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18.87%-efficient inverted pyramid structured silicon solar cell by one-step Cu-assisted texturization technique

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ABSTRACT

We achieved an inverted pyramid structure, meeting the tradeoff between the light reflection minimization and carrier recombination by adjusting the one-step Cu-assisted texturization of silicon wafer, and silicon solar cells based on this structure were fabricated, which gained a high conversion efficiency of 18.87% without using any complex techniques. These data were compared with the performance of conventional upright pyramid silicon solar cells as manufactured using identical raw wafers, the Cu-etched inverted pyramid silicon cells collected 0.59 mA/cm^2 more short-circuit current density and 0.47% more efficiency. Importantly, our data demonstrate the better performance and manufacturability of inverted pyramid structured silicon solar cell and as such may open new perspectives for high efficiency solar cell applications.

1. Introduction

Metal-assisted chemical etching has been widely used for fabricating black silicon (B-Si), and there has been significant interest in using this B-Si as an antireflection (AR) coating for Si solar cells not only because of its superior AR effect but also the cost savings and simplicity during mass production [1–7]. B-Si solar cells with efficiency of 17.1% and 18.2% were achieved by Au and Ag-assisted chemical etching, respectively [5,8]. In contrast to Au and Ag, the Cu-assisted chemical etching is more promising for commercial fabrication of Si solar cells because of its much lower cost [9,10]. Nevertheless, although such Cu-assisted chemical etching method has the cost advantage, this method has yet to be commercialized because Cu^{2+}/Cu exhibit much lower redox potential, poorly matching the valence band of Si [3]. In the previous Cu-etched works, only shallow pits were demonstrated [11–13], or with increased etching time Cu tends to form a dense film on the Si surface [14], which will hinder the etching of Si, making it impossible to obtain B-Si. Recently, by introducing H_3PO_3 to the etching solution as a reducing agent and extending the etching time to 8 h, Lu *et al.* synthesized inverted pyramid nanopore-type B-Si with low mean reflectivity of 0.96% at room temperature [15]. Toor *et al.* finally achieved B-Si with mean reflectivity of 3.1% by rising the etching temperature to 50 °C via two-steps Cu-assisted chemical etching method. They also fabricated a solar cell with a conversion efficiency of 17.0% using Cu-etched nanoporous B-Si on pyramidal-textured Si substrate [16]. It should be noted that the B-Si for commercial solar cells fabricated by the above Au, Ag or Cu-assisted etching methods can only be obtained on polished, pyramidal-structured or other textured Si substrate, but not raw Si, because the saw damage layer can't be totally removed during the etching process.

As a result of our recent work, inverted pyramid structures, instead of above-mentioned nanostructures, were fabricated by one-step maskless Cu-assisted texturization of the raw Si [17]. This Cu-etched method can efficiently remove the saw damage layer on raw Si and form inverted pyramids. Moreover, this inverted pyramid structured Si will avoid severe recombination losses encountered by the nanostructured B-Si thanks to its big and open structure characteristic. The surface area of the micrometer-scale inverted pyramids is almost the same as that of pyramids, indicating that the surface passivation for our inverted pyramids is not more difficult than that for pyramids, but much easier than that for nanostructured one. Importantly, in addition to the low reflectivity superiority, these inverted pyramid structures are characterized with recessed and wide deeps, making this texture very applicable for conformal coating and filling, such as for the coverage of SiN_x and the filling of metal electrodes in photovoltaic devices [18]. Except for these superior structure characteristics, our inverted pyramid fabrication is proceeded at 50 °C for about 15 min, reducing the energy consumption and time cost in comparison with the upright

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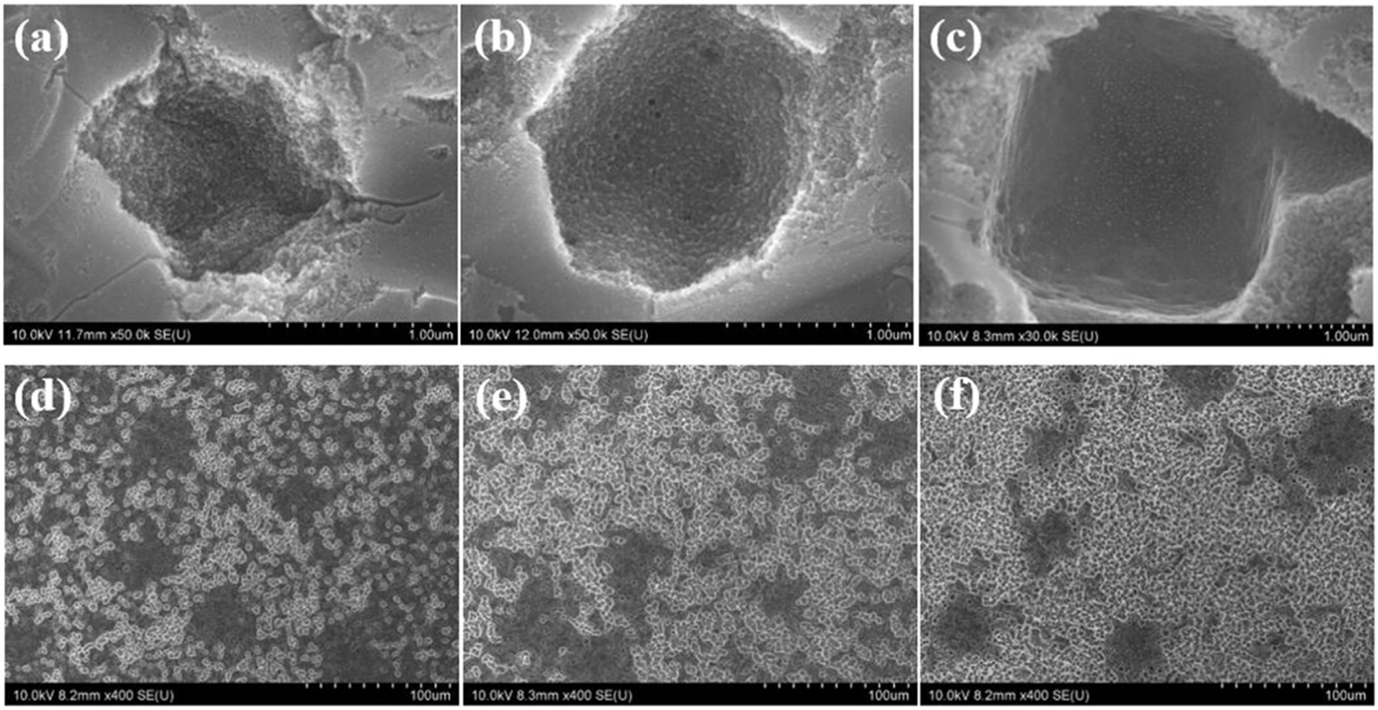

