

PECVD SHADOW MASK DEPOSITION OF AMORPHOUS SILICON – A SHORTCUT TO LOCAL PASSIVATING CONTACTS

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ABSTRACT: We develop and investigate shadow masks for the local PECVD deposition of amorphous Si (a-Si) fingers to be applied as local poly-crystalline Si (poly-Si) passivating contacts in the industrial fabrication of novel solar cell concepts such as TOPCon, PERC+POLO and POLO-IBC. We first apply a nickel-based test mask with varying mask opening widths and demonstrate narrow poly-Si fingers down to 70 μm width suitable for application on the front side of solar cells. However, the aspect ratio of the finger opening width and the mask thickness is limiting the deposition rate of as-deposited a-Si fingers. Using a glass-based mask, we verify that the a-Si finger position is identical to the mask layout over the size of a M2 silicon wafer. The passivation quality of the n-type poly-Si is demonstrated on symmetrical lifetime samples using n-type Cz wafers, a thermal oxide interface, PECVD n-a-Si and a subsequent high-temperature anneal. We measure carrier lifetimes up to 7.78 ms corresponding to an implied V_{oc} up to 738 mV.

Keywords: local passivating contacts, PECVD deposition, shadow mask

1 INTRODUCTION

The solar cell industry has widely introduced the Passivated Emitter and Rear Cell (PERC) concept into manufacturing with conversion efficiencies around 22.5% [1]. As a next solar cell technology, passivating contacts based on poly-Si are intensively evaluated for the front and / or rear side with a highest simulated efficiency potential around 25% for two-sided poly-Si contacts [2]. Due to its high light absorption, the poly-Si has to be absent between the metal fingers when applied to the cells front side. Likewise, structuring is required using poly-Si on the rear side of IBC solar cells. So far, the approaches to structure poly-Si involve multiple process steps including a full-area poly-Si deposition, masking and etching which results in high expenses and hence have not yet been applied in mass production [3].

In this paper, we evaluate a potentially cost-effective and lean manufacturing of structured poly-Si fingers by shadow-masked PECVD deposition. We use several shadow mask designs and deposit in-situ phosphorous-doped amorphous silicon (n-a-Si) fingers by PECVD, placing the shadow mask between the plasma and the Si wafer. In literature, PECVD shadow masks were used to deposit about 200 μm wide a-Si fingers on the rear of IBC heterojunction solar cells [4, 5]. Recently, we published PECVD shadow mask-deposited a-Si fingers as narrow as 70 μm [6], which we present here again. Additionally, we evaluate the position accuracy of the a-Si fingers across the M2-wafer with respect to the corresponding shadow mask layout. Furthermore, we apply our PECVD deposited n-a-Si on top of a thin SiO_x layer and crystallize the stack to n-type poly-Si on oxide (POLO) in a subsequent inert high temperature step. We analyze the passivation quality of the POLO-stack by quasi-steady state photo-conductance (QSSPC) measurements.

2 LAB-TYPE NICKEL SHADOW MASK

The local deposition of a-Si was first evaluated using a lab-type nickel shadow mask (Veco Precision). The

layout features six parallel line openings with 40 mm opening length and varying opening widths of 40 μm , 60 μm , 80 μm , 120 μm , 150 μm and 200 μm . The line openings are separated by 1.2 mm. Multiple groups of line openings are distributed over a M2-wafer sized nickel foil. The shadow mask exhibits μm -precise line openings and therefore, allows detailed studies of deposited finger geometries.

We apply the nickel shadow mask within a PECVD tool (Von Ardenne CS 400P, described in Ref. 7) using an inductively coupled plasma source (ICP), SiH_4 and H_2 to deposit intrinsic a-Si fingers through the shadow mask openings on top of polished float zone (FZ) Si wafers. The resulting a-Si finger geometries are investigated by optical profilometry (Wyko NT9100, Veeco Instruments). Figure 1 shows the height profile of a deposited a-Si finger corresponding to a 40 μm mask opening width. The a-Si finger is roughly 40 μm wide and up to 250 nm thick indicating a high accuracy of the local deposition process. However, both the Si wafer surface and the a-Si finger surface feature a surface roughness of around 100 nm which originates from the float zone wafer and hinders an exact evaluation of the finger edges.

