MONOLITHIC SERIES INTERCONNECTION FOR THIN-FILM SILICON SOLAR CELLS ON STEEL FOIL

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Roll-to-roll production facilitates flexible PV modules and a significant decrease of production costs for thin-film silicon solar cells. However, no standard processes for monolithic series interconnection on foil substrates are readily available. ECN is currently developing the technology and setting up a pilot line for the production of single junction and tandem solar cells based on microcrystalline and amorphous silicon on steel foil substrates. To allow monolithic series interconnection on these electrically conducting substrates, an insulating layer is required. In the presented module concept, first all layers of the solar cell are deposited, and after that series interconnection is realized by three depth selective laser scribes which are filled by insulating and electrically conductive inks.
In this paper, we present the current status of development for all key technologies required for the presented module concept: comprising a pinhole free insulating layer, an embossing process for this layer to apply light trapping textures on sub-micrometer scale, depth selective laser scribing by solid state YAG lasers, and screen printing pastes and processes for insulating and conductive inks curable at low temperature. First test samples have demonstrated the feasibility of the depth selective laser scribing and electrical series interconnection with the developed screen printing processes. Interconnection losses below 10% with respect to individual cells are anticipated when combining the presented processes for actual fabrication of monolithically interconnected thin-film silicon solar cells on steel foil.

Keywords: roll-to-roll processing, laser scribing, interconnection

1 INTRODUCTION

Roll-to-roll production facilitates flexible PV modules and a significant decrease of production cost for thin-film silicon solar cells. However, in contrast to more conventional glass based technology working with pin cells [1], no standard processes for monolithic series interconnection of nip cells on opaque foil substrates are readily available. ECN is currently developing the technology and setting up a pilot line for the production of single junction and tandem solar cells based on microcrystalline and amorphous silicon on steel foil substrates. To allow monolithic series interconnection on these electrically conducting substrates, an insulating layer is required. In the presented module concept (see Figure 1), first all layers of the solar cell are deposited, and after that series interconnection is realized by three depth selective laser scribes, (indicated as P1, P2, and P3) which are filled by insulating and electrically conductive inks.

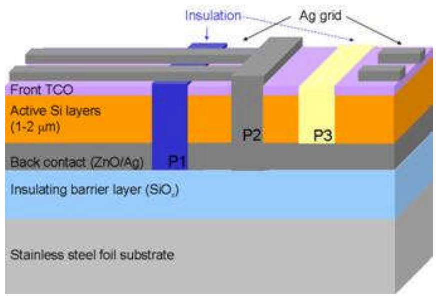

Figure 1. Module concept for monolithic series interconnection of thin-film silicon solar cells on electrically insulated steel foil.

Therefore, compared to widely applied interconnection schemes of thin-film silicon pin cells on glass/TCO based superstrates, the substrate concept presented here requires three key technologies:

- Pinhole free insulation layer with embossed submicron textures for light trapping
- Depth selective laser scribing
- Screen printing of low-temperature curing silver and insulating pastes

In this contribution the developed materials and processes are described, and the current status of development at ECN is presented. The roll-to-roll PECVD of amorphous and microcrystalline silicon by linear RF and microwave sources has been described previously [2], and first solar cells prepared in the FLEXICOAT300 system are presented at this conference [3].

2 EXPERIMENTAL

The insulating layer consists of a thermally curing SiO_x-polymer sol-gel coating that can by applied by either spray coating or roll coating. After application, the layer is dried for a short period of time to such an extent that the coating is dust-dry but still is plastically deformable. At this point, a texture can be applied to the sol-gel layer by embossing. The texture of a metal master is transferred by applying pressure in a hydraulic press with heated anvils, resulting in the inverse of the original morphology being stamped into the coating. In order to verify the insulating properties, resistance and break-down voltage were measured on both flat and textured layers at voltages of 100 up to 1000 V on surface areas of 4×4 mm^2 and 10×10 mm^2.

For the depth selective laser scribing, ns pulsed YAG lasers with the fundamental, second and third harmonic wavelengths of 1064, 532 and 355 nm , respectively, have been applied. All scribes were made with the substrates fixed and the laser beam scanned over the sample with a galvo head. The laser scribes have been characterized by optical, confocal and electron microscopy, the latter accompanied by EDX analysis.

An Ekra batch type screen printer has been used for the experiments with low-temperature curing silver and insulating inks. The materials were printed on glass and TCO surfaces, and for the curing a belt furnace and a box oven were available. Line and insulation resistances were measured with a Keithley source-measure unit in 4-point probe configuration, mainly to eliminate the influence of the resistance of the probe cables. The height and width of the prints have been determined by a stylus step profiler and optical microscopy, respectively.

