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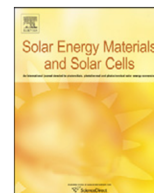

Point contact openings in surface passivated macroporous silicon layers

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ABSTRACT

In this paper we demonstrate the preparation of point contact openings in surface passivated macroporous silicon layers. In our experiments we control the etching parameters to vary the percentage of these non-passivated local openings from 0% to 1.6%. We investigate the impact of these local openings in the passivating layer on the effective carrier lifetime. These local openings reduce the measured effective carrier lifetime with increasing percentage of the non-passivated areas. We measure effective carrier lifetimes up to 10 μs on 29 μm-thick fully passivated macroporous silicon samples. We develop and apply a 3-dimensional numerical model to calculate carrier lifetimes as a function of pore morphology, surface recombination, percentage of non-passivated area, and bulk lifetime. The model agrees with the experimental measurements. We find a surface recombination velocity of ($S_{pass} = 22.8^{+1.6}_{-1.4}$) cm s^{-1} for the passivated surfaces and S_{np}=(2200^{+1500}_{-1400}) cm s^{-1} for the non-passivated surface.

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1. Introduction

The typical thickness of monocrystalline silicon solar cells is currently around 200 μm with an additional kerf loss of 150–200 μm. Since the silicon wafer makes around one-third of the module costs [1], it is highly desirable to reduce the wafer thickness and the kerf loss while maintaining the high efficiency potential of monocrystalline silicon [2].

Currently, several approaches in fabricating thin monocrystalline silicon solar cells are under investigation. One promising approach is the layer transfer process of epitaxially-grown thin crystalline silicon films [3,4]. Recently, high efficiencies over 19% were reported for a layer thickness of 43 μm using this technique [5]. Nevertheless, the non-availability of low-cost high throughput epitaxial reactors is still a barrier for an industrial application of this process. Henley et al. demonstrated a thin-film process that involves proton implantation and lift-off at a depth of a few tens of micrometers that yields (111)-oriented layers. However, this surface orientation does not show anisotropic etching and can therefore not be structured with conventional processes for light trapping [6]. Another approach applies macropores that are thermally reorganized at high temperatures. These macropores are fabricated by deep-UV lithography and reactive ion etching. Solar cells with efficiencies of up to 4.1% have been reported applying this technique [7].

The macroporous silicon process (MacPSi) [8], is a separation technique for detaching thin monocrystalline layers with thicknesses of around 20–30 μm from CZ silicon wafers. In this process, small cylindrical holes are etched into the surface of a silicon substrate by means of electrochemical etching. These holes are broadened in a depth of about 20–30 μm – the thickness of the later absorber layer – to form a highly porous separation layer. We investigate macroporous silicon as an absorber material for thin monocrystalline solar cells.

Light-generated carriers in thin macroporous silicon absorbers recombine in the bulk or, more likely at the large surface of the pores. Understanding the measured effective carrier lifetime is important for process optimization and for designing a device. The surface recombination velocity of passivated silicon surfaces by thermally grown oxide layers depends on the crystallographic orientation [13]. Since the macroporous surface shows various surface orientations, the SRV cannot be determined using planar reference samples [11]. Instead an average SRV needs to be determined experimentally.

In a recent paper we measured effective carrier lifetimes of passivated macroporous silicon layers and derived an analytical model to describe effective carrier lifetimes as a function of pore morphology, bulk recombination, and surface recombination [9]. Therein we investigated the impact of the layer thickness on the effective carrier lifetime of passivated macroporous silicon samples experimentally and applied our analytical model to determine an

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average surface recombination velocity (SRV) $S=75\ \text{cm s}^{-1}$ on passivated macroporous silicon samples by fitting the model to the measurements. This surface recombination velocity was higher than the surface recombination velocity $S=24\ \text{cm s}^{-1}$ that we measured on non-porous reference samples passivated in the same process. This discrepancy could not solely be explained by the various surface orientations. Instead, we explained the discrepancy in the surface recombination velocity with the existence of local openings in the passivating layer that we observed in scanning electron micrographs. However, such openings were not included in our previous model [9].

In this contribution we therefore develop a three-dimensional numerical model that accounts for the non-passivated openings. We verify the numerical model experimentally by preparing macroporous silicon samples with defined openings in the passivation layer.

2. Sample preparation

We use (100)-oriented, n-type float zone crystalline Si wafers that have a resistivity of $(7.5 \pm 0.1)\ \Omega\,\text{cm}$. The thickness of the wafer is $(674 \pm 10)\ \mu\text{m}$. The wafer surface is structured with a hexagonal array of inverted pyramids as shown in Fig. 1. The pyramids are defined by photolithography. The distance of the pyramids is 8.3 μm and the edge length is 4 μm as measured by means of scanning electron microscope (SEM) analysis (S-4800 from Hitachi).

A phosphorous diffusion at the rear side with a sheet resistance of 40 Ω/sq. improves the contact during electrochemical etching in 3 wt % hydrofluoric acid at 20 °C. Photogenerated holes are required for dissolving n-type Si in HF-containing electrolytes. Thus we use rear side illumination [10]. The illumination source is an array of LEDs which emit light at a wavelength of 880 nm. The etched area is circular with an area of 1 cm^2.

