). In contrast, the laser-doped area of wafers using a UV laser shows a much smoother surface (Figs. 2c, 2d, 2e & 2f). Furthermore, the finger width of the LDSE area depends on the spot size of the beam and the laser's wavelength. Applying different laser parameters when using the UV laser results in a different surface morphology and finger width as shown in Figs. 2c and 2e. The morphology of the latter shows smoother grooves, while a narrower finger width, brought about by use of different laser parameters, is visible in Fig. 2c. The optimized parameters of UV lasers show a narrower finger width of 9µm in Figs. 2e and 2f.

Another use of these lasers is doping of the busbar. The surface conditions of laser-doped busbars following plating with nickel and silver are shown in Fig. 3. The busbar consists of many interconnected fingers, each of which

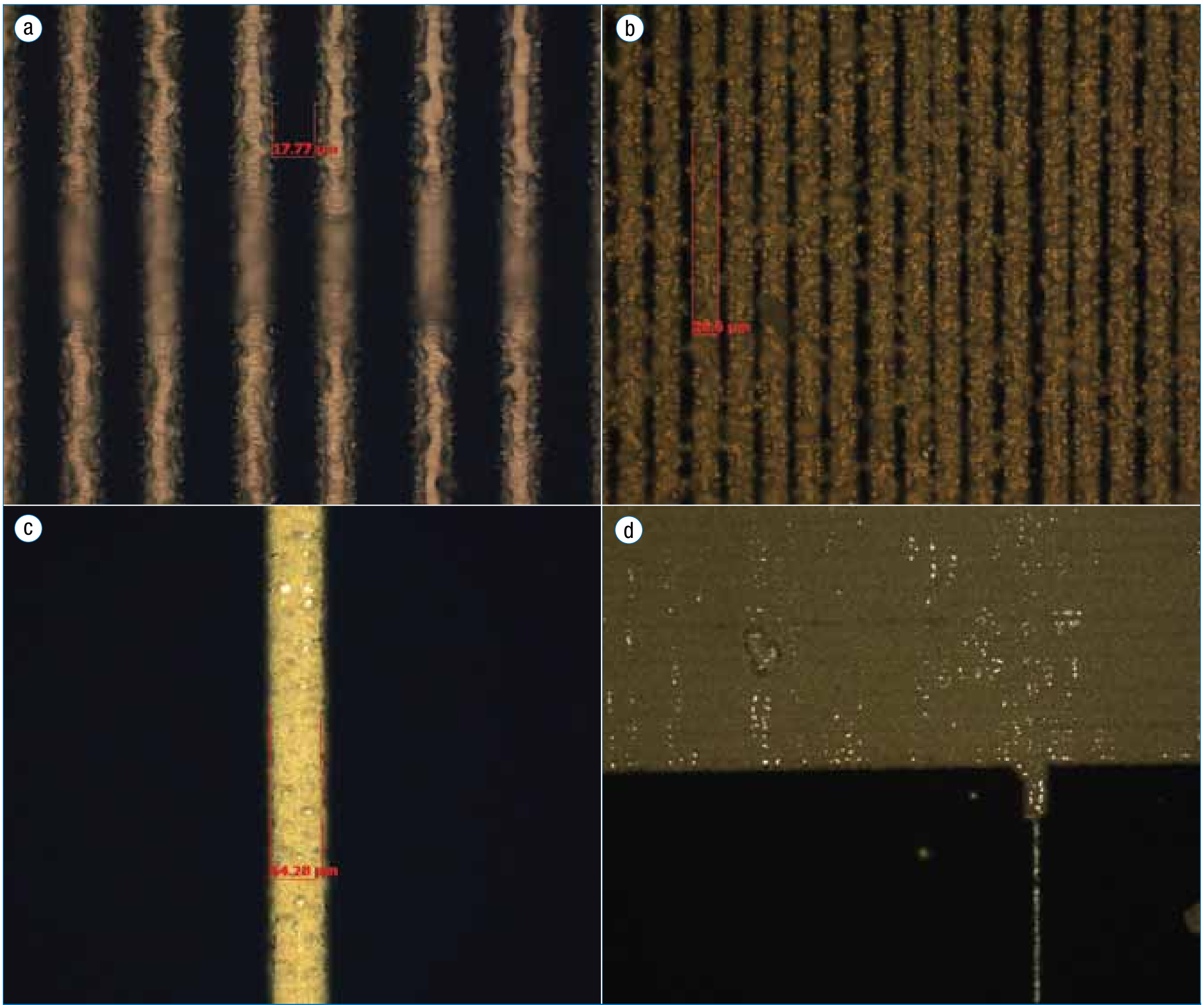

Figure 3. Laser-scanning microscopy images showing: laser-doped busbar after Ni plating (a); LIP Ag (b); prolonged LIP Ag time (c); and contact area between busbar and finger (d).

is about 17μm in width after Ni plating and 24μm after Ag plating (Figs. 3a and 3b). The surfaces are smoothed by the Ag plating (Fig. 3b). As the finger width approaches approximately 54μm, the grooves become a whole and continuous finger in the busbar. Ag is also present on non-metal areas, a result of deposition of silver on the top of pyramids (Fig. 3d).

At present, the performance of LDSE cells is not wholly satisfactory, which could be for a variety of non-optimized process reasons, including: laser-doping profile; nickel and silver plating; sintering condition, etc. Further research into all parameters and cell structure optimization are ongoing at China Sunergy.

Inkjet technology is one of most promising technologies used in the pattern formation of front metallization [4-6]. Table 2 shows the detailed parameters of processes for different samples. Average emitter sheet resistances are 80Ω/square for group A; the others are 60Ω/square. The average finger thickness is 6.6μm for groups A, B and E and the thicknesses of the seed layers are 7.8μm and 5.4μm for groups C and D, respectively. The width of all samples after printing is about 50μm, which increases to 70μm after silver LIP treatment.