3 RESULTS AND DISCUSSION

3.1 Pinhole free insulating barrier layer and embossing of light trapping structures

A pinhole free insulating layer is the prerequisite to allow monolithic series interconnection on a conductive steel foil substrate. The chosen material for the insulating layer, a wet-chemically applied SiO_x-polymer, combines several attractive properties. Besides the low material cost, it can be applied on large scale by cheap, non-vacuum roll-to-roll coating processes. Breakdown voltages exceeding 1000 V have been achieved, and pinhole free samples, prepared by spraying on A4 size, and by roll coating on 30 cm wide and > 100 m long foils, have been obtained. Figure 2 shows a uniform layer applied on a 30 cm wide steel foil obtained by reverse roll coating, an easily scalable roll-to-roll process.

Figure 2. The 30 cm wide steel foil with an insulating SiO_x barrier layer applied by roll-coating.

In addition to the insulating properties, two important morphological aspects of the layer for the subsequent deposition of nip solar cells can be utilized. On the one hand, the layer will even out irregularities and potential spikes at the surface of the steel foil, which may otherwise cause shunting of the solar cell. On the other hand, the layer can be textured by embossing techniques to create light scattering interfaces in the solar cell structures required for advanced light trapping [4]. Figure 3 shows such a sample after embossing a regular grating structure.

A comparable periodic structure consisting of a mixture of submicron grooves was used to test the electrical insulation of textured barrier layers with various feature sizes in one experiment. The flat reference sample was part of the same 10 by 10 cm^2 piece of coated foil, in order to cancel out any differences in layer properties between barrier layer depositions. Table I shows the average breakdown voltage and resistance values. Although texturing the foil reduces the resistance of the layer typically by a factor 4, the breakdown voltage remains higher than 1000 V. Thus, the insulating properties remain well within the specifications for application in the ECN solar cell concept.

Figure 3. Regular grating structure embossed into the insulating barrier layer, efficiently dispersing the light. The observed rainbow colors are due to dispersion, demonstrating the successful replication of the master into the insulating layer

Table I. Resistances R_{100V} and R_{500V} measured at 100 and 500 V DC, respectively, and breakdown voltage of flat and textured insulating barrier layers for 0.16 cm^2 and 1 cm^2 contact pads.

	$R_{100\,V}$ (GΩ)	$R_{500\,V}$ (GΩ)	$V_{breakdown}$ (V)
Flat, 0.16 cm²	165	93	>1000
Flat, 1 cm²	89	33	>1000
Textured, 0.16 cm²	40	20	>1000
Textured, 1 cm²	10	4	>1000
Required, 0.16 cm²		6-30	>1000
Required, 1 cm²		1-5	>1000

3.2 Depth selective laser scribing

Several laser parameter combinations (pump diode current, pulse repetition rate, scan speed) have been found to make scribes that meet the requirements of the interconnection concept sketched in Figure 1. It turned out that the pulse overlap should be small to prevent negative side effects such as cracks, warping at the scribe walls, or occasional damage to the underlying layer. The laser fluence should be adapted such that approximately the desired depth is reached in a single shot.

The function of the P1 scribe is to separate adjacent cells which will be series connected in the next steps. Therefore, complete cells including the rear contacts should be fully isolated from each other, but the underlying insulating layer should not be damaged during the laser scribing. In first instance, we concentrated on test samples consisting only of ZnO/Ag rear contacts on top of the insulating layer and obtained an isolation > 20 MΩ for a scribe length of a few cm.

In the next step, we investigated scribing of the complete layer stack including the silicon layers. Figure 4 shows the confocal microscopy image for this laser scribe, clearly demonstrating that the silicon and rear contact layers are removed over the width of the scribe. Also important is the fact that the SiO_x layer still has a very flat surface after laser scribing, indicating that there is no significant damage to this layer. This is confirmed by a closer analysis of the confocal microscopy results, see the right part of Figure 4. The confocal microscope actually finds a strong signal for all reflecting interfaces that are illuminated during the scan. As the SiO_x layer is transparent, the microscope measures a high intensity of reflected light at two different heights, corresponding to the surface of the steel substrate and the surface of the insulating layer. The appearance of these two peaks confirms the complete removal of the non-transparent rear contact. The distance between the peaks indicates the thickness of the insulating layer.

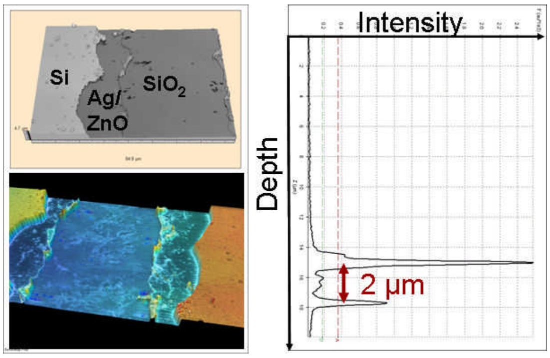

Figure 4. Confocal microscopy analysis of the P1 laser scribe.