Fig. 1. SEM images of the inverted pyramid structures for **(a)** and **(d)** 5 s processing, **(b)** and **(e)** 25 s processing, **(c)** and **(f)** 60 s processing.

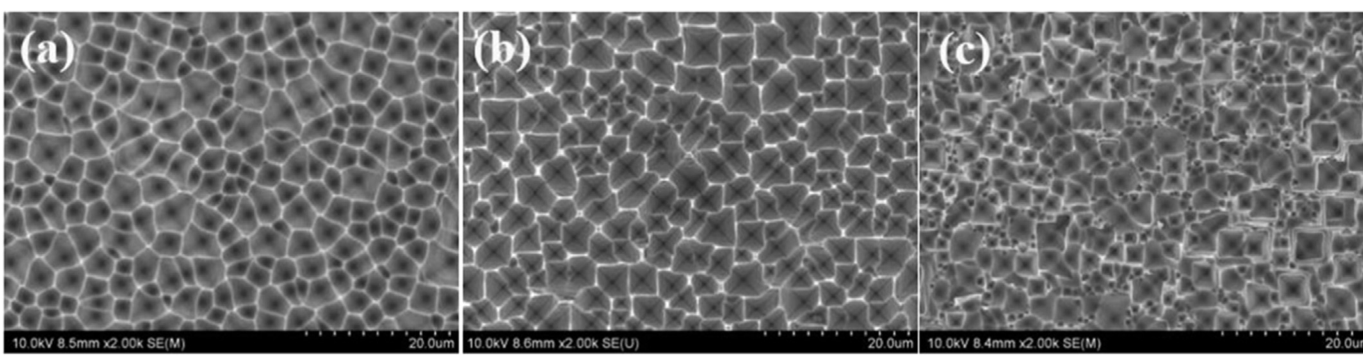

Fig. 2. SEM images of the inverted pyramid structures for **(a)** 10 min processing, **(b)** 15 min processing and **(c)** 20 min processing.

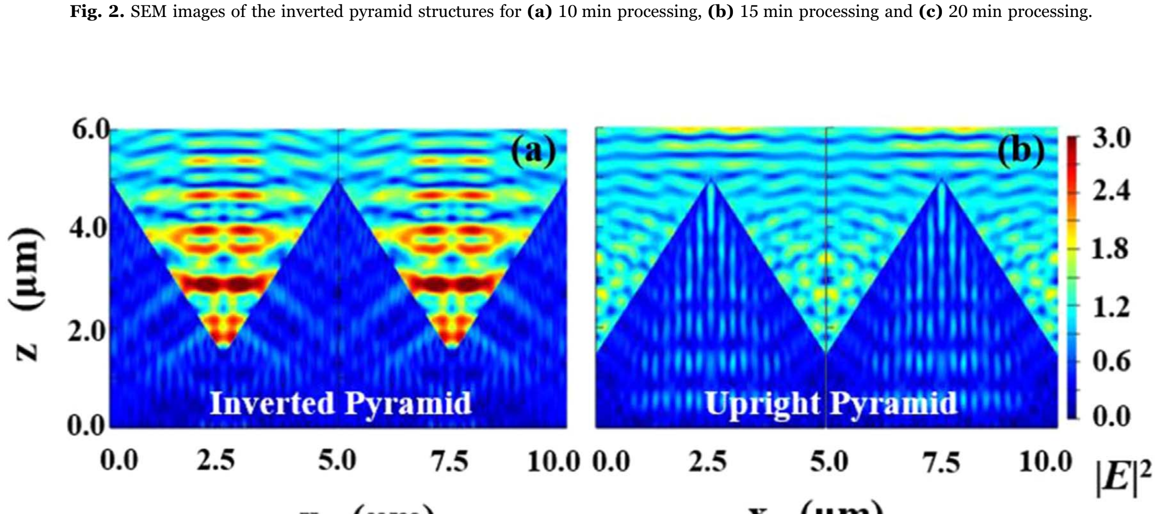

Fig. 3. FDTD simulation results of the electric field intensity distributions in **(a)** inverted pyramid structured Si and **(b)** upright pyramid structured Si.