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Ultrathin interdigitated back-contacted silicon solar cell with light-trapping structures of Si nanowire arrays

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Abstract

With the very high efficiency that has been achieved in silicon-based solar cells, the international technology roadmap for photovoltaics foresees a steady decrease in the thicknesses of such cells over the next decade. In this paper, we present an ultrathin interdigitated back-contacted silicon solar cell fabricated using 30-μm-thick Si substrates. In consideration of the special light-trapping and passivation requirements for ultrathin wafers, Si nanowire arrays coated with Al_2O_3 were used to significantly reduce the reflectance in the visible region of the solar spectrum. The 15-nm-thick conformal Al_2O_3 coating improved the effective minority carrier lifetime of the silicon nanowires and exhibited competitive passivation performance. Furthermore, the photovoltaic properties of the fabricated ultrathin solar cell were investigated and a relatively high conversion efficiency of 16.61% was determined for a thickness of 30 μm. The findings of this study confirm the feasibility of producing ultrathin silicon-based photovoltaic devices.

Keywords: Ultrathin; Light-trapping; Si nanowire; Al_2O_3 passivation

1. Introduction

With the employment of more novel technologies, the market competition of Si-based photovoltaic solar cells has increased drastically in recent times (Jay et al., 2014; Li et al., 2013; Kim et al., 2013; Wang et al., 2014). However, the production cost of crystalline Si solar cells is still high compared to that of traditional fossil-fuel-based technologies. To achieve cost parity, two major ideas have been explored by numerous researchers, and these involve the optimization of structures and processes to achieve high efficiency (Li et al., 2014; Dullweber et al., 2011; Zhao and Wang, 2006; Kanevce and Metzger, 2009; Green, 2009) and the use of fewer materials to reduce cost without sacrificing efficiency (Lee et al., 2014; Willeke, 2002; Wang et al., 2013). Over the past decade, the interdigitated back-contacted (IBC) solar cell, which was first proposed by Schwartz and Lammert (1975), has attracted increasing interest owing to its specific advantages regarding its structure and potential high efficiency (Verlinden, 2012; Payo et al., 2014; Frederic et al., 2013; Pierre et al., 2014). A schematic diagram of the conventional IBC solar cell is shown in Fig. 1a. The most prominent advantage of an IBC solar cell is the elimination of optical shading losses

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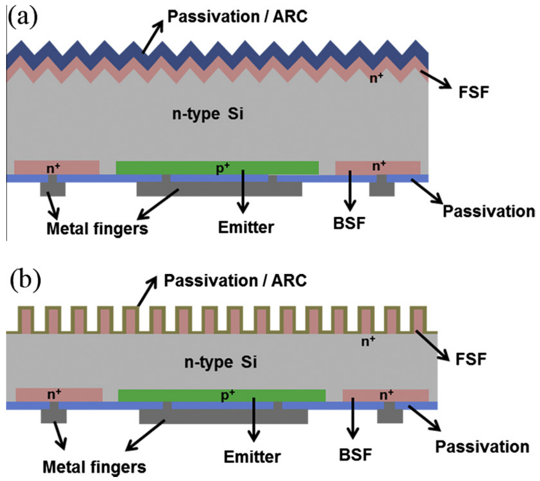

Fig. 1. The schematic diagrams of IBC solar cells with structures of (a) conventional pyramids and (b) nanowire arrays.

by the adoption of all-rear contacts, which improves light absorption and the short-circuit current density. In addition, the base metallization fingers at the rear of the cell reduce the series resistance of the metal contacts. However, the emitter of an IBC solar cell is located at the rear, and this requires the carriers generated close to the front to move to the rear junctions. This implies the need for a longer diffusion length; otherwise, the generated carriers would recombine before reaching the rear junctions. Generally, the diffusion length of the minority charge carriers must be several times the thickness of the cell. Thus, reduction of the silicon wafer thickness is an effective means of shortening the essential diffusion length of the minority charge carriers, thereby reducing their bulk recombination (Munzer et al., 1999; Zhang et al., 2014). Moreover, reduction of the wafer thickness is very crucial to decreasing resource consumption. However, almost all previously reported high-efficiency IBC solar cells were fabricated on silicon wafers of thickness more than 180 μm.

