

# Nanostructured back reflectors produced using polystyrene assisted lithography for enhanced light trapping in silicon thin film solar cells

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## ABSTRACT

We study light trapping in hydrogenated amorphous silicon thin film solar cells fabricated by plasma-enhanced chemical vapor deposition on various nanostructured back reflectors. The back reflectors are patterned using polystyrene assisted lithography. We have investigated the correlation between the back reflector optical properties and the corresponding solar cell performance. We have introduced double size polystyrene sphere patterned back reflectors and have provided experimental evidence for improved light trapping performance compared to single size polystyrene sphere patterned back reflectors. We have achieved high performing nanostructured amorphous silicon solar cells with an initial power conversion efficiency of 7.53% and over 20% enhancement of the short-circuit current compared with the reference flat solar cell.

## 1. Introduction

WE discuss photovoltaic devices fabricated by plasma-enhanced chemical vapor deposition (PECVD) of hydrogenated amorphous silicon thin films at low temperatures (around 150 °C) on various nanostructured back reflector (BR) substrates. There are two forms of thin film silicon solar cells: hydrogenated amorphous silicon solar cells (a-Si:H) and hydrogenated microcrystalline silicon solar cells ( $\mu$ c-Si:H). Compared to wafer based crystalline silicon solar cells, such photovoltaic devices possess advantages including lesser material usage, compatible with roll to roll processes on flexible substrates, robustness in controlling the device shape and material properties, etc. Compared to other thin film solar cell technologies which rely on the less abundant and in some cases toxic materials, such as CdS, silicon thin film technologies are preferred from the perspective of a sustainable industrial development and an environmental friendly solar energy collection process.

However, due to their short minority carrier diffusion length, the thickness of silicon thin films is limited to a few hundreds of nanometers for a-Si:H and a few micrometers for  $\mu$ c-Si:H solar cells. To improve the performance, effective light trapping strategies were extensively researched during the last decade (Ferry et al., 2009; Ouyang et al., 2011; Haug and Ballif, 2015; Sai et al., 2017). Various

nanostructures applied to silicon thin film solar cells have produced strong localized light resonance modes and increased optical paths, which contributed to the improved light absorption hence photocurrent generation (Atwater and Polman, 2010; Liang et al., 2014). Depending on the location of the nanostructures with respect to incident light, the most typical classes of nanostructured solar cells use front scatterers or back reflectors (BRs) Jang et al., 2016. Aiming at its best performance, a typical front scatterer utilizes metallic nanostructures, which induces a plasmonic near field enhancement effect (Ferry et al., 2010). A typical back reflector utilizes metallic or metal/dielectric nanostructures, which produce a far field scattering effect (Chen et al., 2012). Depending on the periodicity of the nanostructures, existing literature remains controversial on whether random transparent ZnO electrodes or periodic photonic nanostructures can demonstrate a better light trapping performance (Hsu et al., 2012; Battaglia et al., 2012; Micco et al., 2013). Paetzold et al. (2014) concluded that the light trapping effect increases further with increasing disorder of periodic photonic nanostructures. In addition, some of authors have recently shown that partial disorder of otherwise periodic nanostructures can indeed improve the optical performance (Foldyna et al., 2017) and that mixing two different nanostructure sizes can theoretically lead to an improved performance (Foldyna et al., 2013).

In this work, we study a-Si:H solar cells fabricated by PECVD,

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incorporating different semi-periodic nanostructured BRs. The BRs are fabricated by applying polystyrene (PS) sphere assisted lithography (Colson et al., 2013) to pattern Ag nanostructures followed by sputtered Ag and ZnO:Al as the reflective layer and optical spacer respectively, hereafter referred as polystyrene sphere patterned (PSP) BRs. The use of BRs instead of front scatterers allows better controllability of the Ag nanostructure formation. Besides, it also bypasses the high temperature annealing step that is usually required for the formation of top surface Ag nanostructures starting from a thin Ag film. Hence it is fully compatible with the low temperature PECVD fabrication process. By mixing two sizes of PS spheres during the patterning step, we further improve the power conversion efficiency (PCE) by introducing more randomized Ag nanostructures in the BRs. An initial 7.53% PCE has been achieved with only  $\sim 230$  nm of a-Si:H active layer. Note that no special attention has been paid to the optimization of the doped layers, so further improvement can be expected.

## 2. Experimental details

### 2.1. PS assisted lithography for Ag nanostructures on glass

The PS spheres used in this work were an aqueous monodispersed suspension of 5 wt% obtained from microparticles GmbH with nominal diameters of  $425 \pm 10$  nm,  $607 \pm 15$  nm and  $784 \pm 23$  nm (thereafter referred to as 400, 600 and 800 nm PS spheres). The solutions were uniformly mixed with methanol as the spreading agent in 1:1 vol ratio. Prior to the PS sphere monolayer transfer, Corning glass was cleaned with acetone, isopropanol and de-ionized (DI) water in ultrasonic bath, followed with a 10 min UV-Ozone treatment to keep the surface hydrophilic. After a monolayer of PS spheres been transferred on Corning glass using the floating transfer technique (Colson et al., 2013), a 100 nm layer of Ag was thermally evaporated on top. For a complete PS sphere removal and yet to retain the formed Ag nanostructures on glass, a low power ultrasonic bath in toluene was applied for 20 min, followed with 10 min isopropanol and DI water ultrasonic bath for a complete removal of any organic solvent residue. The overall fabrication process of Ag nanostructures is schematically shown in Fig. 1(a).

