Black silicon solar cells with black bus-bar strings

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Abstract — **We present the combination of black silicon texturing and blackened bus-bar strings as a potential method for obtaining all-black solar panels, while using conventional, front-contacted solar cells. Black silicon was realized by mask-less reactive ion etching resulting in total, average reflectance below 0.5% across a 156x156 mm^2 silicon wafer. Four different methods to obtain blackened bus-bar strings were compared with respect to reflectance, and two of these methods (i.e., oxidized copper and etched solder) were used to fabricate functional all-black solar 9-cell panels. The black bus-bars (e.g., by oxidized copper) have a reflectance below 3% in the entire visible wavelength range. The combination of black silicon cells and blackened bus-bars results in aesthetic, all-black panels based on conventional, front-contacted solar cells without compromising efficiency.**

I. Introduction

Nanoscale texturing of Si surfaces has been shown [1,2] to reduce the total weighted average optical reflectance to well below 1% over a broad range of wavelengths and incident angles. Compared to the typical front surface reflectance of ~2 and ~8%, from conventionally textured mono- [3] and multi-crystalline [4] Si solar cells, respectively, nanoscale texturing offers a potential for improved power conversion efficiency of Si solar cells due to reduced reflectance loss. Nanostructured Si surfaces suppress the reflectance of light from the surface due to the resulting graded refractive index at the Si-air interface. We use mask-less reactive ion etching (RIE) to produce nanostructured Si, also known as 'black silicon' [5, 6], applied as texturing for front-contacted Si solar cells.

Apart from maximizing the power conversion efficiency, there is commercial interest in and customer demand for aesthetic solar solutions and building-integrated solar cells and panels. We present a potential solution to this issue by combining black silicon texturing with blackened bus-bar strings in order to obtain an all-black panel, while using conventional, front-contacted Si cells.

II. Black Silicon

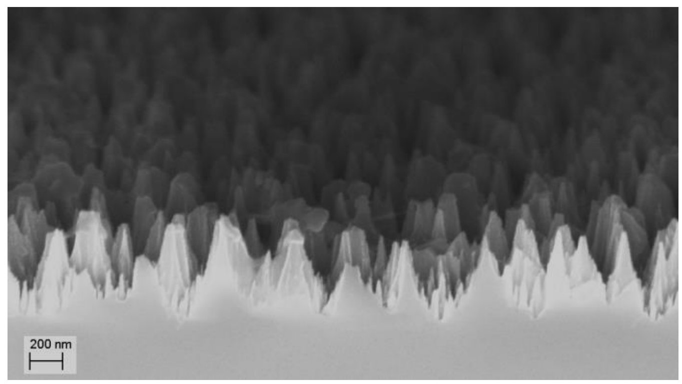

Figure 1: Scanning electron microscope image of the nanostructure topology resulting from mask-less reactive ion etching.

Black silicon was realized on 156x156 mm^2 p-type Czochralski (CZ) mono-crystalline Si wafers by mask-less reactive ion etching (RIE) in SF_6 and O_2 plasma at room temperature. Figure 1 shows a scanning electron microscope (SEM) image of the resulting nanostructure topology. The nanostructure topology consists of conical-like hillocks with average height of 300 nm and average spacing of 300 nm.

The RIE-textured Si wafers were passivated by hydrogenated silicon nitride (SiN_x:H) deposited by plasma-enhanced chemical vapor deposition (PECVD). Emitter diffusion was realized using $POCl_3$ as phosphorus dopant source prior to the deposition of the SiN_x:H AR coating in order to take into account the effect of emitter diffusion on the optical properties.

Normal incidence reflectance measurements of the RIE-textured Si surfaces were performed using a broadband light source (Mikropack DH-2000), an integrating sphere (Mikropack ISP-30-6-R), and a spectrometer (Ocean Optics QE65000, 300-1000 nm). The reference solar spectral irradiance for AM1.5G was used to calculate the total,

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average reflectance in the wavelength range from 300-1000 nm.

Since the graded refractive index of black Si is fundamentally different from that of conventionally textured or planar Si, it is not obvious, which thickness of SiN_x:H AR-coating is optimal for black Si. In order to investigate this the deposition time of the plasma enhanced chemical vapor deposition (PECVD) SiN_x:H deposition was varied in steps of 2 minutes from the 'standard' time of 6 minutes and 30 seconds to 12 minutes and 30 seconds. The reflectance was then measured for the different SiN_x:H thicknesses on RIE-textured Si wafers. The result is shown in Figure 2.