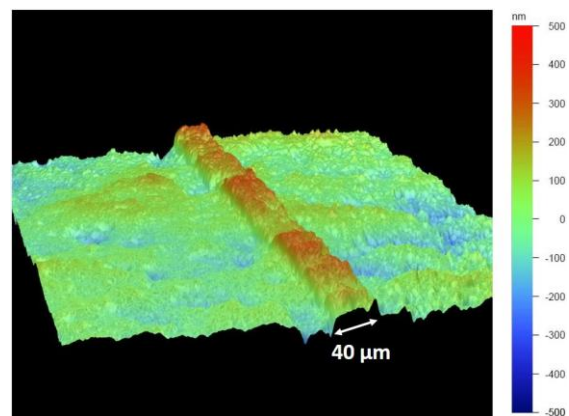


Figure 1: Profilometer image of a 250 nm high and 40 μm narrow a-Si finger deposited by PECVD through a nickel shadow mask on top of a polished FZ Si wafer.

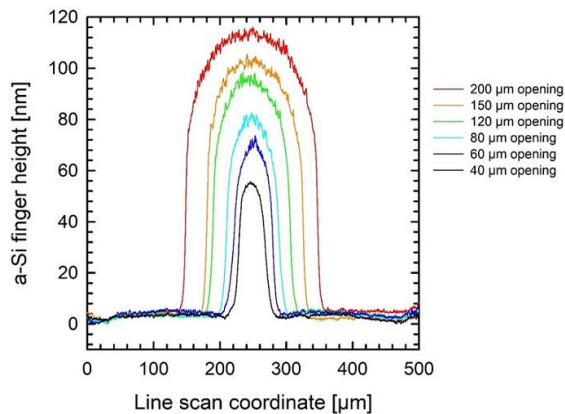


Figure 2: Line scans of a-Si fingers deposited on a nm-flat glass substrate through a nickel shadow mask with different line openings ranging from 40 μm to 200 μm opening widths revealing minimum a-Si finger widths of 70 μm which are suitable for the solar cells front side.

For an accurate and detailed analysis of the influence of the mask openings on the a-Si finger geometries, the nickel shadow mask is placed on top of a glass substrate, which exhibits surface roughness below 5 nm. An ICP plasma with SiH_4 gas flow of 40 sccm and a H_2 gas flow of 160 sccm is applied for 90 seconds which results in around 120 nm thick a-Si layers. The resulting finger profiles are investigated using a mechanical profilometer (Dektak 150, Veeco Instruments). The corresponding line scans are shown in Figure 2 for different mask opening widths. We observe that both the finger width and height decreases with decreasing mask opening width. For each mask opening width, we determine the a-Si finger width at two different finger heights, namely the finger width at half maximum height (full width at half maximum = FWHM) as well as the finger width at the bottom close to the substrate. As presented in Figure 3a), the bottom finger widths are 20 to 30 μm wider than the mask opening widths revealing some parasitic deposition of a-Si below the shadow mask. This parasitic deposition is about 5-7 nm thick. The a-Si finger width at FWHM is identical to the mask opening width. Hence, a mask opening of 40 μm enables a-Si finger widths of 70 μm (considering bottom width), which is sufficiently narrow to be implemented on the front side e.g. in PERC+POLO cells or TOPCon cells as outlined in Ref. 6.

As evident from in Figure 3b), the a-Si finger height decreases from 110 nm for 200 μm mask opening to 55 nm for 40 μm mask opening corresponding to a reduction of material throughput of approximately 50%, most probably triggered by parasitic deposition of a-Si on the finger opening sidewalls. In general, finger heights around 100 nm are required in order to avoid firing-through of the screen printed Ag paste in solar cell front side application. The a-Si finger height can be controlled by adjusting deposition times or by increasing the deposition rate of the ICP process, see e.g. Figure 1 with 250 nm finger height. Furthermore, the material throughput is further improved by increasing the aspect ratio or i.e. by reducing the mask thickness.