### 2.2. Back reflectors fabrication

A set of cleaned Ag nanostructures on glass, flat glass and ASAHI glass have been sputtered with a layer of 200 nm Ag using an RF (13.56 MHz) magnetron system under the following process conditions at room temperature: argon flow rate of 41 sccm, RF power of 50 W and process pressure of  $5.7 \times 10^{-3}$  mbar. Without breaking the vacuum, ZnO:Al with 100 nm thickness was sputtered under the following process conditions at room temperature: argon flow rate of 30 sccm, RF power of 250 W and process pressure of  $4.3 \times 10^{-3}$  mbar. The fabrication process on the three substrates is schematically shown in Fig. 1(b).

### 2.3. Solar cell fabrication

Amorphous silicon thin films were deposited in a 13.56 MHz radio frequency (RF) PECVD system (Roca i Cabarrocas et al., 1991). Three plasma chambers sharing the same vacuum pump were used to separate n-type, intrinsic and p-type a-Si:H deposition to avoid any cross contamination. Firstly, a 25 nm thick n-type microcrystalline silicon oxide layer was deposited on the BR (Abolmasov et al., 2014). Without breaking the vacuum,  $\sim 230$  nm of intrinsic amorphous silicon layer has been deposited using a  $\text{SiH}_4/\text{H}_2$  plasma, followed by a 25 nm thick p-type amorphous silicon carbide layer. Finally, an 80 nm thick indium tin oxide (ITO) was deposited to form the top contacts and to define cells with an area of  $0.126 \text{ cm}^2$ . Such photovoltaic device was often referred to n-i-p solar cell (Kim et al., 2013). A schematic image of the side view of the device and a corresponding SEM image acquired using Hitachi S-4700 is shown in Fig. 2.

### 2.4. Characterization

The current density-voltage ( $J$ - $V$ ) characteristics of the solar cells were measured under AM1.5G illumination with a commercial solar simulator (Oriel AAA), calibrated using a crystalline Si reference cell. Total and diffused reflectance was measured using a Perkin-Elmer Lambda 950 spectrometer with a 150 mm integrating sphere and an InGaAs detector.

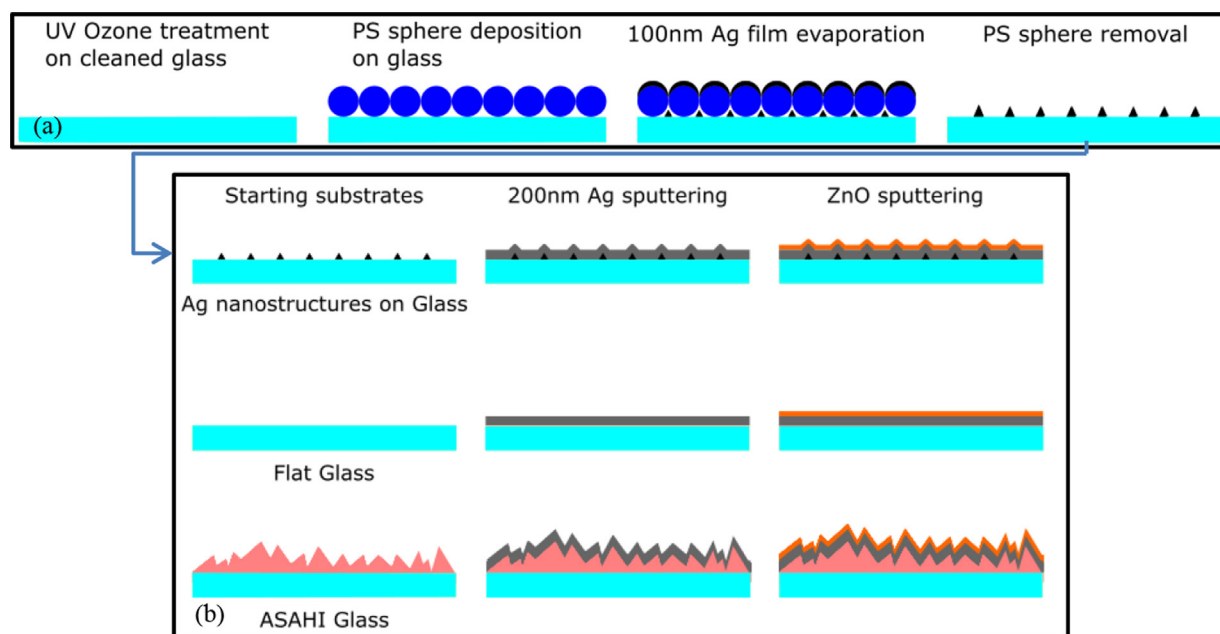


Fig. 1. (a) Fabrication process for Ag nanostructure on glass; (b) fabrication process for back reflectors.

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