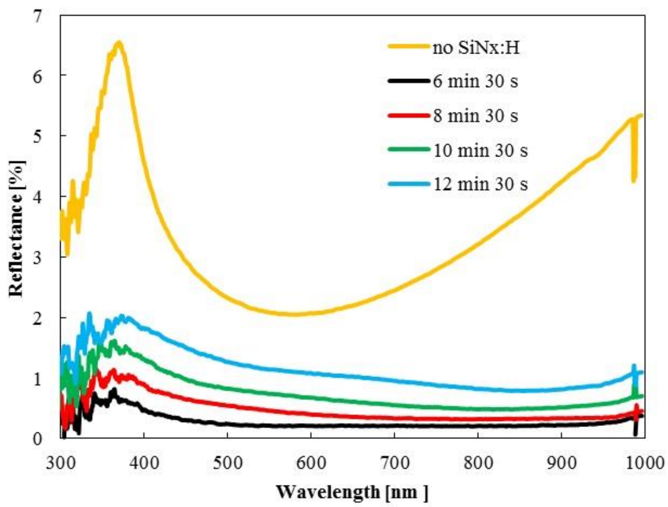

Figure 2: Measured total (diffuse+specular) reflectance of black Si with SiN_x:H AR-coating as a function of wavelength in the range 300-1000 nm for four different PECVD SiN_x:H deposition times representing four different SiN_x:H thicknesses.

Figure 2 shows that a PECVD SiN_x:H deposition time of 6 minutes and 30 seconds yields the lowest reflectance of the black Si surface. In general the SiN_x:H AR-coating reduces the reflectance of black Si. The deposition times are stated instead of the SiN_x:H thickness, since the exact thickness on black Si is not fully known due to the complicated surface morphology. On conventionally textured Si a 6 minutes and 30 seconds deposition yields a SiN_x:H thickness of ~ 60 nm. Due to the broadband anti-reflective properties of black Si the SiN_x:H thickness does not need to be optimized in the same way as for conventional texturing in terms of minimized reflectance at a certain wavelength. It seems from Figure 2 that the reflectance increases monotonically with SiN_x:H thickness in the thickness range investigated.

In order to quantify the spatial uniformity of RIE-texturing, the reflectance was measured at different positions on a 156x156 mm^2 CZ wafer textured by mask-less RIE after $POCl_3$ emitter diffusion and PECVD of SiN_x:H (6 min and 30 s). The total (diffuse + specular) reflectance was measured in the wavelength range 300-1000 nm and the integrated average reflectance is plotted as function of distance from the wafer center in Figure 3.

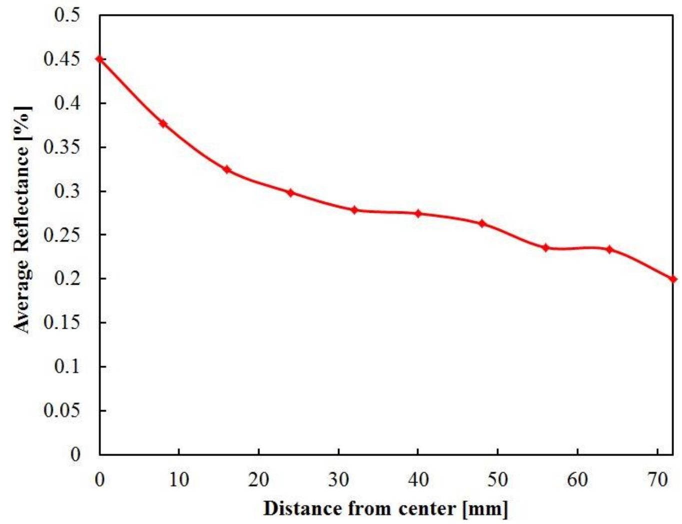

Figure 3: Measured total (diffuse + specular) reflectance of RIE-textured Si with SiN_x:H averaged over the wavelength range 300-1000 nm as function of the distance from the center of a 156x156 mm^2 CZ wafer.

Figure 3 shows that the integrated average reflectance is below 0.5% across the entire 156x156 mm^2 wafer. The average reflectance decreases towards the edge of the wafer, but even though the relative difference in reflectance from center to edge is significant, the absolute difference is on the order of 0.2% points. The deviation in reflectance across the wafer is probably due to the plasma chamber and wafer geometry.

