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Analysis of photo-current potentials and losses in thin film crystalline silicon solar cells

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ABSTRACT

We present a detailed analysis of the photo-current potentials and losses in thin film crystalline silicon solar cells on glass. The effects of texturing the silicon backside, applying a diffuse back reflector and a textured anti-reflection foil were analysed. Light beam induced current measurements were used to determine the losses due to local effects like the absorber contact, cracks in the absorber and grain boundaries. Detailed loss analysis in combination with ray-tracing simulations showed that the maximum light trapping potential imposed by geometrical optics has nearly been achieved. The photocurrent losses due to incomplete carrier collection and parasitic absorption were accounted for using a theoretical model. For the investigated, textured, n-doped cell with reflector and anti-reflection foil, the short circuit current density (J_{SC}) was 28.9 mA/cm^2 and the main loss factors were direct reflection (3.4 mA/cm^2), electrical shading effects due to the absorber contact (3.1 mA/cm^2) and incomplete carrier collection due to surface/bulk recombination (1.6 mA/cm^2). Using the presented light trapping scheme we obtained the following efficiencies: 11.8% for a p-doped and 12.1% for an n-doped crystalline silicon absorber. Finally, the potentials for efficiencies beyond 14% are discussed.

1. Introduction

Many methods are being developed to prepare thin crystalline silicon absorber layers ($<50\ \mu m$) in order to reduce material costs [1,2]. Solid phase crystallisation of 2 μm thick amorphous silicon on textured glass resulted in an efficiency (η) of 10.4% [3], with a J_{SC} of 29.5 mA/cm^2, but with a low open circuit voltage (V_{OC}) of 492 mV. The J_{SC} for this cell was very high for such a thin absorber, because of the excellent anti-reflection and light trapping provided by the strongly textured front-side interfaces. Using liquid phase crystallisation (LPC-Si) it was possible to realize a higher quality crystalline silicon, resulting in a V_{OC} of 545 mV [4] and later 585 mV with an initial efficiency of 11.7% for p-type crystalline silicon absorbers [5]. Mainly due to the use of n-type absorber doping, V_{OC} values well above 600 mV [6] were reached and a highest reported efficiency of 11.8% [7]. However, despite the 10 μm thick absorber, the J_{SC} of the latter cell was only 27.8 mA/cm^2, which is much less than for the 2 μm thick, solid phase crystallised cell.

As silicon is weakly absorbing in the near-infrared (IR) spectrum, due to its indirect bandgap, excellent light trapping[1] is needed to obtain a high current for thin absorber layers [8–10]. However, good light trapping alone is not enough if the parasitic absorption in the other layers, such as contacting layers and substrate, is comparable to the absorption of the silicon absorber in the IR spectrum.

In this study, the effectiveness of different light trapping and anti-reflection techniques and their combination is investigated on 10 μm thick LPC-Si solar cells on glass. The various causes of photo-current loss and their interrelations are identified. By combining a diffuse back reflector, a textured anti-reflection foil and a pyramid-textured Si backside, it will be shown that the obtained light trapping is close to the theoretical maximum for geometrical optics.

After describing the cell preparation and measurement methods, the investigated cells and the measurement results are presented. These results include the local losses, measured by light beam induced current measurement, the reflection losses and the

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[1] In this paper, light trapping refers only to the trapping of the light within the cell and not to other aspects of light management, like anti-reflection.

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quantum efficiency. Subsequently it is shown how the remaining losses can be divided into parasitic absorption and incomplete carrier collection. Finally, ray tracing simulations are used to compare the obtained light trapping to Lambertian light trapping.

2. Experimental

2.1. Solar cell preparation

Fig. 1 shows photographs and schematic representations of the solar cells, which were analysed in the study. $SiN_x/SiO_x/SiO_xN_y$ intermediate layers (IL), intrinsic amorphous silicon (a-Si(i)) precursors (10–15 μm) and thin doped a-Si layers (50–90 nm) were deposited by plasma enhanced chemical vapour deposition (PECVD) on 3.3 mm thick Schott BOROFLOAT 33. A more detailed description can be found in Ref. [11]. Aside from anti-reflection, the IL stack needs to have good wettability (for liquid silicon), adhesion, thermal stability and act as diffusion barrier and passivation layers. This puts some design constraints on their optical optimization, mainly with regard to type of material and minimum thicknesses. Within these constrains, the thicknesses of the IL stack were optimized using optical simulation. The refractive indices of the $SiN_x/SiO_x/SiO_xN_y$ layers, at a wavelength of 632 nm, were 2.06/1.44/1.76 and the optimized layer thicknesses were 15/200/85 nm. Laser crystallisation was done with a continuous-wave infrared (808 nm) laser line of 30 mm width from Lissotschenko Mikrooptik GmbH in an air atmosphere. After H_2 plasma passivation, some of the samples were etched with potassium hydroxide (KOH) to create a surface texture for light trapping. KOH anisotropically etches silicon with the highest rate for < 100 > oriented silicon and the lowest for < 111 > crystal orientations [12]. Therefore, it creates tilted pyramids with < 111 > oriented facets. Hence, the light scattering of the resulting