3 INDUSTRIAL GLASS SHADOW MASK

The application of nickel shadow masks for industrial processes comes along with limiting disadvantages. In

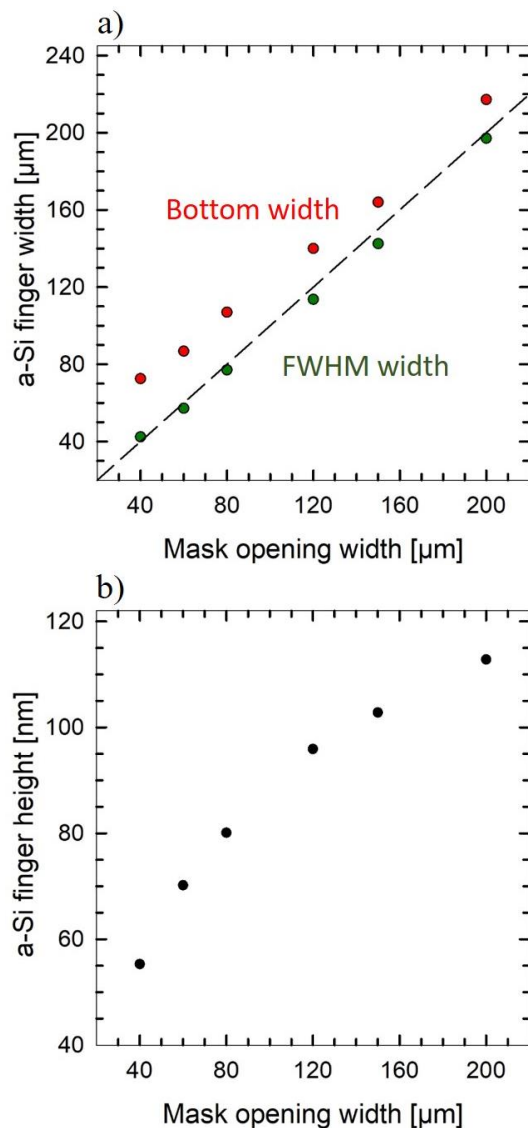


Figure 3: Detailed analysis of the a-Si finger width and height based on the line scans in Figure 2. a) displays measured a-Si finger widths at half-maximum finger height (FWHM width) and at the finger bottom (Bottom width) revealing a ~20 μm wide parasitic a-Si deposition below the mask. b) The a-Si finger height decreases with narrower mask openings. With 40 μm mask opening, 70 μm narrow and 55 nm to 250 nm (see Figure 1) thick a-Si fingers have been obtained.

particular, nickel might contaminate the surface of the silicon wafer during PECVD deposition. Moreover, the thin Ni masks are very flexible which makes it challenging to integrate the shadow masks in industrial-type PECVD carriers.

We address these issues by changing the shadow mask material from nickel to glass due to the following reasons: 1) cleaned glass fulfills the high-purity requirements of silicon solar cells, 2) sufficiently thick glass sheets are mechanically very stable, 3) the thermal expansion coefficient of glass can be matched to silicon.

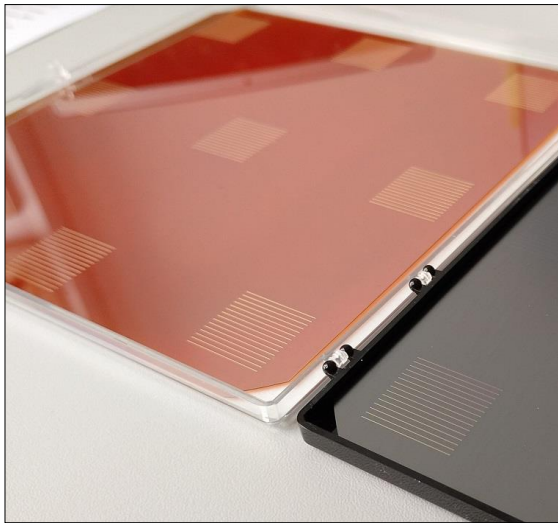


Figure 4: Photograph of the glass shadow mask (orange), showing the layout with 9 groups of 15 line openings after PECVD a-Si deposition. On the right side, a grey silicon wafer with 15 a-Si fingers can be observed.

A first glass-based shadow mask is manufactured by LPKF applying their novel Laser-Induced Deep Etching (LIDE) glass structuring technology. The LIDE process performs a μm -precise local laser-induced modification of the glass sheet followed by a wet-chemical etching step which selectively removes the laser-processed glass.

