Inkjet Masking for Industrial Solar Cell Processes

J.P. Hermans, R. van Knippenberg, R. Eijmberts, P. van de Haar*; OTB Solar B.V. (Roth & Rau Group); Eindhoven, the Netherlands.
B. Ketelaars, T. Wijnstekers, K. Knechten, H. Veenstra; Océ Technologies B.V. (Canon Group); Venlo, the Netherlands.
**** Now at Holland Innovative B.V.; Eindhoven, the Netherlands.***

Abstract

Masking by inkjet printing has potential benefits for solar cell manufacturing by improving the conversion efficiency and production yield. In industry and on lab scale it has been shown that there are many applications for inkjet masking to improve the solar cell efficiency. These applications include honeycomb texturisation, selective emitter, plating of front side electrodes and using inkjet masking for low-cost rear-side patterning for back-contact cells. Key success factors for inkjet masking are its small feature size and high flexibility. Furthermore the contact-less print method is in line with the general trend towards thinner wafers to reduce the material costs.

However, inkjet technology is initially developed for graphical printing, which has less demanding print reliability criteria. In the photovoltaic (PV) industry one malfunctioning nozzle in the inkjet printing system can result in significant decreased device performance or clear visual defects. Therefore the transition from graphical printing to solar cell production cannot be made without a significant improvement in reliability.

In 2011 OTB Solar B.V. started the development of the PiXDRO JETx, a high volume industrial inkjet printing system (up to 2400 wafers/hour) which addresses inkjet masking as a first application. For this application a joint development with Océ Technologies targets to demonstrate an inkjet print reliability and accuracy which meets the standards for solar cell manufacturing. The use of self-diagnosing print heads of Océ, redundant print strategies and the automation from OTB Solar form the basis to combine high reliability with industrial throughput and the printing of fine structures with a drop placement accuracy of 7.5µm 3sigma.

Introduction

In order to reduce the cost per watt peak PV module manufacturers are constantly investigating new process applications which can provide an improvement in conversion efficiency at low cost. Many of those applications include deposition of fine lines with features <50µm and complex structuring of thin layers.

The cost per watt peak can also be reduced by lowering the wafer costs, which is achieved by reducing the Si wafer thickness. Reduced wafer thickness, however, also makes the wafers more susceptible to breakage or performance loss due to (micro-)cracks. At various stages in the solar cell and module production process these vulnerable wafers are subjected to stress caused by process and handling equipment. The cost resulting from wafer breakage is severely magnified when this breakage happens further downstream in the module production process and can even result in complete loss of modules. Wafer breakage not only results in direct costs, but the overall equipment efficiency is also reduced due to unscheduled downtime. Therefore these fragile wafers require non-contact deposition techniques.

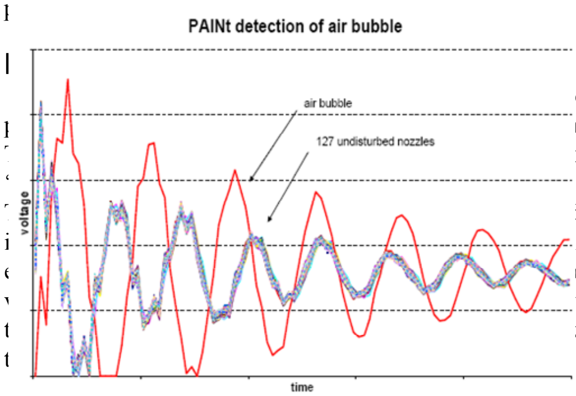
In recent years inkjet printing has attracted great interest for mass production because of this non-contact deposition and other advantages like high precision, low cost, high flexibility and low temperature deposition. Industrial inkjet printing has been widely applied in the graphical industry and for the fabrication of electronic devices such as organic light emitting diodes (OLED), printed circuit boards (PCB), radio-frequency identification (RFID) or even for medical usage [1,2]. For solar cell mass production inkjet printing has been introduced with the selective emitter etch back process [3]. On lab scale many other applications have been shown including honeycomb texturisation [4], inverted pyramids and V-grooves [5], plating of front side electrodes [6] and using inkjet masking for low-cost rear side patterning for back-contacted or iPERC/iPERL (Industrial Passivated Emitter and Rear Cell / Industrial Passivated Emitter and Rear with Locally diffused areas) type cells [7,8,9].

