BACK CONTACT MONOCRYSTALLINE THIN-FILM SILICON SOLAR CELLS FROM THE POROUS SILICON PROCESS

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ABSTRACT

We develop a back contact monocrystalline thin-film silicon solar cell using the porous silicon process. Laser processes are applied for all structuring steps. Thus no photolithography or other masking techniques are required. A single evaporation step is used to metallize the cell. Laser scribing is used for contact separation. The cell has a planar front surface, an area of 79.2 cm^2 and a cell thickness of 30 µm. We reach an efficiency of 13.5 %. The open-circuit voltage is 633 mV and the short-circuit current density is 28.7 mA/cm^2.

INTRODUCTION

Layer transfer cells based on epitaxial deposition of the absorber layer on monocrystalline porous silicon (PSI) [1],[2] substrates offer the opportunity to combine high cell efficiencies with low material and energy consumption. The use of monocrystalline silicon growth substrates permits lowest defect densities for high-quality absorbers. In contrast to most wafering techniques, layer transfer processes like the PSI process avoid kerf loss and enable cell thicknesses down to a few micrometers with high material quality.

Cells fabricated by layer transfer processes with contacts on both sides, achieved efficiencies of about 17 % [3] on a cell thickness of 50 µm and an area of 2 cm^2 using photolithography. Our group demonstrated 15.4 % [4] on a cell thickness of 25.5 µm and an area of 3.88 cm^2 and 14.1 % [5] on a cell thickness of 25 µm and an area of 95.5 cm^2. In both cases no photolithography was applied [4,5]. However, as only one side of the absorber layer is accessible to processing while being attached to its substrate wafer, it is natural to develop a PSI cell process featuring contacts on only one side of the cell, i.e. a back contact cell. The connection of back contact cells that is required to form modules may also be easier than that of two-side-metalized cells [6]. Good alignment of contact fingers, contact openings and metallization are mandatory for back contact cells. Kraiem et al [7] made a back contact thin film monocrystalline solar cell with cell efficiencies of about 8 % on an area of 0.5 cm^2. These cells were limited by shunt and series resistance due to bad alignment. In our case we use UV lasers for all structuring steps which permit good alignment avoiding shunts and have a potential for high throughput.

DEVICE FABRICATION

The substrate wafer is a monocrystalline Czochralski-grown p-type silicon wafer with 10 mΩcm resistivity and a diameter of 6 inch. Electrochemical etching forms a porous double layer into the top surface of the wafer with a low porosity at the surface and a high porosity beneath. The low porosity layer serves as seed layer for growing a 30 µm-thick epitaxial silicon layer from atmospheric pressure chemical vapour deposition and the high porosity layer is used as predetermined breaking point for the lift-off of the epitaxial layer. The accessible (upper) side becomes the rear side of the cell. An interdigitated grid is formed on the accessible (upper) side of the cell after epitaxy of the absorber layer. To this end a full area 100 Ω/sq emitter forms during phosphorous diffusion which is structured afterwards.

Figure 1a demonstrates how a Nd:YVO$_4$ laser with a wavelength of λ = 355 nm and a pulse length of 8 to 9 ps ablates a SiN layer on top of the emitter in the area of the later base region. A KOH solution etches the emitter and the laser damage within the opened base region. Afterwards the SiN etching barrier is removed in HF.

Figure 1b shows the passivation of the the whole surface with an a-Si/SiN double layer [8]. The same laser locally removes this double layer to permits a silicon to metal contact [9].

Figure 1c illustrates how an electron beam evaporation of a aluminum layer forms the contacts which are covered by a SiO$_2$ film. The separation of the contacts is realized by opening the SiO$_2$ layer with a Nd:YVO$_4$ laser with a wavelength of λ = 355 nm and a pulse length of 20 ns followed by immersing the cell in a $H_2O/HNO_3/H_3PO_4/CH_3COOH$ etching bath. The SiO$_2$ film is an etching barrier for the etching solution, which finally separates the aluminum fingers.

Figure 1d shows the gluing of a glass substrate which supports the thin cell mechanical during lift-off. The high porous layer serves as pre-defined breaking point to separate the cell from the substrate.

