AEROSOL JET® PRINTING SYSTEM FOR HIGH SPEED, NON-CONTACT FRONT SIDE METALLIZATION OF SILICON SOLAR CELLS

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ABSTRACT: Highly efficient solar cells can be produced by applying the front side metallization in a two-step process. A seed layer is printed followed by an electroplating step to increase thickness and reduce current loss. While traditional screen-printing can be used to print the seed layer, greater benefit is realized by utilizing a direct-write approach to simultaneously reduce the width and thickness of the seed layer. Aerosol Jet Printing is a non-contact direct-write approach that has been shown to have advantages for printing the seed layer. However, the throughput from a typical single-nozzle print head is too low to be useful for production. To increase throughput to a level comparable to screen-printing, a multi-nozzle print head was developed. A modified screen-printing paste was used to print a seed layer for collector lines on 156 x 156 mm^2 multi-crystalline silicon wafers. Wafer printing times of approximately 15 seconds/wafer were measured, representing a 10-fold reduction in printing time over a single-nozzle system. An average line width of 55.7+/-1.2 microns was measured over 10 wafers printed sequentially. An average line width of 54.5+/-2.0 microns was measured for wafers printed hourly over 10 hours of continuous operation. A prototype Print Head for printing bus bars was demonstrated. Bus bars could likewise be printed with a print time of 15 seconds/wafer.
Keywords: Contact, Silicon, Manufacturing and Processing, Direct-Write

1 INTRODUCTION

Screen-printing is the most common technique in use today for the front side metallization of multicrystalline silicon solar cells. However, this approach is reaching its limits as the industry pushes for higher efficiency cells and thinner wafers. For example, losses due to shadowing can be reduced by printing conductive lines that are narrower than what is capable with screen-printing. Further, as thinner silicon wafers are introduced into production lines, waste due to wafer breakage becomes more significant. It is desirable to utilize a printing approach that simultaneously can reduce line width and print in a non-contact fashion.

Further increases in efficiency can also be achieved by utilizing a two-layer structure for the collector lines. Traditionally, collector lines must be highly loaded with glass in order to reduce the contact resistance with the underlying silicon. However, this high glass concentration increases the resistance and hence the current loss of the collector line. By decoupling the part of the collector that makes contact to the emitter from the part that carries the current, overall higher efficiencies are possible. This is most easily achieved by first printing a seed layer, followed by a subsequent plating step. One such process for achieving this is the Light Induced Plating (LIP) process [1]

Several possible approaches exist for printing seed layers for a subsequent plating step. Ink Jet offers a potential non-contact printing approach [2]. However it has several known limitations. Inks must be dilute, requiring multiple passes to build adequate thickness. Printing of commercial screen-printing pastes is not possible, necessitating the development of specialized nanoparticle or organometallic inks. Droplets are relatively large, resulting in line widths that are no better than those achievable by screen-printing. The gap between the substrate and the print head is critical, resulting in low tolerance to uneven substrates.

Optomec has developed a new approach for non-contact printing of electrical traces, known as Aerosol Jetting. Recently, this approach has been applied to produce efficient silicon solar cells using a commercial screen-printing paste and the LIP process [3]. A single nozzle Aerosol Jet printing system was used to print a seed layer with good mechanical contact and low contact resistance. LIP was then used to plate a thick conductive trace with low series resistance. The cells produced by this approach had efficiencies as high as 16.4%.

To move this technology into manufacturing, Optomec is developing multi-nozzle print heads that enable higher throughput printing of collector lines. The current multi-nozzle print head is capable of printing the collector lines for a single 156 mm x 156 mm solar cell in 15 seconds. Increased nozzle count will further reduce the printing time by as much as an order of magnitude.

In order to realize the full advantages of Aerosol Jetting for the front side metallization, it is also necessary to print the bus bars. The requirements for bus lines are significantly different than for collector lines (i.e. 1-2mm wide vs. < 50 microns). Thus, work has also begun on a single nozzle design optimized for printing bus bars.

2 AEROSOL JET PRINTING

2.1 Background

The Maskless Mesoscale Material Deposition ($M^3D^®$) Aerosol Jet System is capable of depositing inks, pastes, or other liquid materials onto a variety of surfaces, with printed feature sizes below 10 microns. The process is non-contact and conformal, allowing patterning over existing structures, across curved surfaces and into channels or vias.

