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A thin-film silicon/silicon hetero-junction hybrid solar cell for photoelectrochemical water-reduction applications

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ABSTRACT

A hybrid tandem solar cell consisting of a thin-film, nanocrystalline silicon top junction and a silicon heterojunction bottom junction is proposed as a supporting solar cell for photoelectrochemical applications. Tunneling recombination junction engineering is shown to be an important consideration in designing this type of solar cell. The best hybrid cell produced has a spectral utilization of 30.6 mA cm^{-2} a J_{SC} of 14 mA cm^{-2}, a V_{OC} of 1.1 V, a fill factor of 0.67 and thus an efficiency of 10.3%. A high solar-to-hydrogen efficiency of 7.9% can be predicted when using the hybrid cell in conjunction with current a-SiC photocathode technology.

1. Introduction

Photoelectrochemical (PEC) water splitting is becoming a viable and important method for solar energy conversion in the form of hydrogen fuels. A complete PEC cell requires two electrodes where one of them is photoactive (either a photocathode or photoanode) and the other electrode is called the counterelectrode. Solar-to-hydrogen (STH) conversion efficiencies of up to 18.3% have been reported [1]. However, these devices use expensive, scarce materials such as gallium arsenide and gallium indium phosphide, which are also not highly water-resistant [1,2]. Thin-film amorphous silicon carbide (a-SiC:H) has been used as a photocathode material for water reduction as it is a much more practical material for larger scale applications [3–6]. This technology is showing a lot of promise as a photocathode based on a-$Si_{0.9}C_{0.1}$:H can theoretically generate a maximum photocurrent density of 15 mA cm^{-2} or a STH efficiency of 18% corresponding to its bandgap of 2.0 eV [7,8]. Fig. 1 illustrates the fundamental components of an a-SiC:H based photocathode consisting of a thin intrinsic a-SiC:H absorber as well as a gradient doped boron-doped a-SiC:H (p) layer and a phosphorous doped nanocrystalline silicon oxide (nc-SiO_x) layer.

A challenge to achieving a high STH efficiency is that the low photovoltage of photocathodes (0.8 V in the case of a-SiC:H technology) is not enough to overcome the thermodynamic water-splitting potential of 1.23 V [9]. In addition to this 1.23 V the overpotentials necessary to drive the overall redox reactions need to be considered [10]. As a result, an external bias is required for this structure to achieve its maximum current density [4].

Integrating a solar cell at the back of the PEC device to realize a monolithic PEC/PV device can directly produce hydrogen without any external bias [11–13]. Various PEC/PV configurations have been demonstrated based on amorphous silicon alloys, such as a-SiC:H/a-Si:H, a-SiC:H/a-Si:H/nc-Si:H, and a-SiC:H/nc-Si:H/nc-Si:H junctions [8]. The STH efficiency in all of these cases is primarily hindered by the potential current density of the supporting solar cell based on thin-film silicon technology.

For typical lab-scale PV device engineering, the target is usually to achieve the highest solar-to-electricity (STE) efficiency under an AM 1.5 spectrum. For PV devices that support PEC structures in a monolithic device, however, the role of the PV supporting structure is to overcome the water-splitting overpotentials while

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driving the necessary current to maximize the STH efficiency that the photoactive electrode is capable of. Another way of saying this is that the *J–V* curve of the PV device under the transmitted light spectrum of the PEC junction should intersect the saturation current of the PEC. In this work, an alternative PV structure is proposed for the a-SiC:H photocathode to realize a silicon based and bias free prototype with a high STH efficiency. This PV component consists of a thin-film, nano-crystalline silicon (nc-Si:H) top cell and a silicon heterojunction (SHJ) bottom cell. A schematic of the monolithic structure with an a-SiC:H photocathode and the supporting nc-Si:H/SHJ stack is given in Fig. 2a. It should be noted that to achieve a monolithic support structure, the solar cell should be illuminated from the n-side rather than traditional p-side illumination for nc-Si:H and SHJ technology. For the SHJ cell, in particular, this resulted in a decision to use a p-type wafer instead of the traditional n-type wafer. Though state of the art SHJ solar cells based on n-type wafers can achieve efficiencies of up to 25.6%, [14] progress has also been made on p-type c-Si wafers [15,16]. A cross-sectional scanning electron microscope (SEM) image of the hybrid cell highlighting the high quality nc-Si:H junction is shown in Fig. 2b.

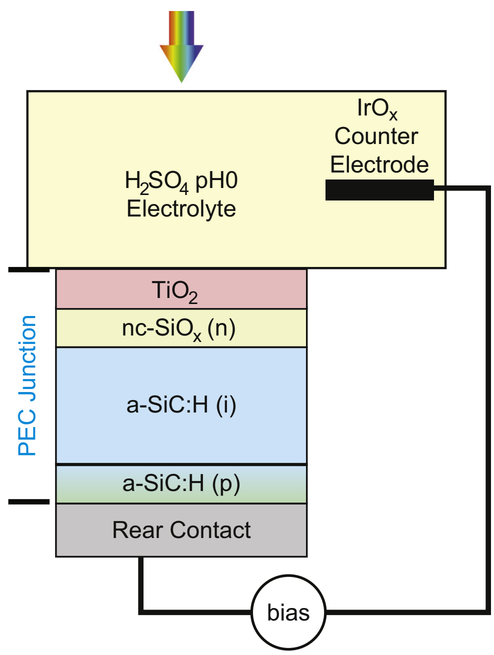

Fig. 1. Schematic illustration of an a-SiC:H photocathode. Note a 1 nm platinum catalyst is not present in the sketch.