Figure 1e illustrates the etching of the remaining porous silicon on the substrate (sunny) side of the cell in a KOH solution. This side of the cell is now accessible for passivation by a-Si and an anti reflection coating by SiN.

The silicon covering the busbars from the sunny side is finally removed by reactive ion etching to access the busbars for electrical measurements [10].

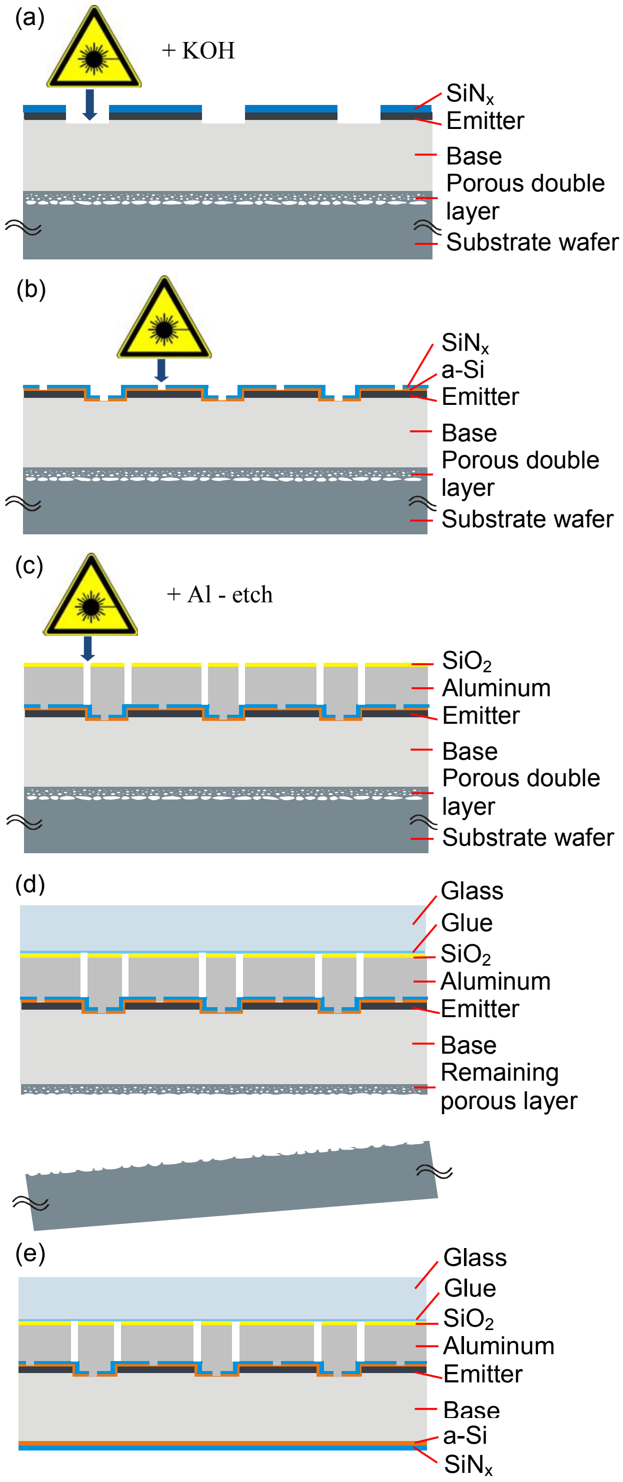

FIG. 1. Device fabrication of the back contact PSI cell. The upper side of the cell is the back side.

DEVICE CHARACTERIZATION

Figure 2 show the shifted IV-curves of our back contact monocrystalline thin-film silicon solar cell measured under a halogen spectrum using a spectral mismatch correction for calibration. Table 1 shows the measured IV-parameters of the cell. Its efficiency is 13.5 % on 79.2 cm^2. A short-circuit current density of J_{SC} = 28.7 mA/cm^2 is reached without applying a front texture. The open-circuit voltage is V_{OC} = 633 mV which is the second highest ever on PSI-cells. The highest is 641 mV achieved using photolithographic processing [3]. The fill factor is 74.0 %.