III. BLACK BUS-BARS

Four different processes for blackening bus-bars were used. Nickel based coatings of NiZnS and NiCuCo alloys, respectively, were deposited directly on Cu bus-bar strings with soldering coating. Dark bus-bars were prepared by etching the surface of the bus-bars with a solution containing nitric acid and copper nitrate. Copper bus-bar strings with a black oxidized surface were created using a chemical oxidation process. The electroplating was conducted in a beaker with electrolytes containing sulfate salts and a nickel anode, a power supply and heater.

Reflection measurements on the bare and coated surfaces were performed using a spectrophotometer (Shimadzu 2600). Figure 4 shows the measured reflectance of the black coatings and bus-bars. Reflectance of the bus-bars with solder is high due to the bright metal surface, while the copper surface has a lower reflectance which increases above 600 nm, causing the red color of the Cu surface. All of the black coatings have significantly reduced reflectance. Etched bus-bars and NiCuCo have quite similar reflectance spectra. Both of them appear gray and have a higher reflectance, when compared with the other black surfaces, also, the reflectance of etched bus-bars and NiCuCo increase slightly towards longer wavelengths. The reflectance curve for NiZnS is quite flat and featureless with a very dark grey appearance.

Oxidized copper has the lowest reflectance, which increases slightly at longer wavelength; indicating that the surface color has a red element due to copper presence in coating or due to the copper substrate. In summary, the copper bus-bars with oxidized surfaces are the best match for black silicon because of the comparatively low reflectance.

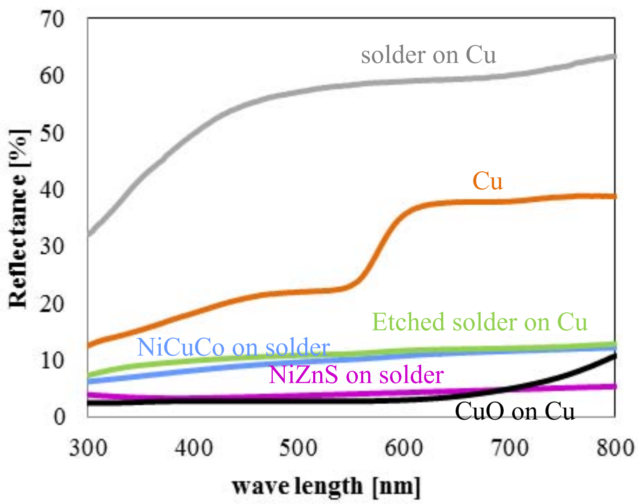

Figure 4: Measured reflectance as function of wavelength of bus-bars without (bare Cu, and Cu with solder) and with (NiCuCo, NiZnS, etched solder and CuO) black coatings.

IV. Complete Test Panel

Finally, the black CuO-coated and etched busbar strings were used to connect screen-printed black Si solar cells into 4- and 9-cell test panels. Figure 5 shows a photograph of one of the produced panels.

Figure 5: Photograph of a 4-cell panel based on screen-printed black Si solar cells and interconnected with black CuO-coated bus-bar strings.

Solar cells were fabricated from 156x156 mm^2 p-type CZ Si wafers using the following process steps:

1. Saw damage removal using an HF:HNO_3:CH_3COOH etchant mixture
2. Maskless RIE texturing
3. Diffusion of n-type emitter in a tube furnace using a $POCl_3$ source to obtain a sheet resistance of ~120 Ω/sq.
4. Deposition of SiN_x:H anti-reflection coating on the front surface by plasma enhanced chemical vapour deposition (PECVD)
5. Screen-printing and firing of front and rear metal contacts
6. Laser edge isolation

The formation of an n-type emitter, using $POCl_3$ as the phosphorous doping source, was carried out using a Tempress TS-8603 tube furnace at a temperature of 836-838 ºC for 37 minutes, followed by a 10 minutes drive-in at the same temperature. Hydrogenated amorphous silicon nitride (a-SiN_x:H) was deposited using an Oxford Instruments PlasmaLab System133 PECVD tool with silane, ammonia and nitrogen at a temperature of 400 ºC and a pressure of 800 mTorr for 6 minutes and 30 seconds. For the contact formation, an EKRA X5-STS semi-automatic screen-printing machine was used. The contacts were printed using Ag paste (DuPont PV18A) on the front and Al paste (Monocrystal PASE-1207) on the rear. The contacted cells were subsequently dried and co-fired in a belt furnace with temperatures in the range of 780-945°C and a belt speed of 520 cm/min. Edge isolation was performed by laser ablation using a J-1030-515-343 FS System from Oxford Lasers. A wavelength of 515 nm and a repetition rate of 50 kHz were used for the laser scribing. The final cells were cut in 100x100 mm^2 squares in the edge isolation.