Aerosol Jet Printing begins with the atomization of the ink, producing droplets on the order of one micron in diameter. The atomized droplets are entrained in a gas stream and delivered to the Print Head. Here, an annular flow of clean gas is introduced around the aerosol stream, which functions to eliminate clogging of the nozzle. The combined gas streams exit the print head through a converging nozzle that compresses the aerosol stream to a diameter less than 10 microns. The jet of droplets exits the Print Head at high velocity (~50 m/s) and impinges upon the substrate. Patterns are then formed by moving the Print Head relative to the substrate.

The high velocity of the jet enables a relatively large separation between the Print Head and the substrate, typically 1-5 mm. The droplets remain tightly focused over this distance, resulting in the ability to print over uneven substrates [4]. Despite the high velocity, the printing process is gentle; substrate damage does not occur and there is generally no splatter from the droplets.

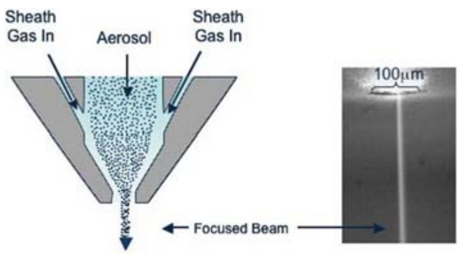

Figure 1: Aerosol Jet Print Head

Once patterning is complete, the printed ink typically requires post-treatment to attain final mechanical and electrical properties. Post-treatment is driven more by the specific ink and substrate combination than by the printing process. The one exception to this is laser processing; Aerosol Jet printing can result in layers that are thin enough to laser process without excessive power requirements or substrate damage.

The atomization step is very flexible compared to inkjet. Particulate suspensions are easily atomized although, as a general rule, suspended particles should be on the order of 0.5 microns or less. Ink viscosity may be in the range of 1-5000 cP, although it may be necessary to optimize viscosity for a particular application. The construction materials of the printing system are generally not sensitive to attack from solvents, allowing a range of solvent vehicles to be used.

2.2 Solar Cells via Aerosol Jet Printing and LIP

A schematic of the process required to produce front side metallization via Aerosol Jet Printing combined with LIP is shown in Figure 2. All steps up to the font side metallization step remain the same as previously. Aerosol Jet printing of the seed layers for the Collector and Bus lines is performed in place of traditional screen-printing. After conventional drying and high temperature firing, LIP is performed to build highly conductive collector and bus lines.

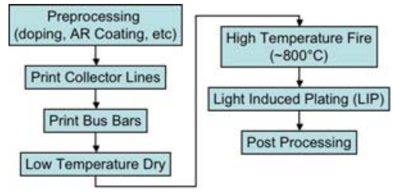

Figure 2: Solar Cell processing via Aerosol Jet and Light Induced Plating (LIP).

3 MULTINOZZLE PRINT HEAD

Optomec has developed several prototype multi-nozzle print heads. Applications for these multi-nozzle print heads have ranged from deposition of biological material to printing of P-OLEDs. However, this is the first time Optomec has developed a head specifically for solar cell applications.

3.1 Deposition Head

An example of a multi-nozzle print head is shown in Figure 3. The principles of operation are the same as for the single-nozzle system. However, the internal geometry has been reduced significantly to allow a nozzle-to-nozzle pitch as small as 4mm. Sheath gas and aerosol are introduced into manifolds and distributed evenly to all nozzles.

The nozzle-to-nozzle pitch is fixed, however in principle a print head can be designed with any pitch of about 4mm or larger. Tighter printed pitches are achieved by printing a first set of lines, then indexing the head by a distance less than the nozzle-to-nozzle spacing to print additional sets of lines.

Figure 3: Multi-Nozzle Print Head. The Aerosol enters a manifold at the top of the Print Head and is distributed evenly among all nozzles.

3.2 Atomizer

Despite requiring approximately 10x the aerosol output, it was found that the Pneumatic Atomizer originally designed for the single-nozzle print head was capable of producing enough mist for the multi-nozzle print head. It was necessary to increase the atomizing gas flow rate substantially in order to generate enough aerosol for the multi-nozzle print head. Minor modifications were required to stabilize the atomizer for long-term (> 8 hours) operation.

4 COLLECTOR LINE PRINTING

Printing trials were conducted to test the suitability of the multi-nozzle system for printing the seed layers for subsequent plating via LIP. Characterization focused on geometric capability, reliability and repeatability. As Optomec's core expertise is in the area of print system development, no attempt was made to fire or plate the wafers to produce functioning cells.