To shorten the diffusion length of the minority charge carriers, reduce material consumption, and possibly enhance flexibility, silicon wafers of thickness 30 μm were used as the substrates for fabricating solar cells in the present study. Owing to the requirement of high material quality for IBC solar cells, we used n-type crystal silicon wafers as the substrates. This was informed by their better tolerance of impurities compared to p-type Si wafers (Macdonald and Geerligs, 2004), resulting in longer minority carrier diffusion lengths. In consideration of the fact that the absorption of the near-infrared region (NIR) of the solar spectrum is significantly lower in thinner wafers (Ingenito et al., 2014), a more efficient light-trapping structure, replacing the traditional pyramid structure, is required. Hence, Si nanowire (NW) arrays, which have very suitable morphology to confine incident light (Lachiheb et al., 2014), were used to enhance broadband optical absorption. Furthermore, in view of the requirement of excellent front surface passivation in IBC solar cells, a highly conformal Al_2O_3 layer produced by atomic layer deposition (ALD) was effectively used to passivate the NW arrays. Owing to the high density of the negative fixed charges and low density of the interface defects, the Al_2O_3 layers afforded excellent field-effect passivation. Moreover, Al_2O_3 passivation can be done at a lower temperature than traditional SiO_2 or SiN passivation, and may also produce an anti-reflective layer comparable to that of SiN_x.

Hence, in this study, we fabricated an ultrathin interdigitated back-contacted silicon solar cell with a light-trapping structure comprising Si NW arrays. The structure of the cell is shown in Fig. 1b. The passivation performances of Al_2O_3 layers of different thicknesses and the effects of NW arrays of different lengths on the performance of the fabricated solar cell are discussed in this paper.

2. Experimental methods

2.1. Fabrication of the ultrathin Si wafers

The ultrathin Si wafers that were used as the substrates were produced by etching 180-μm-thickdouble-sided polished n-type solar-grade Si (100) wafers. Before etching, the Si wafers were initially cleaned in a mixture of NH_4OH, H_2O_2, and H_2O (1:1:5), and then in a mixture of HCl, H_2O_2, and H_2O (1:1:5). Diluted HF solution was subsequently used to remove the surface oxides. The cleaned Si wafers were then immersed in KOH (50 wt%) at 80 °C for 3.5 h. During the etching process, the backsides of the Si wafers were protected by a Teflon container. The etching rate was 40 μm/h approximately.

2.2. Preparation and passivation of the Si NW arrays

The well-aligned Si NWs were prepared by the metal-assisted chemical etching method (Li et al., 2014). The ultrathin Si substrates were immersed in a mixture of $AgNO_3$ (0.02 M) and HF (5.0 M) at 50 °C for different durations of time (1.5, 3, and 5 min) to obtain different lengths. After etching, the samples were immersed in HNO_3 (50 wt%) and then in HF (5 wt%) to remove the residual Ag particles and SiO_2. Finally, the samples were rinsed using deionized water and dried in a flux of nitrogen.

Amorphous aluminum oxide (Al_2O_3) films were deposited on the surface of the dried Si NWs by ALD to suppress surface recombination. During the ALD process, trimethylaluminum (TMA, $Al(CH_3)_3$) and ozone (O_3) were used as precursors. High-purity nitrogen (N_2) was also used as the carrier and purging gas. Different processing temperatures and deposition cycles were employed to examine the effect of the technological conditions on the passivation performance. To measure the effective lifetimes of the substrates, an Al_2O_3 film was deposited at their rear under the same conditions. The samples were subsequently annealed at 400 °C for 30 min in an atmosphere of Ar/H_2.