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Ink Jet Printing Approaches to Solar Cell Contacts

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Ink Jet Printing Approaches to Solar Cell Contacts

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ABSTRACT

We are developing inkjet printing as a low cost, high throughput approach to the deposition of front contacts for Si solar cells. High deposition rates of 1μm per printing pass were achieved with a new metalorganic ink composed of silver(trifluoroacetate) in ethylene glycol. The printing conditions were optimized to achieve a relatively high line resolution of 120 μm. The optimal parameters for the piezoelectric inkjet were a pulse frequency of 50 Hz and pulse amplitude of 25 V. The best resolution and the line quality were achieved at a substrate temperature of 180 °C and drop separation of 40 μm.

1. Introduction

Inkjet-printing is an attractive alternative to screen-printing or vacuum evaporation for fabrication of the front contacts to solar cells[1]. Vacuum evaporation is effective but requires patterning and is capital intensive. Screen-printing is a low-cost, atmospheric printing technique, but has resolution and throughput problems. Inkjet printing is an inherently suitable approach to mass manufacturing and conveyor processing of cells and modules. Inkjet printing should also provide better line resolution and improved aspect ratios for the conducting grid lines, which would lead to improved solar cell performance. A significant advantage of inkjet printing over screen-printing is that it is a non-contact, conformal deposition technique and therefore it is especially suitable for processing fragile and uneven poly-Si wafers.

An essential element in the development of inkjet-based contacts is the formulation of the ink. For contact grids the optimization of the ink components is focused on achieving high deposition rates, good line resolution, high conductivity of the printed lines, and high quality ohmic contact to the substrate. Such inks should have a long storage and use life and be suitable for the chosen inkjet.

In previous work, we have demonstrated highly conductive inkjet and spray-printed silver layers [2-4] deposited at elevated temperatures (300-400 °C) from a metalorganic (MO) silver ink. The deposition rate reported for these inks was rather low 300-500 Å per printing pass. The lines that were inkjet-printed from these inks were either broad and thin or composed of isolated islands [2].

We report here on improved deposition rates and line qualities for inkjet-printed silver contact patterns. We have achieved resolution and aspect ratios comparable to those for screen-printed lines. The ink composition and the processing parameters were optimized to achieve higher deposition rates and to control the spreading of the drops to achieve better continuity and resolution. The details of the optimization study will be presented below.

2. Experiment and Results

To achieve practical deposition rates, concentrated solutions of the metalorganic precursors are required. A new metalorganic precursor (proprietary formulation) with silver loading of 20 mass % was developed and used for inkjet printing of silver lines and patterns. The printer set up consisted of a stationary drop-on-demand piezoelectric inkjet from Microfab with a 50-micron orifice. A resistive substrate heater plate positioned on an X-Y stage directly under the inkjet served to provide heating and x-y positioning to 1 μm. Processing parameters such as substrate temperature and the translation speed as well as the inkjet driving parameters, the frequency and the amplitude of the controlling impulses, were varied to optimize the quality of the printed lines. AR-coated Si ribbons provided by Evergreen Solar were used as substrates in the optimization study.

The effect of substrate temperature on quality of the printed lines was evaluated by printing single-line patterns at various substrate temperatures from 50 °C to 200 °C. All other printing parameters were kept constant (frequency of 500 Hz, pulse amplitude of 50 V and the translation speed of 24 mm/s). After printing and prior to microscope inspection the patterns were dried on a hot plate by gradually increasing the temperature from 25 °C to 220 °C. The 50x image of the lines printed at 50 °C, 120 °C and 180 °C are presented on Figure 1.

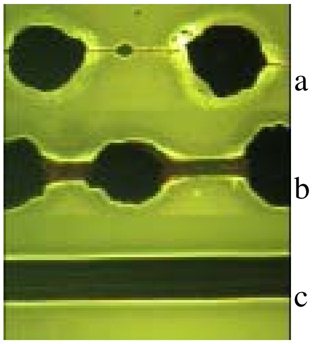

Figure 1. 50 x optical microscope images of the line patterns inkjet-printed at substrate temperatures of 50 °C (a), 120 °C (b) and 180 °C (c) and then dried on a hot plate.

The shape of the lines printed at lower deposition temperatures (40 °C and 120 °C) suggests the merging of the individual printed drops prior to complete solvent evaporation. Increasing the temperature to 180 °C led to a gradual improvement in the line quality. This may be due to increased evaporation rates. Raising the substrate temperature above 180 °C and approaching or exceeding the boiling point of the ethylene glycol (197 °C) resulted in splattering of the ink and loss of line quality.

The optimal translation speed of the X-Y table had to be found in order to achieve well-shaped lines. Single-line patterns were printed at the optimal deposition temperature of 180 °C, a frequency of 100 Hz, and pulse amplitude of 35 V with the translation speed varied between 4 mm/s to 28 mm/s. Changing the translation speed of the stage changes the distance between the deposited drops. When the distance exceeded the diameter of the deposited drops (in our case 160 µm) the printed pattern consisted of individual dots as in Figure 2a. Reducing the translation speed so that adjacent drops started overlapping led to a regrouping of the drops on the substrate surface. For example at a 100 µm distance the adjacent drops merged forming the chain of larger diameter drops (compare Figures 2a and b). Further reduction of the distance between the drops to 40 µm (a quarter of the drop diameter) produced solid straight lines (Figure 2c). Reducing the drop separation below 40 µm provided no further improvement in the line shape and led to increase in the line width.