4.1 Printing Trials

Two sets of experiments were performed to test the printing capabilities of the multi-nozzle system. First, 10 wafers were printed sequentially to determine average line width and wafer-to-wafer repeatability. Second, the print system was run continuously for 10 hours, with one wafer printed every hour to determine long-term stability.

The wafers were multi-crystalline silicon wafers that had been previously etched and nitrided. The wafers measured 156mm x 156mm. A total of 80 collector lines per wafer were printed. Collector lines were printed in an interdigitated fashion, due to the pitch restrictions (4mm) of the print head. Multiple passes of the print head were employed in order to print all 80 lines. The target line width for these trials was 50 microns +/- 10 microns (20%).

A modified screen-printing paste was used to print the collector lines. The solids content was comparable to a conventional screen-printing paste (~70wt%).

The typical time to print one wafer was 15 seconds. Due to the manual nature of the printing system, wafers were loaded and unloaded by hand. This resulted in a typical throughput of 1 wafer/minute. After printing, the collector lines were dried in an oven at 80C for 10 minutes. An example of a printed wafer is shown in Figure 4. The Bus lines were printed in a separate step, described below in Section 5.

Figure 4: As-Printed Silicon Wafer with collector lines and bus bars. Collector and bus lines were printed in separate steps using a multi-nozzle print head and a bus bar printing head.

4.2 Characterization

Line width measurements were taken from all printed wafers. Measurements were made using a digital camera installed on a light microscope. Ten lines across the wafer were selected for measurement. The average, high and low values for each wafer are reported below.

In addition, all wafers were inspected visually for evidence of opens or paste stains.

4.3 Results and Discussion

The average line widths for 10 wafers printed sequentially are shown in Figure 5. The average line width for all 10 wafers was 55.7 microns with a standard deviation of 1.2 microns. The average was higher than the target average of 50 microns, but was within the target range of +/-20%. Averages for individual wafers were likewise within the target range. The wider than expected line width is due to spreading of the ink after printing.

The average values are graphed in the order in which the wafers were printed. There is no systematic pattern evident in the graph. This observation, combined with the tight distribution of line widths, is indicative of a repeatable process.

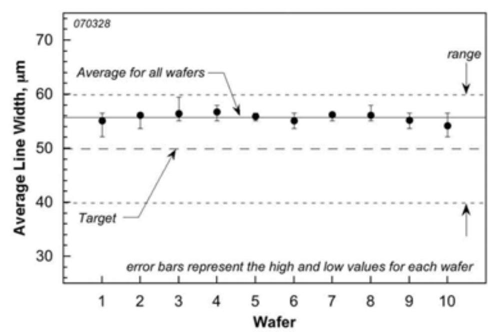

Figure 5: Average Line Width – 10 Wafers printed sequentially

The average line widths for wafers printed over a 10-hour period are shown in Figure 6. The average line width for the 10-hour period was 54.5 microns with a standard deviation of 2.0 microns. Again, the average was higher than the target average, but well within the target range. The average line width for individual wafers was once again within the target range.

There was a slight downward trend in the average line width noted over the 10-hour run; the average over the first two hours was 55.9 microns compared to 52.9 microns over the last two hours. However, the standard deviation remained nearly constant over this time period, indicating that the process is relatively stable. The downward drift is due to slightly reduced output from the pneumatic atomizer over time.

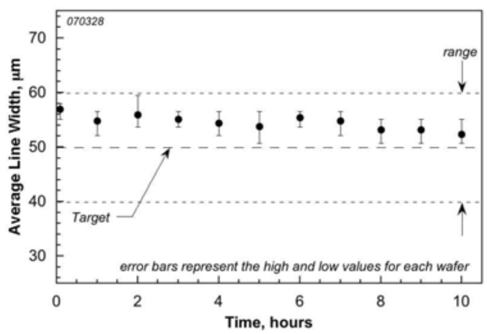

Figure 6: Average Line Width – Wafers printed at 1 hour intervals over a continuous 10-hour period

In addition to line width characterization, all wafers were inspected for opens or stains. No visible opens were observed on any of the wafers. A single wafer showed evidence of a stain, however this appeared to be a result of handling rather than any dripping from the print head.