The laser scribe P2, necessary for the connection of the front contact of one cell to the rear contact of the adjacent cell has also been achieved, see Figure 5. This scribe should remove the front TCO and the silicon layers, but leave the ZnO/Ag rear contact unaffected. This is confirmed by the appearance of only one peak in the confocal microscopy analysis (not shown), indicating that there is still a non-transparent layer present. EDX analysis indicated that there is probably no damage to the rear contact at all: The ZnO layer on top of the Ag is still present.

These same scribing parameters can also be used for the third scribe P3, which has to prevent lateral conductance by the front TCO and doped silicon layers.

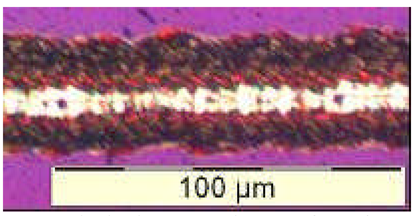

Figure 5. Optical microscopy image of a P2/P3 scribe.

3.3 Screen printing of low-temperature curing silver

One major challenge in the field of screen printing for the presented module interconnection concept is the development of materials which can be cured at sufficiently low temperatures below 200 °C. This means a serious restriction, especially for the electrically conductive silver pastes, compared to the commonly applied pastes for crystalline silicon wafer based solar cells, where during a high-temperature curing step all organic compounds of the pastes are burnt and bulk metallic silver is formed through sintering. In contrast, for the low-temperature curing pastes, one has to rely on electrical conduction through percolation between nanometer and/or micrometer sized silver particles embedded within a non-conductive matrix. We have tested several low-temperature curing silver pastes, and optimized the screens and printing parameters to achieve narrow and high lines which will result in lowest series resistance and shadowing losses for the current-collecting grid fingers in the presented module concept.

Combining the appropriate screens and pastes, 50 µm narrow silver lines with sheet resistances below 25 mΩ / square have been obtained. Upcoming paste materials containing silver nano-particles have shown even better performance. Figure 6 shows the achieved sheet resistance values of the printed lines for polymeric and nano-particle based silver pastes cured below 200ºC. Besides the low absolute level of these resistance values, an important achievement was to maintain the low sheet resistance of wide lines also for features as narrow as 50 µm, without suffering from line interruptions or height limitations often observed in fine line printing.

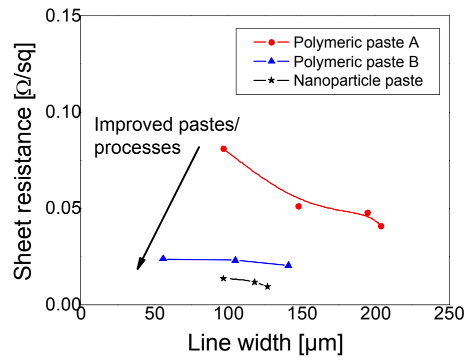

Figure 6. Sheet resistance of narrow low-temperature curing silver lines

3.4 Screen printing of insulating paste

The insulating paste used to fill the P1 scribe has been tested in the configuration sketched in Figure 7, allowing a direct assessment of the insulating properties in vertical direction as required in the ECN module concept.

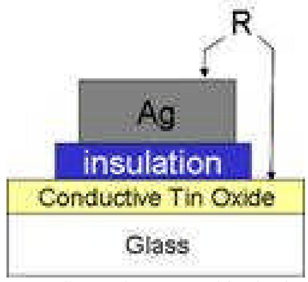

Figure 7. Test configuration to verify the isolation of the screen printing paste used for filling the P1 scribe.

The material has to be pinhole free to prevent shunting in the P1 scribe due to the silver printed over the insulation. Besides these insulation properties, the height of the printed paste should not be too large in order to prevent interruption of the Ag interconnection and/or collecting fingers.

Excellent results have been obtained by screen printing a single layer which is only 4 to 5 µm thin, and results in a high resistance value of 10 MΩcm^2, thus comfortably meeting the required specifications.

4. CONCLUSIONS

The three key supporting technologies for monolithic series interconnection of thin-film silicon solar cells in nip configuration on steel foil have been developed.

As pinhole free insulating barrier layer an SiO_x-polymer can be applied by roll-to-roll coating. Submicron textures have been successfully embossed into this layer for light trapping without significantly sacrificing the insulating properties. Depth selective laser scribes have been demonstrated using ns pulsed YAG lasers with wavelengths of 355, 532, and 1064 nm. Finally, low-temperature curing pastes and optimized screen printing processes are available for printing shallow isolation into the P1 scribe, and to obtain narrow, highly conductive Ag lines with high aspect ratio for low-resistive current collection and series connection.

First test samples have demonstrated the feasibility of the selected screen printing pastes for series connection with low losses. Currently we are working towards the integration of all the presented steps to realize monolithic series interconnection of thin-film silicon nip cells on electrically insulated steel foil by laser scribing and screen printing.

Based on simulations published in [5] series interconnection losses well below 10% with respect to individual cells are anticipated.

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