Fig. 2 shows the set values of the etching current density. By controlling the illumination intensity a current density of $6\ \text{mA cm}^{-2}$ is generated and the pores start growing at the tips of the inverted pyramids with an etching rate of $0.68\ \mu\text{m min}^{-1}$. The pore diameter is a function of the current density, therefore the pores are broadened in a depth of about 30 μm by increasing the illumination intensity. The current increases linearly from $6\ \text{mA cm}^{-2}$ to values of $18–20\ \text{mA cm}^{-2}$ within 6 min. At this level, the current is maintained for 6 min to form a highly porous separation layer.

The porosity of the separation layer controls the width of the weak bridges between the substrate and the separation layer.

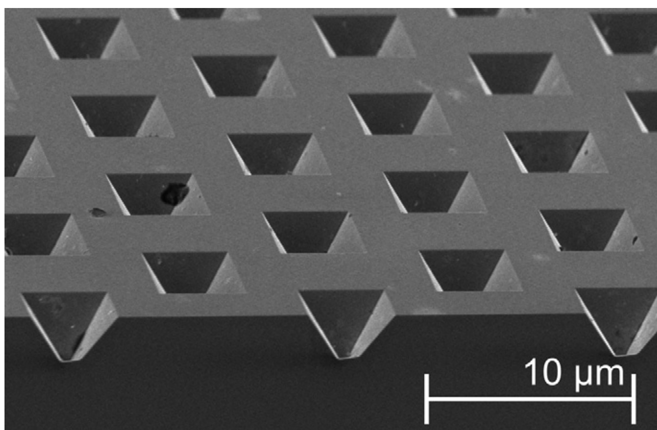

Fig. 1. SEM-image showing an oblique view onto a silicon surface with inverted pyramids defined by photolithography. The distance of the pyramids tips is 8.3 μm.

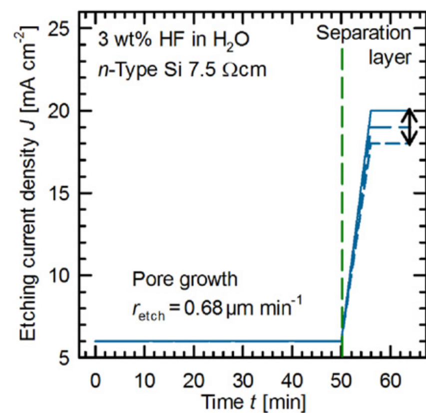

Fig. 2. Etching current density profile to form an approximately 30 μm thick macroporous silicon layer with a highly porous separation layer. We use three different current densities between 18 (short dashed line) and $20\ \text{mA cm}^{-2}$ (solid line) to form the separation layer with varied porosity.

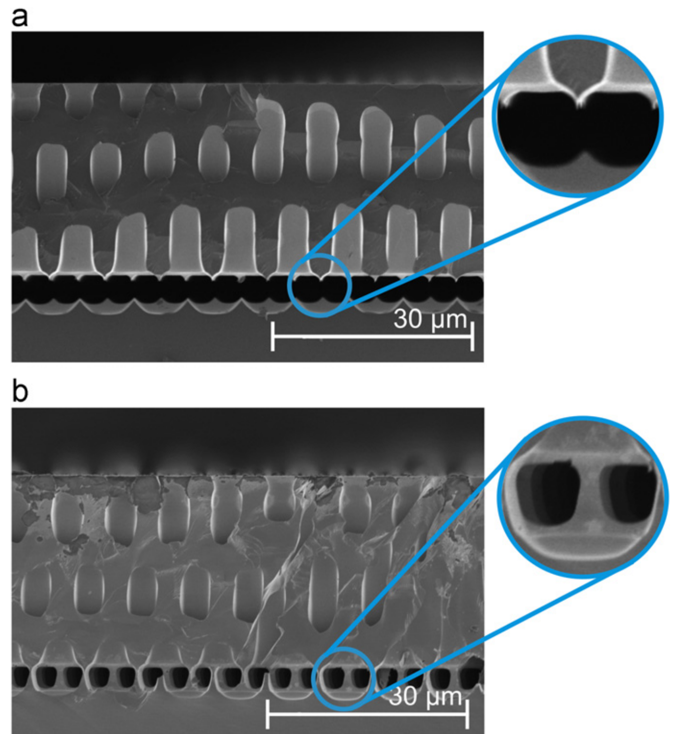

Fig. 3. Cross sectional SEM-images of prepared samples with separation layer current density of (a) $20\ \text{mA/cm}^2$ and (b) $18\ \text{mA/cm}^2$. The width of the weak bridges is approximately 800 nm in case (b).

Fig. 3a shows the $20\ \text{mA cm}^{-2}$ case. The porosity of the separation layer is 100%, i.e. no weak bridges remain between the substrate and the macroporous layer. The layer is only attached to the substrate at the border of the etched area. Fig. 3b shows a cross-sectional SEM-image of the $18\ \text{mA cm}^{-2}$ case. Here the width of the weak bridges is approximately 800 nm. We find $18\ \text{mA cm}^{-2}$ to be the lower limit to remain the detachability of the macroporous layer.

We prepare a set of three samples for each separation layer current density 18, 19, and $20\ \text{mA cm}^{-2}$. Finally, dry thermal oxidization at 900 °C creates a 30 nm thick passivating SiO_2-layer. The passivated macroporous silicon samples are subsequently detached by mechanical force and non-passivated areas remain at the broken bridges.

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