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Potential of interdigitated back-contact silicon heterojunction solar cells for liquid phase crystallized silicon on glass with efficiency above 14%

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ABSTRACT

Liquid phase crystallization of silicon (LPC-Si) on glass is a promising method to produce high quality multi-crystalline Si films with macroscopic grains. In this study, we report on recent improvements of our interdigitated back-contact silicon heterojunction contact system (IBC-SHJ), which enabled open circuit voltages as high as 661 mV and efficiencies up to 14.2% using a 13 µm thin n-type LPC-Si absorbers on glass. The influence of the BSF width on the cell performance is investigated both experimentally and numerically. We combine 1D optical simulations using GenPro4 and 2D electrical simulations using Sentaurus™ TCAD to determine the optical and electrical loss mechanisms in order to estimate the potential of our current LPC-Si absorbers. The simulations reveal an effective minority carrier diffusion length of 26 µm and further demonstrate that a doping concentration of 4×10^{16} cm^{-3} and a back surface field width of 60 µm are optimum values to further increase cell efficiencies.

1. Introduction

Renewable energy revolution has boosted the growth of photovoltaic industry in recent years. According to international technology roadmap for photovoltaics (ITRPV), the levelized cost of electricity (LCOE) will continuously decrease and the price of large-scale systems is estimated to drop to 680 US$/KWp in the next 10 years [1]. One main key for cost reduction is saving material during the cell fabrication process, in particular, Silicon as it accounts for up to 40% of the cell price [2]. Therefore, in the past a lot of technologies were developed to fabricate high-quality c-Si thin films [3], such as solid phase crystallization (SPC) [4], seed layer approach (i.e. metal induced crystallization (ALILE) [5]) or direct crystalline epitaxial growth [6]. However, these technologies suffered from a high defect density in the bulk, limiting the achievable open circuit voltage (V_{oc}) to 560 mV [7]. Liquid phase crystallization of silicon (LPC-Si) is a promising method to grow large-grain silicon film on glass by using line-shaped energy sources, such as a laser or an electron beam [8]. This method is able to crystallize thin Si films with thicknesses as high as 40 µm and with grain size up to centimeters in length and a few millimeters in width [9–11]. A high open circuit voltage (V_{oc}) of 656 mV was achieved with a 10 µm-thick LPC-Si absorber [10], which is close to the V_{oc} of conventional multi-crystalline Si [10,12]. This absorber was crystallized by an electron beam and a stable efficiency of 11.5% was obtained for a back-contacted solar cell design [10]. The LPC-Si technique based on a continuous wave electron beam was developed by Amkreutz *et al.*. A later study showed no detectable difference in bulk quality of the Si absorber crystallized by laser or e-beam [13]. Optimization of the crystallization process and a mature interface engineering of the intermediate layers (ILs) between glass and Si are crucial steps to enhance absorber quality. ILs have to fulfill a variety of requirements, such as providing adhesion during the crystallization process, preventing impurity diffusion from glass, acting as antireflective coating, and passivating interface defects. The ILs are mainly based on amorphous silicon oxide (SiO_x), amorphous silicon nitride (SiN_x), amorphous silicon oxynitride (SiO_xN_y), amorphous silicon carbide (SiC_x) and aluminum oxide (AlO_x) prepared by plasma-enhanced chemical vapor deposition (PECVD), reactive RF-magnetron sputtering (PVD) or atomic layer deposition (ALD) [7,14–20]. Dore et al. found that the layer in direct contact to the Silicon plays a significant role on enhancing electronic quality of the absorber and the best efficiency for LPC-Si solar cell on glass was realized by a triple stack of $SiO_x/SiN_x/SiO_x$ (ONO) [16]. Amkreutz et al. also reported a V_{oc} above 620 mV and an efficiency up to 11.8% for a back-contacted solar cell with laser crystallized Si on

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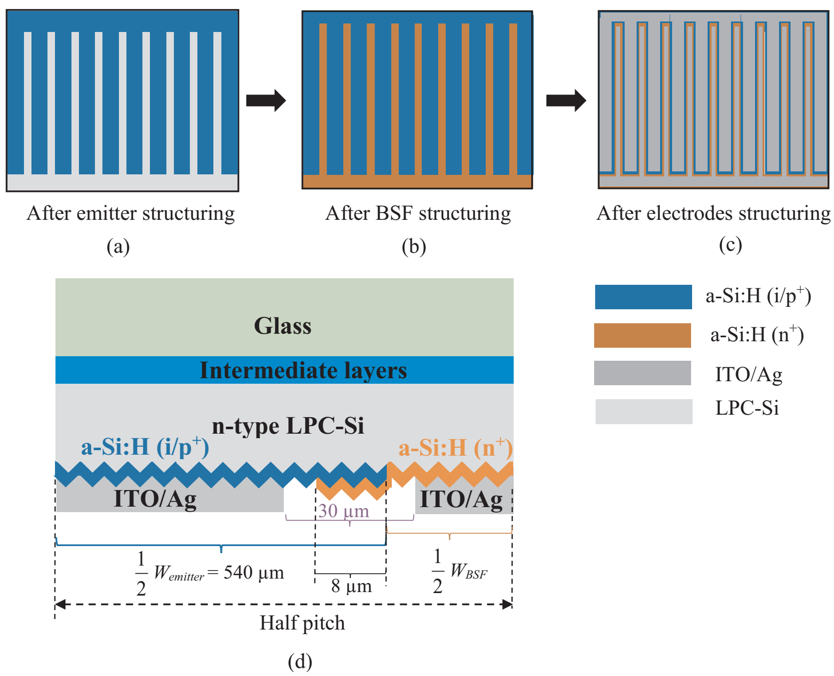

