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Non-Contact Printed Aluminum Metallization of Si Photovoltaic Devices

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***Abstract* — Alternative solution-based techniques such as aerosol jet printing offer the dual benefits of contactless pattern deposition and high material utilization. We have used aerosol jet printing to investigate non-contact printed Al metal ink as a replacement for screen printed Al back contacts on wafer Si solar cells. This particle-based ink can be prepared at high loadings of 60 weight % metal, which enables rapid deposition of 1 - 10 µm thick lines. Al lines printed on Si wafers and heated between 550 and 800 °C form low resistance contacts suitable for current extraction. The effectiveness of these printed Al back contacts has further been demonstrated by incorporating them into a series of 21 cm² crystalline Si solar cells that produced a champion power conversion efficiency of 13%.**

***Index Terms* — printing, aluminum, photovoltaic cells, silicon.**

I. Introduction

Rapid deposition of electrically active metal patterns on Si wafers can be accomplished by a variety of techniques in the large-scale manufacturing environment. Screen printing of metal contacts is the usual method of choice for solar cell production because it is relatively simple and reliable.[1] Cost savings efforts are driving Si wafers thinner, however, and contact metallization methods like screen printing must be replaced by non-contact methods in order to prevent a concurrent increase in broken wafers. Any non-contact technique that replaces screen printing in large-scale manufacturing must also be capable of depositing films and patterns very quickly (>2000 wafers/hour). Solution-based techniques such as spray pyrolysis and aerosol or ink jet printing satisfy both of these criteria. These large-area ink deposition tools have been incorporated into the Atmospheric Processing Platform (APP) at NREL,[2] along with complementary rapid thermal processing and characterization equipment. The APP provides an inert environment in which substrates up to 156 mm x 156 mm can be placed to deposit metal films and lines to act as front and back contacts for a wide variety of solar cells.

We have used the aerosol jet printing capability in the APP to investigate non-contact printed Al metal ink as a possible low-cost replacement for screen printed Al back contacts on wafer Si solar cells. The printed Al features have been heated over a wide temperature range to form low resistance contacts to Si that are suitable for extracting current from solar cells. The effectiveness of these printed Al back contacts has further been demonstrated by incorporating them into a series of 21 cm² Si solar cells that produced champion efficiencies of 13%.

II. Methods and Results

A. Aerosol jet printed Al lines

Aerosol jet printing is a very versatile technique that can handle inks that have a wide range of viscosities and components.[3] This is particularly advantageous for printing Applied Nanotech's particle-based Al ink, which can be prepared at high loadings of 60 weight % metal. This ink has been used to deposit lines with thicknesses in the range of 1 to 120 µm thick. As the 10 µm thick line in Figure 1 shows, these lines are just over 100 µm wide with very little overspray beyond the edges of the lines. The resistivities of such lines printed on glass are 10 µΩ-cm (~6 x bulk Al) after appropriate sintering.

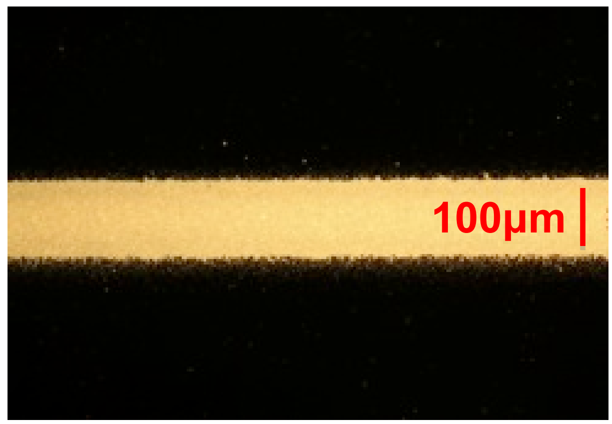

Figure 1. Top down image of an aerosol jet printed Al line.

