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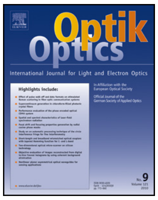

Improved crystalline silicon solar cells by light harvesting zinc oxide nanowire arrays

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ABSTRACT

In this paper, the performance of crystalline silicon solar cells was improved by integrating ZnO nanowire array antireflection coating by hydrothermal growth method. The average length and diameter of the ZnO nanowires are around 5 µm and 50 nm. Scanning electron microscope and X-ray diffraction patterns revealed that the ZnO nanowire array are vertically aligned to the substrate and highly crystalline. Optical data confirms that the ZnO nanowire array effectively reduces the reflectance, especially between wavelength from 200 to 100 nm. Compared to uncoated devices, the ZnO nanowire array improved the overall conversion by around 25%.

1. Introduction

Recently, there is an increasing research interests in renewable energy due to the environmental pollutions caused by traditional energy sources (e.g. burning fossil fuels) [1]. Proposed renewable energy technologies include wind, biomass, tidal, geothermal and photovoltaics [2–4]. Amongst these different technologies, photovoltaics are attractive as it offers acceptable energy conversion and can be fabricated using well-established silicon manufacturing facilities [5,6]. Currently, crystalline silicon (c-Si) –based photovoltaic is the market leading technology with power conversion efficiency (η) ~20% and good reliability (25 years guarantee) [7]. However, the development of c-Si solar cells have stagnated with no appreciable increase in performance in recent years. One of the ways to improve c-Si solar cell is by reducing the reflection losses, which enhances light absorbance and increases the rate of electron-hole pair production [8,9]. Typically, bare c-Si substrate loses 31% of incident sunlight due to reflection [10]. To reduce this reflection, a thin film of Si_3N_4 is commonly deposited on top of the silicon and serves as antireflection coating (ARC) [11]. However, when Si_3N_4 is deposited onto a c-Si substrate, the short-circuit current density is strongly reduced [12] due to the large amount of fixed positive charges associated with the Si_3N_4 layer that induce an inversion layer in the p-type Si/Si_3N_4 interface. Therefore, an ideal ARC should offer the combination of reduction in optical reflection and good degree of surface passivation. By selecting the appropriate refractive indexes and optimized thicknesses, traditional ARC (such as Si_3N_4) reduces reflection by interference. On the other hand, light can also be trapped by employing nanomaterials (nanoporous film, nanoparticles, nanowires) [13,14]. An excellent example of nanomaterial-based ARC is the demonstration of the use of indium tin oxide nanowires that also served as conductive oxide electrode [15,16]. Over the years, ZnO nanowire arrays have proven to be excellent ARC material that provide broadband reflection suppression without significant wavelength dependence due to their refractive index gradient

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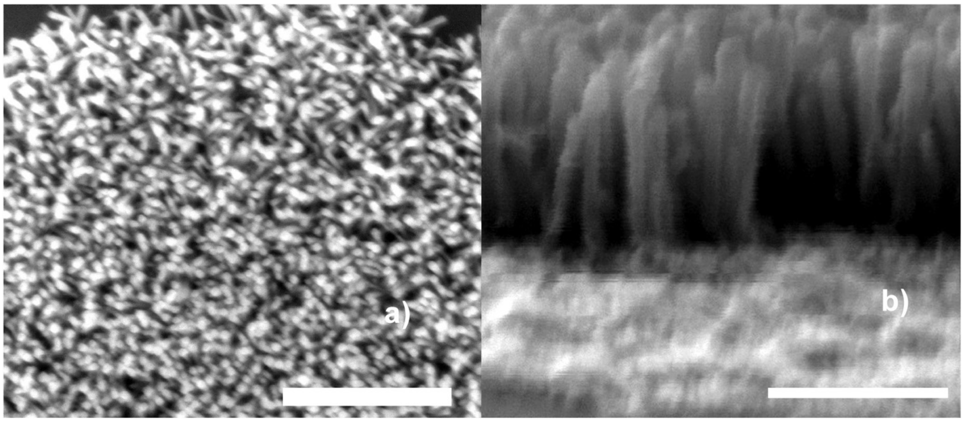