Reliability

Universities and institutes investigating photovoltaics make extensive use of inkjet printing because of its unique property of digital imaging which offers very high flexibility. Inkjet systems which allow for a quick exchange of print heads enable testing of a wide range of functional materials in a short period of time. The transition, however, from lab scale solar cell research to mass production has been hampered by the availability of suitable high volume inkjet printing systems and skepticism on the reliability of inkjet printing. Solar cell mass production equipment requires a throughput of around 2400 wafers/hour with a yield higher than 99.8%. To obtain these yield values an inkjet printing system cannot permit to have failing nozzles during printing. In solar cell applications a complete line of missing droplets will severely hamper the device performance or cause cell breakage, e.g. in honeycomb texturisation a line of unprinted droplets will cause very deep etching, reducing the wafer strength; in applications with front-side plating a line of unprinted droplets can result in ghost-plating which renders the cell unsellable due to low aesthetic quality. Here lies the challenge: the required combination of high volume and high reliability is challenging for inkjet printing systems. For other high volume industries like document printing some failing nozzles are still acceptable. Other applications require very high reliability, like printing reagents in DNA micro-arrays [10] that detect forms of cancer, but in those cases low throughput is accepted.

The main factor in the reliability of an inkjet printing system is the combination of print head and ink which should be carefully optimized for each other. Nozzle failure, however, is inevitable in low-cost mass production inkjet printing. To obtain acceptable yields the reliability of the inkjet system needs to be improved. From the graphical industry various solutions are known to improve the reliability, but these all affect the throughput. Another option is to diminish the effects of nozzle failure by making sure a failing nozzle does not result in a complete line being misprinted (so called dithering mask). By printing a single line in the print direction with multiple nozzles the effect of one malfunctioning nozzle is diminished, but this also increases the amount of print movements needed to finish the pattern and therefore severely reduces the throughput.

The reliability can also be improved by detection of failing nozzles and using redundant printing strategies to correct for these failing nozzles. This detection of failing nozzles can be performed by inspecting the print pattern after printing and forming a feed-back loop to determine the failing nozzle number, but this type of detection requires expensive high resolution, high speed imaging systems. Before this detection method has identified a failing nozzle many wafers have been printed which will all result in yield loss or need to be reworked to correct this defect. Detection of the condition of a nozzle during printing offers a very short feed-back loop and enables redundant printing strategies without affecting the throughput. In the PiXDRO JETx the detection of the nozzle status is performed by PAINt technology; which is incorporated in the CrystalPoint print head from Océ Technologies. PAINt technology combined with redundant nozzles and redundant



ogy the
sensor.
or softly
the ink.
lo result
e piezo
duces a
stem. If
channel,
see

Figure 1. Based on the characteristics of the signal the distortion is identified and the nozzle condition is classified. In order to determine the response signal characteristics of a certain type of distortion (air bubble, dirt in nozzle chamber, etc.) a CrystalPoint print head has been built with glass nozzles. With a microscope the type of distortion is determined and correlated to the response signal characteristics. Besides air bubbles with different diameters the PAINt detection can distinct dirt inside the nozzle chamber and failure of the electrical actuator. Based on the type of distortion a recommended maintenance action is given.

By comparing the signal characteristics of good functioning nozzles over a longer period of time the aging of the piezo element is characterized. Compensation for this inevitable aging results in consistent drop volume during the whole lifetime of the print head.

In the PiXDRO JETx an array of 9 print heads is used, with each print head having 256 nozzles, as shown in Figure 2.

The PAINt detection on this array of 2304 nozzles takes only 200ms, which is fast enough to be performed between two printing swaths. Combining the nozzle status detection with extremely high data transfer rates allows the system to adjust the drop-on-demand pattern for each print swath. After printing one swath a PAINt

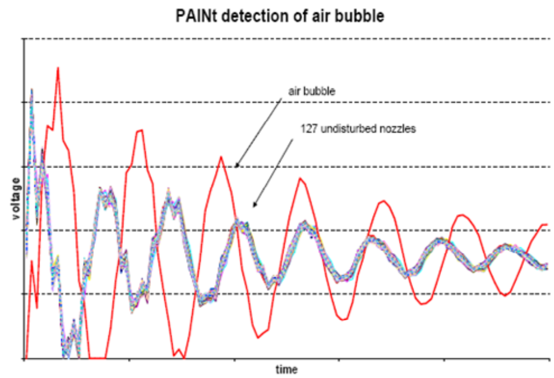


Figure 1, PAINt detection of an air bubble in the nozzle chamber. The response of the nozzle with an air bubble differs from the undisturbed nozzles.

detection is performed; in the following swath the distorted nozzles are paused and redundant nozzles take over the task of jetting droplets in their place. This adjustment is two-fold 1) in the next swath a redundant nozzle takes over the printing task of the distorted nozzle 2) the drops that should have been printed by the distorted nozzle in the first swath will be filled in by printing with a redundant nozzle in the next swath. Meanwhile, the air bubble dissolves in the ink. As soon as the nozzle has an undistorted response this paused nozzle can be reactivated.