5 BUS BAR PRINTING

In order to realize the full advantages of Aerosol Jetting for the front side metallization, it is necessary to print the bus bars as well as the collector lines. The requirements for bus lines are significantly different than for collector lines as the former are significantly wider (i.e. 1-2mm wide vs. 50 microns). It is possible to print the bus lines using a conventional single nozzle print head by rastering many times to build width. However, this is a time-consuming process that takes on average one minute per bus bar (or two minutes per wafer). It is desirable to print with a throughput comparable to that possible with the multi-nozzle print head used to print the collector lines. Thus, work has begun on a print head design optimized for printing bus bars.

5.1 Prototype Bus Bar system

An example of a prototype bus bar printing head is shown in Figure 7. This proof-of-concept design was produced to explore scalability. The principles of operation are the same as for the single-nozzle system. However, the internal geometry has been increased significantly to facilitate printing of a much wider trace than is typically possible with a conventional single-nozzle. The example shown in Figure 8 incorporates dual print heads such that two bus bars may be printed simultaneously. Sheath gas and aerosol delivery lines are split between the two print heads. The Pneumatic Atomizer that was used for the system was identical to the unit used for the multi-nozzles system.

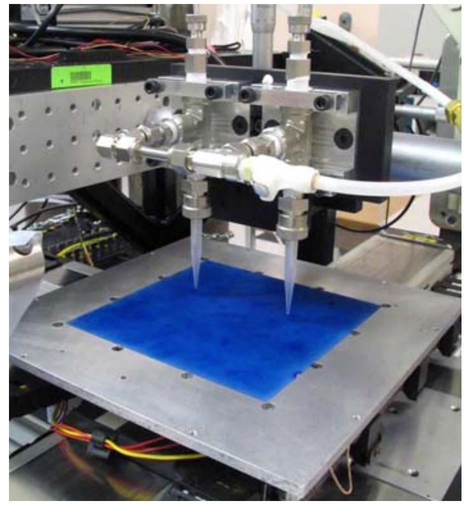

Figure 7: Prototype Bus Bar Printing Head – two bus bars are printed simultaneously.

5.2 Printing

Printing trials were conducted to test the suitability of the bus bar printing system for printing the seed layers for subsequent plating via LIP. For this early, proof-of-concept print head, characterization was limited to geometric capability. Collector lines were first printed using a multi-nozzle print head. The system was then reconfigured with the dual nozzle bus bar print head. The same experimental paste used for the multi-nozzle print study was used to print the bus bars. Target bus bar width was 2.0mm.

5.3 Results

With the prototype system, bus bars could not be printed in a single pass; only traces approximately 500 microns wide could be printed in a single pass. Using multiple passes, bus bars on a single wafer could be printed in approximately 15 seconds, comparable to the speed of collector line printing. Since multiple passes were required to meet the width requirement, the raster spacing was easily adjusted to allow printing of a 2mm wide trace. An example of a wafer with both bus and collector lines printed via Aerosol Jetting is shown in Figure 4.

6 FUTURE WORK

Work has already begun to expand upon the examples presented in this paper. This work falls into two important categories; expansion of the multi-nozzle Print Head to greater nozzle counts per head and development of a bus bar printing head capable of printing a bus bar seed layer in a single pass. Both of these capabilities will enable printing of the seed layer for front side metallization in 3 seconds or less.

To meet the first goal, a multi-nozzle print head consisting of 40 nozzles is currently undergoing laboratory testing. Future work with this print head will focus on process improvements and refinement of the design.

A more robust version of the prototype bus bar printing head is in also being tested. Future work will focus on optimizing the design for printing bus bars of arbitrary width in a single pass. It will also be necessary to verify that the repeatability and reliability of this new print head is comparable to the multi-nozzle Print Head.

Finally, although exploratory work has been performed in this area, a full characterization of wafers printed with these systems after LIP will be needed.

7 CONCLUSIONS

A multi-nozzle Aerosol Jet Print Head was developed to enable high speed printing of conductive traces. This head was used to demonstrate printing of the seed layer for subsequent LIP. Wafer printing times of approximately 15 seconds/wafer were measured, representing a 10-fold reduction in printing time over a single-nozzle system. An average line width of 55.7+/-1.2 microns was measured over 10 wafers printed sequentially. An average line width of 54.5+/-2.0 microns was measured for wafers printed hourly over 10 hours of continuous operation. A prototype Printing Head for printing bus bars was demonstrated.

ACKNOWLEDGEMENTS

The authors would like to thank Stephan Glunz, Philipp Richter and Matthias Hörteis of Fraunhofer ISE for many useful discussions.

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