As displayed in Figure 4, the glass shadow mask features 9 fields with 15 line openings each, distributed over the full area of a M2-wafer. All line openings are $100\ \mu\text{m}$ wide with an opening length of $20\ \text{mm}$. We use a capacitively coupled plasma source (CCP) to locally deposit in-situ doped n-a-Si through the glass shadow mask on top of oxidized silicon wafers. The silicon wafers feature a $50\ \text{nm}$ thick oxide to ensure a good optical contrast between the silicon wafer and the deposited a-Si fingers. The as-deposited a-Si fingers were characterized using a Vertex 311 Multisensor microscope (Micro-Vu Corporation). We determine the lateral xy-coordinates and

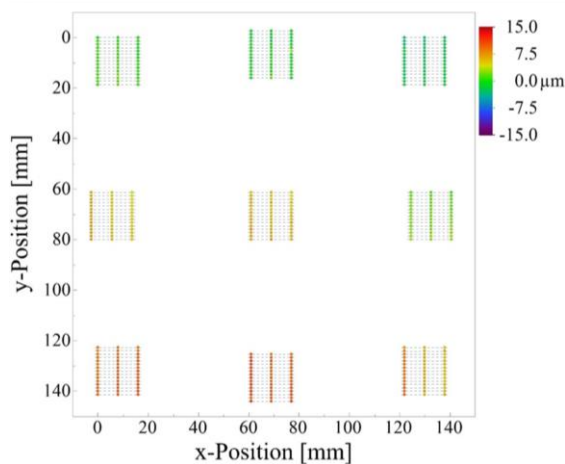


Figure 5: The color map displays the offset in y-direction of the a-Si fingers deposited on a silicon wafer in comparison to the position of the finger opening in the glass shadow mask. The maximum offset is below $13\ \mu\text{m}$. The dotted, grey lines indicate the position of the finger openings in the shadow mask layout.

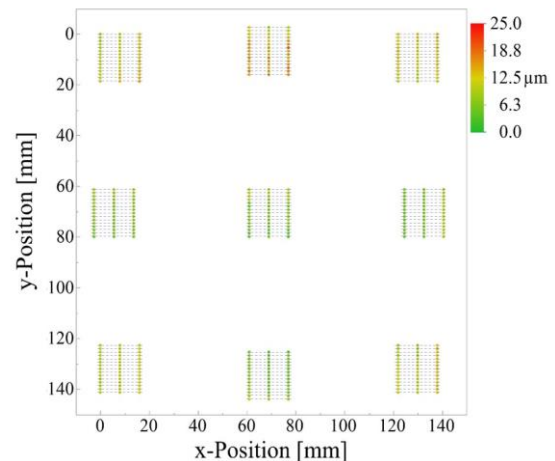


Figure 6: The color map shows the difference between the deposited a-Si finger widths and the corresponding finger opening widths in the glass shadow mask as a function of the measured xy-coordinates. The mean finger opening width amounts to $102.9\ \mu\text{m}$. The dotted, grey lines indicate the position of the finger openings in the shadow mask layout.

the width of both the finger openings in the glass shadow mask and the deposited a-Si fingers on the silicon wafer. From the measured xy-coordinates we calculate the offset between the mask opening position and the corresponding a-Si finger position on the wafer.

Figure 5 displays the offset in y-direction of the a-Si finger position as color coded circles overlaid on top of the corresponding x and y measurement coordinates. The topmost left finger was defined as the origin of coordinates for the shadow mask, i.e. the finger openings, and the deposited fingers, respectively. Each finger was measured at three x-positions. The color map reveals that the offset of the a-Si finger position with respect to the shadow mask opening position increases with increasing distance from the origin in y-direction. The maximum offset accounts to $12.6 \pm 3.4\ \mu\text{m}$.

In industrial solar cell manufacturing, the screen print of the Ag finger contacts has to be aligned to the poly-Si fingers. Presently the Ag fingers exhibit a typical Ag finger width of around $40\ \mu\text{m}$. We consider an alignment tolerance of $20\ \mu\text{m}$ for the screen print and $20\ \mu\text{m}$ offset in xy-coordinates of the poly-Si fingers when deposited with a shadow mask. Consequently, a total poly-Si width of around $80\ \mu\text{m}$ is required to ensure that the Ag fingers are printed on top of the poly-Si fingers, which is compatible with the measured poly-Si widths.