Fig. 1. (a) Top-view SEM image of the ZnO nanowire array (scale bar 2 μm) and (b) tilted view of the ZnO nanowire(scale bar 400 nm).

allowing impedance matching between Si and air [17]. ZnO, is an interesting dielectric material with a wide band gap (3.34 eV),acceptable refractive index (n = 2, at a wavelength of 600 nm) and good transparency ~90% [18,19]. In the past, ZnO films and nanowires have been synthesized by hydrothermal growth method [20], sputtering [21], evaporation [22] and catalytic thermal chemical vapor deposition [23]. Although, it is possible to grow highly crystalline ZnO nanowires by using CVD method on catalyst (Au) coated substrate [23]. It requires a complicated vacuum system. The ARC properties of ZnO nanostructures have already been studied by other scholars with 12.8% and 16% conversion efficiency achieved by polycrystalline and c-Si solar cells, respectively [17]. However, these studies were performed on textured silicon surface, which adds additional process and cost into the overall cost. It would not be cost-effective to incorporate an additional ARC just to absorb a small amount of light. This study utilizes the ZnO nanowire arrays on smooth c-Si wafers without surface texturing. In another word, the ZnO nanowire array completely replaces the conventional texturing technology. To the best of our knowledge, there is no report on the fabrication of a smooth wafer scale single-crystalline Si solar cells with ZnO nanorods as ARC and investigation of the passivation properties of such a layer.

2. Experimental procedure

All of the chemicals used during this study were of reagent grade and used as received. Boron-doped p-type c-Si wafers with resistivity, thickness and size of 2 W-cm, 200 ± 30 μm and 150 × 150 mm, respectively, were selected as a base material in this study. The samples were cleaned using buffered HF. Then, *p-n* junction was formed by diffusion by using $POCl_3$ as the source of phosphorous. For the back electrode contacts, around 500 nm of Al was thermally evaporated and subsequently annealed at 500 °C to form an Al back surface field. For the front contact, Ag pastes were printed onto the front of the substrate. The ZnO nanowires were grown using same procedure from our previous study [18]. Then the glass substrates were dip coated in a 2.5 mM ethanolic solution of zinc acetate dehydrate and annealed at 300 °C to form ZnO seed layer. The seed layer preparation procedure was repeated three times to ensure uniform coating onto the glass substrate. Then ZnO nanowire arrays were grown by vertically suspending the ZnO seed coated glass in equimolar zinc nitrate/hexamine solution. The ZnO nanowire growth proceeded at 90 °C and lasted for 2 h and was terminated by wash under running water and blown dry with using pressurized N_2. Structural and morphological of the resultant products were characterized by an environmental scanning electron microscopy (SEM), model FEI Quanta 400. X-ray diffraction patterns (XRD) were measured by a Siemens D5000 X-ray diffractometer with Cu Kα radiation. Optical properties of the samples were determined through UV–vis NIR spectroscopy (Hitachi U-4100). Photovoltaic performances of the fabricated devices were determined under illumination (100 mW/cm^2), using a solar simulator (Science-tech.).

3. Results and discussions

The morphology and dimensions of the ZnO nanowire array was examined by an ESEM and plotted in Fig. 1(a) and (b). Fig. 1(a) shows the top-view image of ZnO nanowire array. It can be observed from the obtained SEM image that the ZnO nanowire arrays are densely populated and vertically aligned to the substrate with a mean diameter of around 500 nm. The formation mechanism for the ZnO nanowire arrays can be explained by the role of hexamine during growth. Past studies have revealed that the hexamine behaves as a non-polar chelating agent that attach itself to the non-polar facet of the nanowires (110), leaving only the (002) plane exposed for nanowire growth [24]. Fig. 1(b) shows the tilted SEM image of the ZnO nanowire array on c-Si substrate. The average length of these ZnO nanowire array is around 5 μm. The obtained