The short circuit current and FF of group B is larger than that of group A, which could be a result of optimized firing conditions for group B. On a similar note, group A's low efficiency could be because of lower-than-optimal diffusion. The root cause of these results will be investigated further in future studies.

Table 3 illustrates the obvious efficiency improvements gained by increasing the finger thickness, especially in the case of groups C, D, and E, despite the fact that they have similar series resistance (R_S). Group C yielded the highest efficiency, thanks in part to the optimized finger sizes, SHR, optimized contact resistance, shading loss and combination. Higher I_{sc} loss is linked to the greater amount of fingers used in groups C, D, and E. It is probable that with further optimization

Sample	V_{oc} (V)	I_{sc} (A)	R_s (Ω)	R_{sh} (Ω)	FF	Eff
A	0.632	5.47	0.006	25	75.0	0.1731
B	0.630	5.84	0.007	56	76.4	0.1814
C	0.638	5.65	0.005	108	78.7	0.1830
D	0.627	5.59	0.005	44	77.7	0.1758
E	0.621	5.74	0.005	93	77.3	0.1779

Table 3. Typical I-V performance of cells from different group samples.

of the samples in the groups, efficiencies above 18.5% can be easily achieved.

Based on these basic investigations, we can conclude that LDSE technology still needs further optimization in areas such as the doping process, pattern design and surface damage by lasers. Inkjet technology seems to show the most potential; however, the scope of this investigation is just the start of fine-line technology investigation. The ultimate winner will be determined by a variety of factors, including reliability of the tools and equipment used, material quality, etc.

Conclusions

This paper investigated three different technology approaches for the development of fine-line crystalline silicon solar cells, presenting some basic findings of the experiment. Based on the two-step metallization concept, fine-line technology can be realized quickly in the mass production of PV solar cells, as illustrated by the results of this experiment. While there are three different techniques for the formation of seed layers – conventional screen-printing with narrow finger openings, laser scribing and doping, and inkjet technology – inkjet technology-based approaches seem to hold most promise for the future.

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