By combining self-diagnosing print heads with redundant nozzles and redundant printing strategies the PiXDRO JETx targets to meet the standards for a mass production inkjet printing system with throughputs up to 2400 wafers/hour, unmatched reliability and highly consistent drop volume. Specialized wafer handling automation from OTB Solar can be added for loading and unloading of the wafers.

Figure 2, Print head array with 9 CrystalPoint print heads as used in the PiXDRO JETx.

Solar cell applications

In solar cell industry any new process step added to the production line has to realize a reduction in the cost per watt peak of the produced module. In many applications this cost reduction is realized by increasing the cell efficiency or by reducing the material costs; the process equipment also has to meet throughput criteria to maintain the output of the production line. To maximize the throughput of the inkjet printing system the amount of print swaths needed to complete the pattern has to be kept to a minimum. By optimizing the print head rotation together with X- and Y-resolutions this amount of print swaths can be minimized without affecting the quality of the printed pattern. Each application has different properties that are critical to the quality, like line width or line opening, but also the thickness of the deposited layer or thickness variation could be critical to the quality. Often these properties are also affected by many other factors that should be considered when optimizing the quality and throughput, for instance drying time between printed droplets. In the PiXDRO JETx these factors, e.g. resolutions, can easily be optimized while minimizing the amount of print swaths.

OTB Solar is investigating various solar cell applications with a masking ink from Océ Technologies. These applications include plating of front-side electrodes [6] and patterning for iPERC cells [7,8,9]. An individual droplet of this masking ink printed with the CrystalPoint print head has a droplet volume of 30pl, on a silicon wafer this results in a droplet with a diameter of ~47µm, forming an almost perfect semi-sphere on the surface. Printing of a straight line with a single nozzle results in a minimum positive feature size of 35µm, for negative features (line openings) the size can even be reduced to 20µm. The positive feature size of 35µm is smaller than the diameter of individual droplets because the droplets are printed wet-on-wet resulting in slower crystallization in the print direction compared to perpendicular to the printing direction, this makes the droplets more elliptic, effectively decreasing the line width. Figure 3 shows an example of straight lines printed with the CrystalPoint print head and masking ink. One application under investigation is the use of masking ink for plating barriers, preventing the lateral growth of the metallization lines during the plating process, as shown in Figure 4.

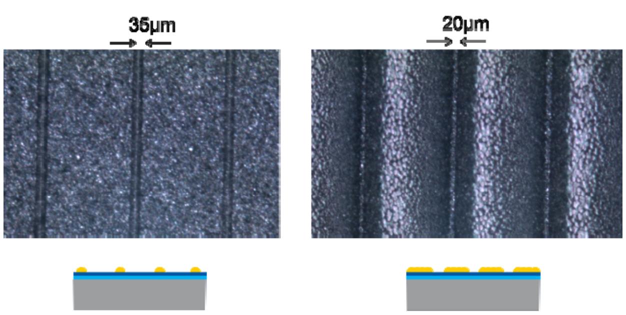


Figure 3, Positive (left) and negative (right) masking structures printed with the CrystalPoint print head, together with the feature size. The pictograms depict a solar cell with on top the masking ink for positive features (left) and negative features or opening (right).

With inkjet printing also dot patterns for rear-side patterning or honeycomb texturisation can be printed; for these patterns the negative feature size can even be reduced to <20µm. An example of a negative dot-pattern for rear-side patterning of iPERC cells is given in Figure 5.

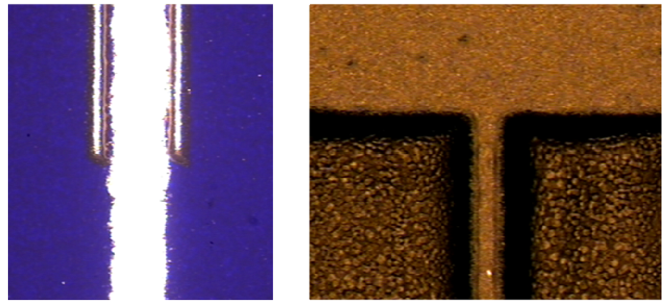


Figure 4, Inkjet printed plating barriers by printing of dikes around a screen printed seed layer (left) or full area covering of the negative H-pattern (right).