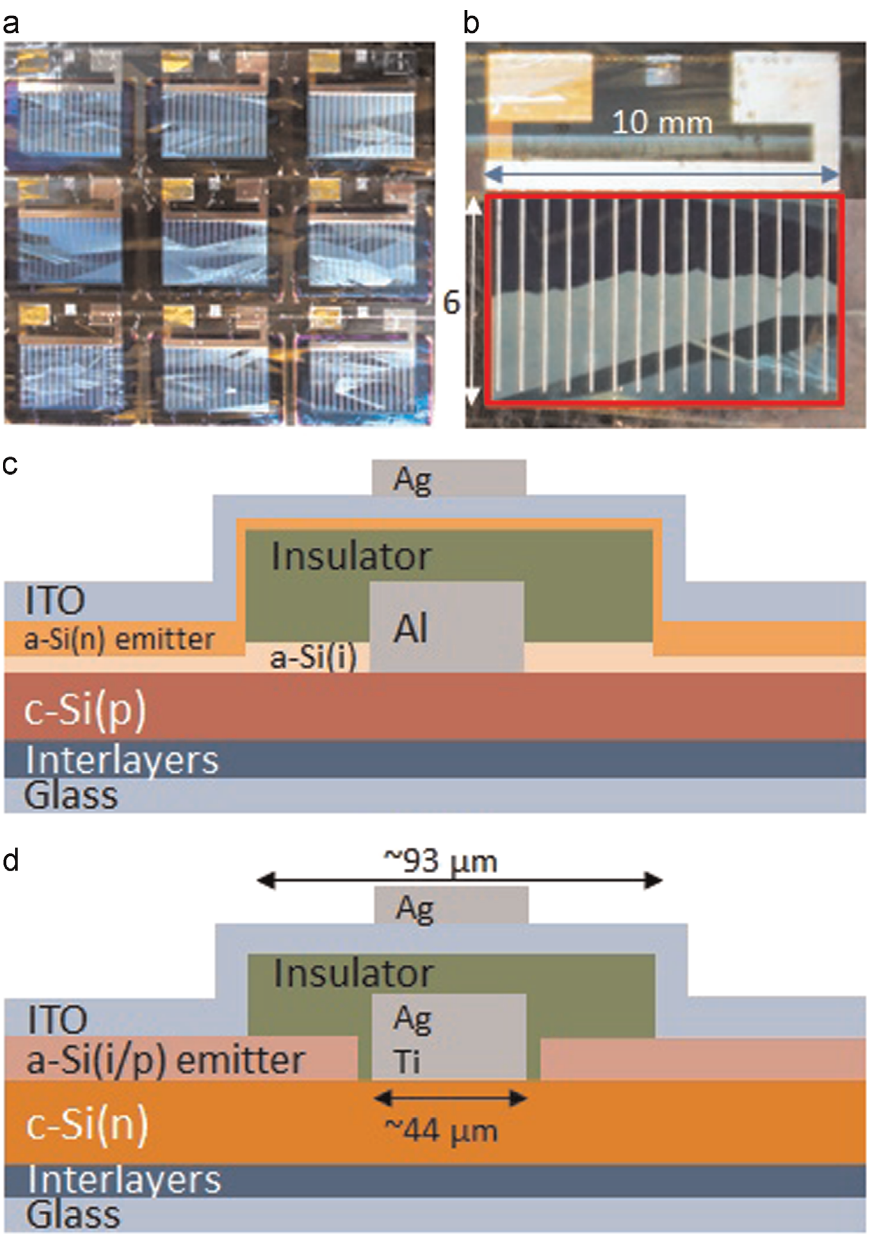

Fig. 1. Photographs as well as schematic cross sections of the bifacial cells used in this study. Figure a shows a representative photograph of a full sample, containing 9 cells. Figure b is a photograph of the investigated "cell B" (Section 3.1). The 6 × 10 mm^2 rectangle indicates the active area. Figure c shows the contacts of the c-Si(p) based cell and figure d shows those of the c-Si(n) based cell.