The black Si solar cells have an average efficiency of ~16% before interconnection. A detailed description of the cell results will be published elsewhere; however, the cell performance is not the main focus of this work.

In order to verify the electrical properties of the black bus-bar strings, current-voltage characteristics of two differently interconnected 9-cell test panels were performed. We used conductive glue for the CuO-coated bus-bar strings, since soldering was not possible for the given batch of strings. For comparison the more reflective etched bus-bar strings were interconnected by soldering to similar black Si cells from the same batch. The resulting IV-measurements are shown in Figure 6.

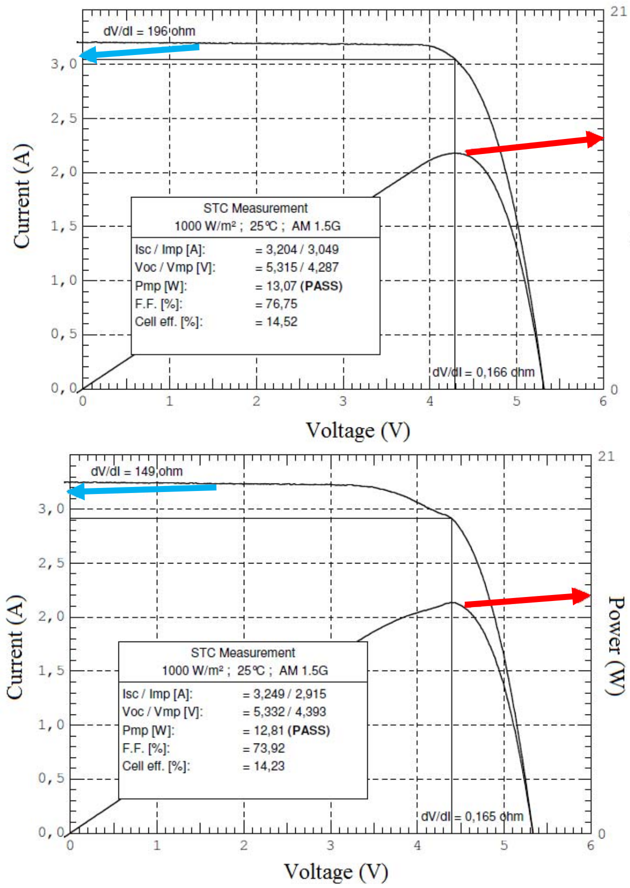

Figure 6: Current-voltage (I-V) and power measurement of two 9-cell test panels based on black Si solar cells interconnected with (top) soldered etched bus-bar strings and (bottom) glued CuO coated strings.

Figure 6 shows that both glued CuO- and soldered etched bus-bar strings gives acceptable fill factors of ~ 0.74 and ~ 0.77, respectively. Based on the calculated resistances on both sides of the maximum power point, the difference does not seem to be due to series resistance, but rather a slightly lower shunt resistance of the glued module and the non-ideal 'kink' on the I-V curve close to the maximum power point of the glued module. The detailed reason for these differences needs to be investigated further in the future. However, these data suggest that the soldered etched bus-bar strings yield higher fill factor, presumably due to the soldering rather than the effect of the coating itself. On the other hand, Figure 4 shows that the CuO-coated strings result in the lowest reflectance of the tested coatings. Thus the ideal solution would probably be CuO-coated bus-bar strings interconnected by soldering or an improved gluing process. This will be investigated further in future work.

V. Conclusion

We have presented the combination of black silicon texturing and blackened bus-bar strings as a potential method for obtaining all-black solar panels, while using conventional, front-contacted silicon solar cells. Black silicon was realized by mask-less reactive ion etching with a resulting total, average reflectance below 0.5% in the wavelength range 300-1000 nm across a 156x156 mm^2 silicon wafer. The absolute difference in reflectance from center to edge of the 156x156 mm^2 silicon wafer was on the order of 0.2% points. Black bus-bar strings were realized by oxidized copper resulting in reflectance below 3% in the entire visible wavelength range. Two types of black bus-bar strings, CuO coated and etched solder bus-bar, were tested in 9-cell panels based on screen-printed black Si solar cells. Soldered etched bus-bar strings resulted in fill factor of ~ 0.77 and glued CuO-coated strings resulted in fill factor of ~ 0.74. The combination of these two technologies, black silicon and black bus-bars, results in aesthetic, all-black panels based on conventional, front-contacted silicon solar cells without compromising efficiency.

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