Fig. 1. Top-view from back side of a sample after (a) emitter structuring (b) back surface field structuring (c) electrodes structuring. (d) Cross sectional structure of an IBC-SHJ cell.

glass with a sputtered ONO stack [13]. For PECVD ONO layers, an annealing step needs to be conducted in order to release mobile hydrogen in ILs, which is detrimental for crystallization. An efficiency of 12.1% was obtained with a LPC-Si absorber using PECVD $SiN_x/SiO_x/SiO_xN_y$ for a point contact cell assisted by a light trapping scheme [20]. Recently, Preissler *et al.* realized that a nitrogen–rich SiN_x layer in a PECVD ONO stack layer enables adhesion without prior annealing [15]. The absence of Si-H bonds in the SiN_x structure enhances its stability during crystallization by avoiding H desorption, thus, preventing peeling off. The interdigitated back-contact silicon heterojunction (IBC-SHJ) solar cell based on LPC-Si on glass was firstly introduced by Sonntag *et al.* [21]. However, the obtained efficiencies < 10% were limited by low fill factors (< 55%). Recently, based on ONO IL developed by Preissler *et al.*, a high efficiency of 13.2% was achieved for IBC-SHJ solar cells for 13 µm-thick n-type LPC-Si on glass [22,23]. This outstanding result was obtained for both high and low doping Si absorber with fill factors of 74.7% and 67.2%, respectively, thanks to improvement in IL engineering, optimum geometric design and cell fabrication processes. However, optimization of the contact system geometries has not been clarified yet. For IBC-SHJ cells, all contacts are placed at the back-side of the absorber, therefore, an ideal geometry is necessary to collect as much current as possible without causing resistive loss or electric shading. For the best cell efficiency with an emitter ratio of 90% (back surface field (BSF) width of 120 µm), almost no current was collected under the BSF finger region due to limitations of the minority diffusion length (< 30 µm). Analysis on light beam induced current (LBIC) mapping revealed that 11% of the loss in short circuit current density (J_{sc}) is dedicated to the BSF fingers and their surrounding area. Therefore, in this study, we focus on developing the geometric structure for IBC-SHJ solar cells for LPC-Si on glass. We firstly work on numerical simulation for the IBC structure to examine the effect of BSF width on the cell performance. Then, experimental results of real IBC-SHJ cells with various BSF widths are reported.

2. Sample preparation and characterization

2.1. Absorber fabrication

Firstly, 10 × 10 cm^2 cleaned aluminosilicate glass substrates (Corning Eagle XG, 1.1 mm thickness) were coated with different ILs. The ILs used in this study include SiO_x/SiN_x (ON), $SiO_x/SiN_x/SiO_x$ (ONO) with a 15 nm-thick SiO_x passivation layer and ON(ON) stack layer in which SiO_x/SiN_x was oxidized by a N_2O plasma for 10 min. Due to this oxidation process a 10 nm-thick SiO_xN_y film can be deposited in a controlled and reproducible way. This process is also considered to increase the homogeneity of the layer in direct contact to the absorber and thus, to provide less scattering of the cell results. Details on the interlayer development and deposition process are described in Ref. [24]. A 14.7 µm-thick undoped silicon layer was deposited on top of the ILs using electron-beam evaporation at a heater temperature of 600 °C and deposition rate of roughly 600 nm/s. An 80 nm-thick phosphorous doped a-Si:H (n+) film was then deposited acting as doping source for the LPC-Si absorber layer. Samples were finally coated with a 100 nm SiO_x layer to avoid dewetting during crystallization under vacuum conditions. All layers were deposited using a Von Ardenne CS400PS integrated CVD/PVD cluster tool. The crystallization process was carried out in a vacuum system using a line-shape continuous wave diode laser (808 nm) at a scan speed of 3 mm/s (power density < 3 kW/cm^2). Vacuum conditions were chosen to avoid contamination during the crystallization process. In accordance with the geometry of the laser line of 52 × 0.3 mm^2, samples were cut into four 5 × 5 cm^2 sub-samples. Before crystallization, samples were preheated to 500 °C surface temperature to reduce thermal stress during crystallization. After crystallization, stress in the glass substrates was released by rapid thermal annealing at 950 °C. The SiO_x cap was removed with diluted hydrofluoric acid (HF, 5%) before a hydrogen plasma treatment was performed to passivate the Si bulk. Damaged Si was removed with an aqueous solution consisting of HF, nitric acid (HNO_3), and phosphoric acid (H_3PO_4). Subsequently the samples were textured with a potassium hydroxide (KOH)-based solution with Alkatex free+ additive at 80 °C for 3 min, resulting in pyramid sizes of 1.5–2.0 µm on initial (100) surface. For other surface orientations, the pyramids are tilted by various angles up to flat surfaces for the (111) orientation. The final thickness of the Si absorber is around 13 µm.

2.2. IBC-SHJ cell fabrication

For this study, cells were designed with various BSF widths (W_{BSF}) of 240 µm, 120 µm, 90 µm and 60 µm. The emitter finger width ($W_{emitter}$) was kept unchanged at 1080 µm. All cells were designed to