Figure 6 shows the difference between the deposited a-Si finger widths and the measured opening widths in the glass shadow mask using the above-mentioned measurement routine. We determine a mean a-Si finger width of $112.9\ \mu\text{m}$ with a standard deviation of $6.1\ \mu\text{m}$ across the wafer. The glass shadow mask exhibits a mean finger opening width of $102.9\ \mu\text{m}$ and a standard deviation of $3.1\ \mu\text{m}$. Similar to the nickel shadow mask, the deposited a-Si fingers are in average $10\ \mu\text{m}$ wider as compared to the opening widths indicating a slight parasitic a-Si deposition below the glass mask. In summary, the a-Si fingers deposited through the glass shadow mask demonstrate an excellent position accuracy as well as very well matched a-Si finger width with respect to the mask layout.

4 PECVD n-POLY-SI PASSIVATION QUALITY

In addition to the shadow mask properties, we study the passivation quality of the PECVD deposited n-a-Si after crystallization to n-poly by thermal annealing. We use planar phosphorous-doped Cz silicon wafer with $2.8 \Omega\text{cm}$ resistivity which initially receive a phosphorous gettering step to improve the bulk lifetime. Afterwards, we remove the phosphorous emitter by a damage etch, clean the wafers and thermally grow a $\sim 1.7 \text{ nm}$ thin interfacial oxide. We deposit 100 nm n-a-Si by CCP PECVD without applying shadow masks on both wafer sides using 20 sccm SiH_4 , 50 sccm H_2 and 50 sccm PH_3 (3% in H_2). After an additional wet chemical cleaning, we expose the $\text{SiO}_x/\text{n-a-Si}$ stack to a 30 minute inert high-temperature anneal at 800°C . Subsequently, we measure the effective carrier lifetime with QSSPC (WCT-120, Sinton Instruments) and obtain carrier lifetimes up to 2.8 ms corresponding to an implied iV_{OC} up to 711 mV at 1 sun irradiation.

Hydrogen saturation of surface states at the Si/SiO_x interface is very important for high quality passivation and deteriorates during high temperature annealing due to hydrogen diffusion [9]. In order to restore the passivation quality, we perform a subsequent hydrogenation by SiN_y deposition and annealing in a forming gas atmosphere at 450°C for 30 minutes. A repeated lifetime measurement reveals that both the effective carrier lifetime and the iV_{OC} increase to 7.78 ms and 738 mV , respectively. Figure 7 displays the effective carrier lifetime versus the excess carrier density before and after the hydrogenation.

5 CONCLUSION

We successfully demonstrate the deposition of well-defined a-Si fingers with finger widths down to $70 \mu\text{m}$ using a lab-type nickel shadow mask. The finger opening widths were found to limit the deposition rate through the shadow mask openings. Furthermore, a glass-based shadow mask enables the local deposition across a full M2-sized Si wafer with excellent position and finger width accuracy with respect to the glass mask layout. The offset

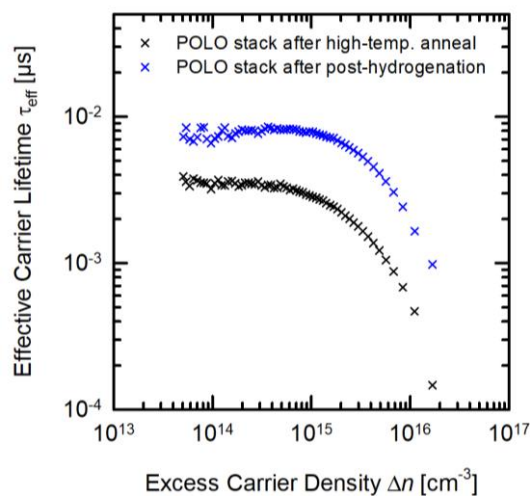


Figure 7: Effective carrier lifetime before and after hydrogenation of a symmetrical lifetime sample featuring a n-type Cz silicon wafer passivated by SiO_x and PECVD n-poly Si. The corresponding iV_{OC} at 1 sun irradiation are 711 mV and 738 mV , respectively.

of the a-Si finger position relative to the mask opening position is below $12.6 \mu\text{m}$. The a-Si fingers are in average $10 \mu\text{m}$ wider as compared to the $103 \mu\text{m}$ mask opening widths revealing a slight parasitic deposition below the mask. However, both the position accuracy as well as the finger widths accuracy are promising for future solar cell production applications of glass-based shadow masks.

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