Nc-Si:H and SHJ technologies were chosen as they can properly utilize the transmitted spectrum of a-SiC:H as shown in Fig. 2c. This transmitted spectrum was measured with the same class AAA solar simulator that is used for *J–V* measurements in this work. Having two PV cells with bandgaps of 1.1 eV is a very effective way to utilize the remaining spectrum shown in red in Fig. 2c. This work shows the optimization of this hybrid nc-Si:H/SHJ solar cell as a component in the silicon based PEC/PV device as well as a simulation of how the hybrid cell will perform in the full PEC/PV monolithic device along with an a-SiC:H photocathode.

2. Experimental setup

2.1. Photocathode preparation

In this work, an a-SiC:H photocathode was fabricated to determine the design rules for the supporting PV structure. The details of its fabrication by radio-frequency plasma-enhanced chemical vapor deposition (RF-PECVD) are shown elsewhere [8]. It was deposited on a corning glass substrate. The photocathode stack consisted of a 10 nm p-doped a-SiC:H(B) layer, a 40 nm gradient p-doped a-SiC:H(B) layer, a 100 nm intrinsic a-SiC:H layer, a 10 nm nc-SiO_x layer with a 25 nm TiO_2 layer coated with a 1 nm platinum catalyst. The individual layers that make up the PEC were independently deposited and measured with spectroscopic ellipsometry (SE) to obtain their optical parameters for use in optical simulations.

The *J–V* of the a-SiC:H photocathode was measured under simulated AM 1.5 solar illumination (100 mW cm^{-2}) using a NEWPORT Sol3A Class AAA solar simulator (type 94023A-SR3). A spot of 6 mm in diameter on the photocathode was illuminated, corresponding to an active area of 0.283 cm^2. A plated iridium oxide (IrO_x) counter-electrode was utilized. An electrolyte with a

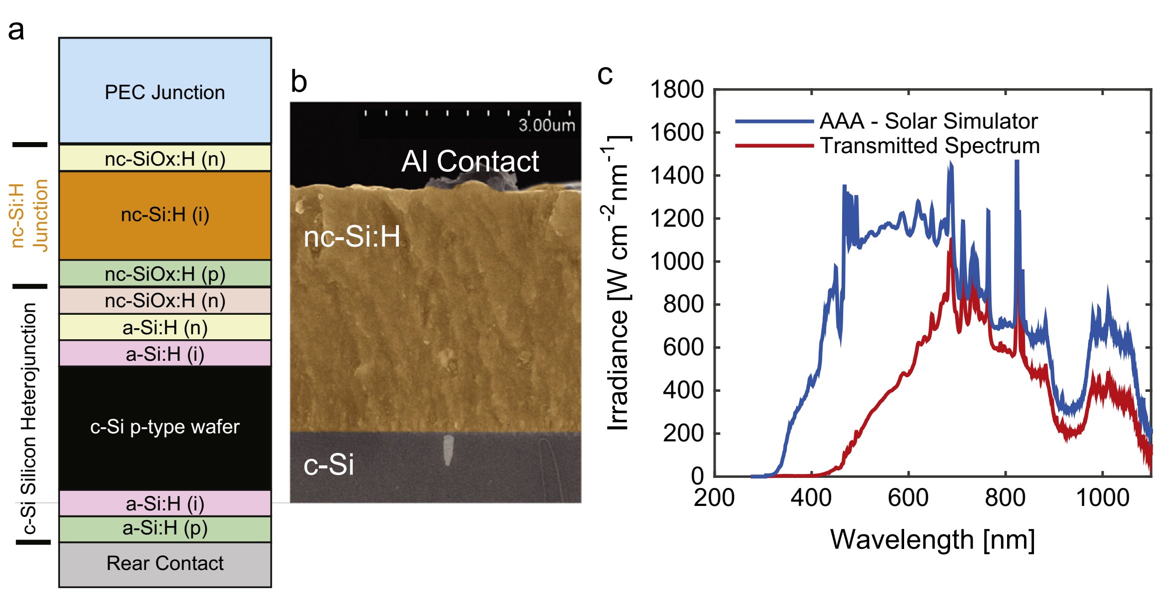

Fig. 2. (a) Schematic illustration of the monolithic PEC/PV cathode based on a-SC:H/nc-Si:H/SHJ structure. (b) SEM cross section of the standalone PV hybrid cell. (c) Measurement of solar simulator spectrum as well as the transmitted spectrum after the a-SiC:H photocathode. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)