B. Al – Si Contact Formation

Al lines printed on Si wafers have been heated over a wide temperature range of 550 – 800 °C to form low resistance ohmic contacts suitable for current extraction. This range includes temperatures above and below the Si-Al eutectic at 577 °C and the melting point of Al at 660 °C. Transfer length method patterns consisting of ten parallel lines with line-to-line spacings ranging from 700 µm to 4800 µm were printed on textured Si wafers and sintered for 4 min at each temperature to determine contact resistivities. These values fell from 80 mΩ-cm^2 at both 550 and 600 °C to 20 mΩ-cm^2 at 800 °C. Profiles of the sintered Al lines in Figure 2 show that

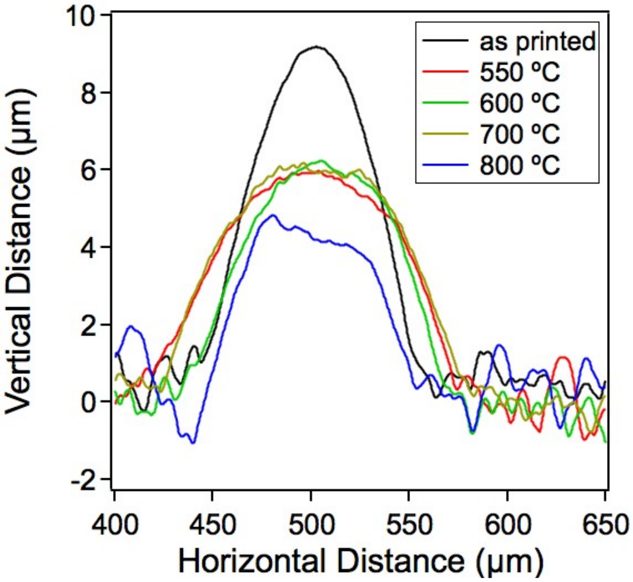

Figure 2. Profiles of Al lines printed on textured Si wafers and fired at the indicated temperatures.

all of the temperatures investigated cause the lines to compress significantly from the original 9 µm thick "as printed" line. This behavior is consistent with the Al melting and Al-Si alloying taking place in this temperature range.

C. Solar Cell Preparation and Performance

The effectiveness of aerosol jet printed Al back contacts has further been demonstrated by incorporating them into 21 cm^2 Si solar cells with Ag grids as the front contacts. Al lines

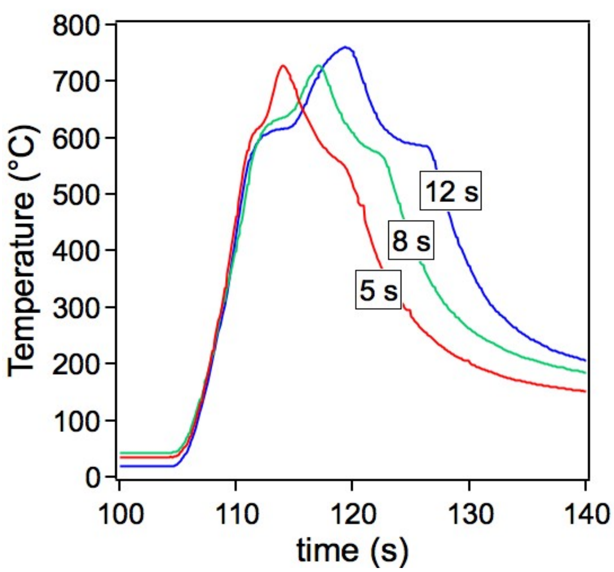

Figure 3. Firing profiles used to form Ag front contacts and Al back contacts to Si solar cells. Labels indicate the length of time above 600 °C.

or pads were printed on the back of Si wafers after commercial Ag paste was screen printed on the SiN_x anti-reflective coating (ARC) on the opposite side. The cells were then fired using a rapid thermal processor to diffuse Al into the back surface of the wafers and burn the Ag paste through the ARC on the front surface.

Co-firing two different metals simultaneously to form useful contacts to both sides of a wafer requires careful consideration of the interaction of both metals with Si. Burning through the ARC also necessitates the inclusion of an oxide-based frit in the Ag paste,[4] which further narrows the processing window. The wide temperature range established for making good electrical contact to Si with non-contact printed Al ink allowed us to focus on finding appropriate firing conditions for the Ag paste. Between 300 and 600 °C the organic binding agents that boost the Ag paste's viscosity will typically burn off as long as there is sufficient oxygen present. Then a short spike into the 700 – 800 °C range drives the frit-SiN_x burn through reaction. Figure 3 shows three of the profiles used to test the effect of the amount of time a wafer spent above 600 °C on the final cell performance. The peak temperature was also varied.