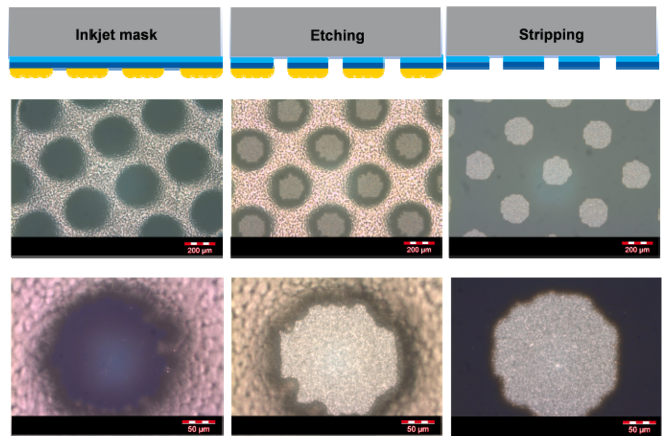


Figure 5, Negative dot-pattern for rear-side patterning after inkjet printing of the mask (left), after etching of the dielectric layers (middle) and after stripping of the masking ink (right). The pictograms indicate the wafer with on the backside the dielectric layers SiNx, SiOx or Al2O3. The masking ink is shown in yellow, covering the dielectric layers.

Discussion and conclusion

Inkjet printing has great potential to reduce the cost per watt peak of solar cells due to the low-cost non-contact deposition and the possibility of creating small feature sizes. Many applications for solar cell efficiency improvement have been shown on lab scale, however the transition from lab scale to mass production has been hampered by the availability of suitable high volume inkjet printing systems and skepticism on the reliability of inkjet printing. In 2011 OTB Solar started the development of the PiXDRO JETx, a high volume inkjet printing system for the solar cell industry. Self-diagnosing print heads with redundant printing strategies minimizes the amount of misprints. By carefully optimizing the print head angle, printing resolutions and application specific parameters the throughput can be maximized without any loss in quality.

Combining the self-diagnosing print heads from Océ Technologies with the automation and system integration from OTB Solar targets to demonstrate an inkjet printing system with high reliability and industrial throughput capable of printing structures, e.g. front-grid H-patterns or rear-side patterning for iPERC, with a drop placement accuracy of 7.5µm 3sigma. A variety of solar cell applications with a masking ink is being investigated, but also inks from other ink suppliers are being tested in the CrystalPoint print head.

The PiXDRO JETx not only offers PV manufacturers a great opportunity to adopt inkjet as a production technology, but it also offers a platform for future new applications in the industrial printing field.

Acknowledgements

The financial support from the Dutch Ministry of Economic Affairs, the Province of Limburg, the Province of Noord-Brabant and the Eindhoven Regional Government is gratefully acknowledged by the authors.

References

[1] C. Williams, Ink-jet printers go beyond paper, Physics World Vol. 19, pp. 24-29 (2006)

[2] H.P.Le, Progress and trends in ink-jet printing technology, Journal of Imaging Science and Technology Vol. 42, pp. 49-62 (1998)

[3] T. Lauermann, INSECT: An inline selective emitter concept with high efficiencies at competitive process costs improved with inkjet masking technology, Proceedings of the 24th European Photovoltaics Solar Energy Conference, Hamburg, Germany, pp. 1767-1770 (2009)

[4] J. Nievendick, An Industrially Applicable Honeycomb Texture, Proceedings of the 26th European Photovoltaics Solar Energy Conference, Hamburg, Germany, pp. 1722-1725 (2011)

[5] N. Borojevic, Inkjet texturing for high efficiency commercial silicon solar cells, Proceedings of the 23rd European Photovoltaics Solar Energy Conference, Valencia, Spain, pp. 1829 – 1832 (2008)

[6] M. Alemán, Industrially feasible front-side metallization based on ink-jet masking and nickel plating, Proceedings of the 23rd European Photovoltaics Solar Energy Conference, Valencia, Spain, pp. 1953-1956 (2008)

[7] A. Fallisch, SiNTO EWT silicon solar cells, Proceedings of the 25th European Photovoltaics Solar Energy Conference, Valencia, Spain, pp. 1991-1996 (2010)

[8] L. Gautero, Comparison of different rear contacting approaches for industrial PERC solar cells on mc-Si wafer, Proceedings of the 25th European Photovoltaics Solar Energy Conference, Valencia, Spain, pp. 1328-1331 (2010)

[9] N. Mingirulli, Hot-melt inkjet as masking technology for back-contacted cells, Proceedings of the 34th IEEE Photovoltaics Specialists Conference, Philadelphia, USA, pp. 001064-001068 (2009)

[10] M.J. Heller: DNA Microarray Technology: Devices, Systems, and Applications, Annual Review of Biomedical Engineering Vol. 4, pp. 129-153 (2002)

Author Biography

Joost Hermans received his MSc in applied physics from the Eindhoven University of Technology (2007). Since then he has worked as a process development engineer at OTB Solar B.V. in Eindhoven, the Netherlands. His work has focused on process optimization and head of process for the commissioning and optimization of production lines for silicon solar cells in Germany, China and India. Since 2011 he is developing and optimizing solar cell processes with inkjet printing technology.