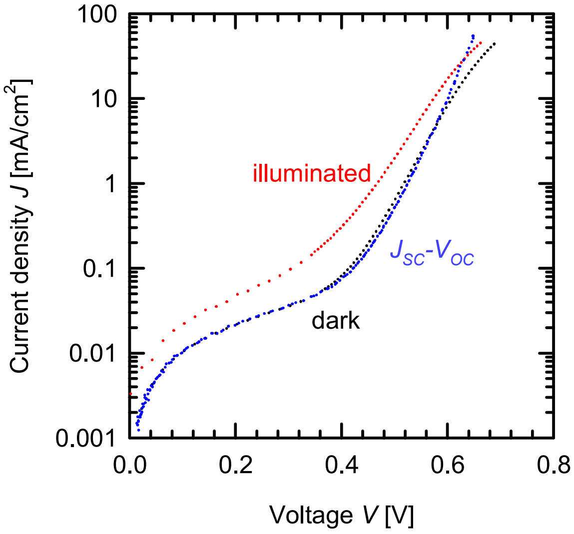

FIG. 2 IV curves of the rear junction rear-contact PSI cell. The cell efficiency is 13.5 %. The cell area is 79.2 cm^2 and the cell thickness is 30 µm. The front side is not textured.

Table 1: Measured IV-parameters of the thin film PSI-cell

Cell area [cm^2]	η [%]	FF [%]	V_{OC} [mV]	J_{SC} [mA/cm^2]
79.2	13.5	74.0	633	28.7

To fit the parameters of the cell we used the two diode model. The first ideality factor is fixed to 1 and the second ideality factor is fixed to 2. The parameters in table 2 are fitted as follows. We estimate the first diode saturation-current density and the series resistance. First we use the dark characteristic in a voltage range of 0 mV to 500 mV where it is identical to the J_{SC}-V_{OC} curve which means that the series resistance has no impact on the dark characteristic. In this range we fit the shunt resistance to 10^4 Ωcm^2 and afterwards the second diode saturation-current density to 25 nA/cm^2. Secondly we use the series resistance free J_{SC}-V_{OC} curve to fit the first diode saturation-current density to 530 fA/cm^2 in the range of

200 mV to 650 mV holding the other parameters constant. In the end we use the curve of the illuminated cell which only differs in the series resistance to the J_{SC}-V_{OC} curve. Out of this difference we fit the series resistance to 1.2 Ωcm^2 in the range of 500 mV to 650 mV.

Setting the second diode saturation-current density to 0 in the two diode model the open-circuit voltage increases only to 637 mV. Therefore the open-circuit voltage is limited by the first diode saturation-current density of J_{01} = 530 fA/cm^2. The fill factor increases to 78.5 % what indicates a non ideal recombination.

The fill factor is not only limited by the second diode saturation current but also by a high series resistance of 1.2 Ωcm^2. Part of this resistance results out of the small cross section of the aluminum fingers which contact the base region. This low cross section is caused by the narrow base finger to keep the emitter/base fraction high. The emitter/base fraction is kept that high to increase the collection probability of the electrons from the base region. This is a trade-off between series resistance which impacts the fill factor and the collection probability which impacts the short-circuit current. Nevertheless the fill factor still reaches 74.0 % due to the high shunt resistance of 10^4 Ωcm^2.

Table 2: Fitted parameters of the thin film PSI-cell

R_{sh} [Ωcm^2]	R_s [Ωcm^2]	J_{01} [fA/cm^2]	J_{02} [nA/cm^2]
10^4	1.2	530	25

CONCLUSIONS

We demonstrated the laser processing of a back contact monocrystalline thin-film silicon solar cell with 13.9 % efficiency. The cell thickness is 30 µm and the cell area is 79.2 cm^2. A single step metallization and the use of laser processes will potentially permit a high throughput. The silicon demand per W_{peak} of the porous silicon process with such a 13.5 % cell is 8 times lower than for an 18 % wafer cell [11]. Further potential for an increasing cell efficiency stems from implementing a surface texture and from higher fill factors by increasing the aluminum thickness or further optimizing the width of the base fingers.

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