Figure 4 provides a summary of the efficiencies of cells fired for three different times above 600 °C. There is a clear

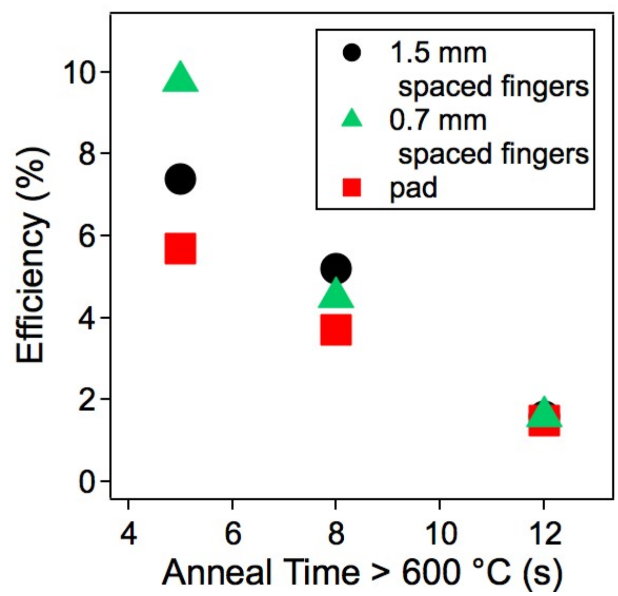

Figure 4. The efficiencies of solar cells heated for different times above 600 °C.

trend toward higher efficiency with shorter firing time, which is driven by a concurrent decrease in the series resistance of the cells. Longer firing times likely cause an increase in series resistance due the reaction of the oxide frit and the oxygen atmosphere with the Si wafer to form some SiO_x. Peak firing temperature also appears to play a role in device performance, as demonstrated by the higher efficiencies of cells fired at 760

°C than those that only reached 730 °C. In this case, the additional activation energy from the higher temperature may drive the burn through reaction faster.

In addition to the firing optimization studies, we also evaluated the impact of the geometry of the Al back contact on the performance of the solar cells. The aerosol jet printer is designed to print straight lines, so fingers were printed across the back of the wafers with either 1.5 or 0.7 mm between them. Overlapping lines were also printed on other cells to form continuous pads. The efficiencies of the cells increased as the space between lines decreased, which is the expected trend with increasing Al coverage on the back of the cell. The efficiencies of the pads decreased again, however (see the 5 s series of cells in Figure 4). This unexpected result may be due to cracking in the pads as the Al contracted during firing, while the additional space around the fingers provided less destructive routes to stress relief during the heating process. Cracks in the pads were easily visible to the eye after firing.

This hypothesis was confirmed by preparing a second series of cells using a different Ag paste and slightly different Al geometries. In addition to full Al pads and 0.7 mm spaced fingers, crossed fingers were printed by repeating the 0.7 mm finger pattern after rotating the original fingers 90°. These cells were fired by rapid thermal processing as described above. Fig. 5 shows the efficiencies of these cells increasing with increasing Al coverage of the back surface of the cell before dropping again when the entire surface is covered with the pad.

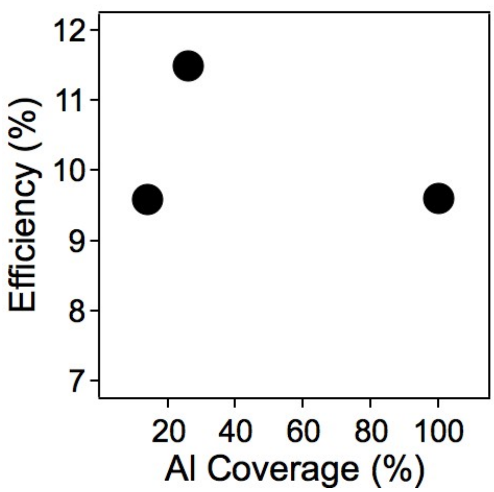

Figure 5. The efficiencies of solar cells prepared with different Al back contact geometries.

III. Conclusion

We have demonstrated non-contact printed Al pads and patterns on Si wafers that can be heated over a wide temperature range to form low resistance contacts suitable for extracting photo-generated current from Si solar cells. The effectiveness of these printed Al back contacts has further been demonstrated by incorporating them into 21 cm^2 crystalline Si solar cells that produced champion efficiencies of 13%. These promising results demonstrate the potential for non-contact printed Al to contribute to the fabrication of low-cost photovoltaic devices.

Acknowledgement

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