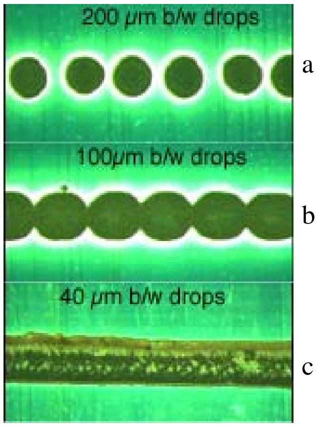

Figure 2. 50 x optical microscope images of single line patterns inkjet-printed at translation speeds corresponding to 200 μm (a), 100 μm (b) and 40 (μm) separations between the deposited drops.

It was observed that the amplitude of the electrical pulses on the piezoelectric driver also affects the line resolution. Single line patterns were printed at 180 °C, 100Hz and a 40-micron separation between the drops. The amplitude of the voltage pulse was varied from 20V (the onset of the stream generation) to 35 V. Up to 25 V the jet was unstable producing poor quality lines. Solid straight lines were achieved starting at 25 V. The line width increased with the amplitude of the driving voltage. At 25 V it was 143 µm and it increased up to 167 µm at 35 V. Increasing the pulse amplitude causes an increase in the volume of the drop and the speed of the jet[5]. Both could be contributing to the increase in the size of the deposited lines. Therefore it appears that the lower pulse amplitudes were advantageous for achieving improved line resolution. The lowest usable value of the pulse amplitude was dictated by jet stability.

Figure 3 shows the effect of drop generation frequency on the line definition. Single line patterns were printed at 180 °C, pulse amplitude of 25 V and with 40-micron separation between the drops. The frequency was varied between 50 and 400 Hz. The average line width did not change with frequency, however the shape and the integrity of the line were better at lower frequencies. Unfortunately, lowering the frequency is associated with reduced printing speed. Frequencies below 50 Hz were found to be impractical.

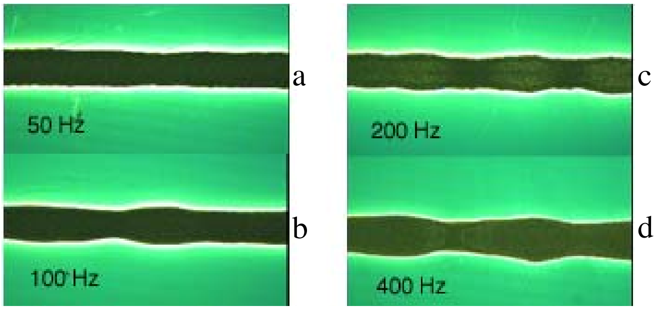

Figure 3. 50 x optical microscope images of single line patterns inkjet-printed using drop generation frequencies of 50 Hz (a), 100 Hz (b), 200 Hz (c), and 400 Hz (d).

Based on the results above the following printing conditions were identified as the optimal for the best line resolution: frequency of 50 Hz, amplitude of 25 V, translation speed of 2 mm/s and the temperature of 180 °C. The lines printed at these conditions were 120 µm wide and ~1 µm thick for a single printing pass. In order to deposit thicker lines multiple passes of the jet were used. The line width slightly increased (resolution decreased) with every pass. Figure 4 shows linear increase of the line width with the number of passes.

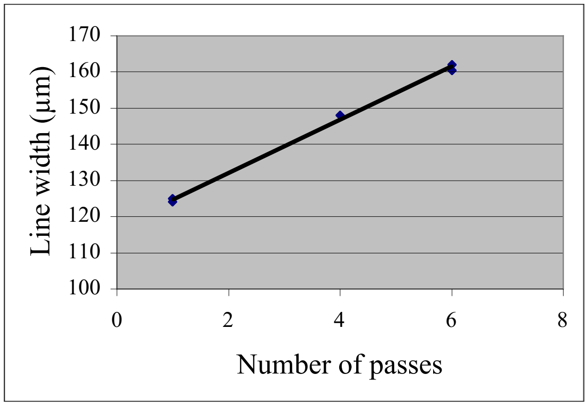

Figure 4. The width of the inkjet-printed lines as a function of the number of passes/layers.

Multiple-layer lines as thick as 15 µm were printed by using multiple passes and demonstrated good adhesion to the substrates. The multiple-pass approach was used to print the 200 µm wide 10 µm thick silver lines for Si solar cells.

The processing details and the results of the electrical testing of these cells will be reported elsewhere. Near bulk resistivity of 2.2 μOhm•cm was achieved in the inkjet-printed silver grids. Improved line resolution and aspect ratio can be achieved by further optimization of the inkjet process. Using smaller jets and optimizing the ink formulation for higher viscosity and surface tension are directions currently under investigation.

3. Conclusions

An improved metalorganic ink formulation has demonstrated increased deposition rates. The printing process was optimized to achieve best line resolution. For the current system the following parameters were identified to be important (optimum value): drop frequency (50 Hz), pulse amplitude (25 V), stage translation speed (2 mm/s) and substrate temperature (180 °C). The lines printed under these conditions were 120 μm wide and ~1 μm thick for a single printing pass. Thicker lines up to 10 μm were produced by multiple-pass printing and demonstrated good conductivity and adhesion to the substrate. The results of the cell testing will be reported in future communications

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