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# Optimized broad band and quasi-omnidirectional anti-reflection properties with moth-eye structures by low cost replica molding

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ABSTRACT

Averaged over wavelength range from 500 to 1600 nm at normal incidence, the reflection losses of silicon wafer as master mold are reduced from original 35% to only 0.2% after integrating surface moth-eye structures, and glass slide suppresses the reflection from 7.5% to near 0.4% after incorporating polymer-based moth eyes on double side by replica molding that enables transferring moth eyes from master mold of silicon onto any substrate. An outstanding anti-reflective property out to large incident angles is realized with the average reflection below 0.5% until 50°, below 2.5% at 60° and below 7.5% at 70°, which holds promise for solar cell application.



## 1. Introduction

Due to the discontinuity of the refractive index between air and materials, Fresnel reflectance occurs and causes additional optical loss at the interface. As one of the most superior broadband and omnidirectional antireflection (AR) options, the biomimetic periodic moth-eye structures [1] have been extensively explored on the surfaces of Si, GaAs, GaSb and AlInP [2–5], which is mainly driven by the pursuit of higher solar-to-electrical power conversion efficiency. Consequently, many fabricating techniques have emerged, such as dry etching with spin-coated monolayer colloidal crystals mask [2], e-beam lithography [6] and soft UV-nanoimprint lithography [5] and so on [7–12]. Nevertheless, these techniques, though elegant, are costly in capital and operating cost. Notably, the resulting moth-eye nanostructures directly patterned on the active surface of solar cell, generally incur recombination centers on the surface [13–15] and therefore have negative effect on the device performance in the absence of additional passivation process. It is also why the combination of surface texturization and quarter-wavelength $Si_3N_4$ layer has become the industry standard of crystalline silicon solar cells, since the introduction of hydrogen can passivate the surface recombination centers during the deposition of $Si_3N_4$.

By contrast, alternative simple and low-cost replica molding based on a soft polymer mold such as poly (dimethylsiloxane) (PDMS) [16], though mostly adopted for transferring patterns onto various surfaces and easy replication of complex nanostructures has been barely performed to gain moth-eye structures [17,18]. In this paper, we demonstrated optimized broad band and full angle moth-eye nanostructures on glass slide and polyethylene terephthalate (PET) by PDMS-based replica molding. More significantly, the resulting moth-eye nanostructures can be mounted on top of the underlying device without introducing recombination centers.

## 2. Experiment and characterization

Fig. 1 (top) shows the schematic illustration of process steps for fabricating moth-eye nanocones on silicon wafer by colloidal template process. Non-close-packed silica particles with the diameter of 100 nm were created by the established spin-coating technique. And interparticle distance of the silica colloidal template is 150 nm by controlling the proportion of composition in colloidal $SiO_2$ suspension (OrganosilicasolTM IPA-ST-ZL, PAA, IPA) and the parameter setup of spin-coating. The STS advanced silicon etcher system (STS ICP RIE System) has been utilized for realizing nanocones shape with the flexible combination of RIE and ICP, since RIE is anisotropic etching, mainly based on

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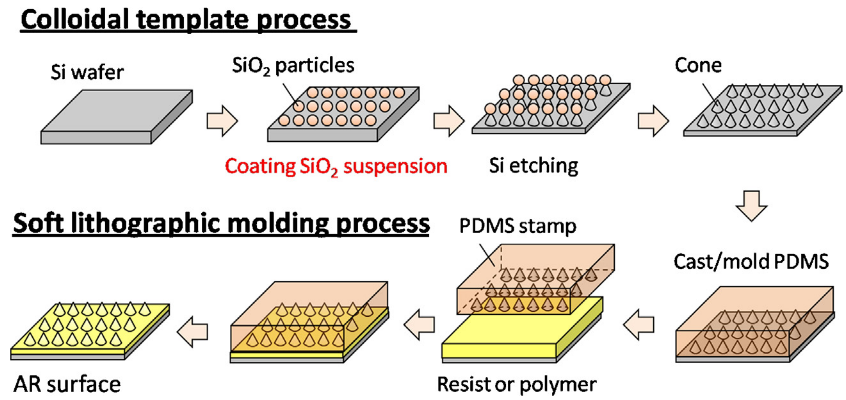


**Fig. 1.** Schematic illustrations of colloidal template process for fabricating moth eye patterns on silicon (top), and of soft lithographic molding process to fabricate a PDMS-based replica on any substrate (bottom).

vertical ionic bombarding; while ICP is isotropic etching, mainly relying on chemical reaction induced by high density ions. The height of the conical structure can be controlled by adjusting the setup of STS ICP RIE for Si etching. For example, to obtain etching depth of 500 nm, the setup of key process for Si etching is shown as below: (step 1) etch/passivation = 1.7 s/1.7 s, 30 cycles; (step 2) 35 sccm $SF_6$, ICP/RIE = 600 W/20 W for etching (step 3) 94 mTorr, 110 sccm $CF_4$, ICP/RIE = 600 W/0 W for passivation. Moth-eye nanocones with different heights were tuned by changing the cycle times. Besides, Fig. 1 (bottom) presents the schematized procedure

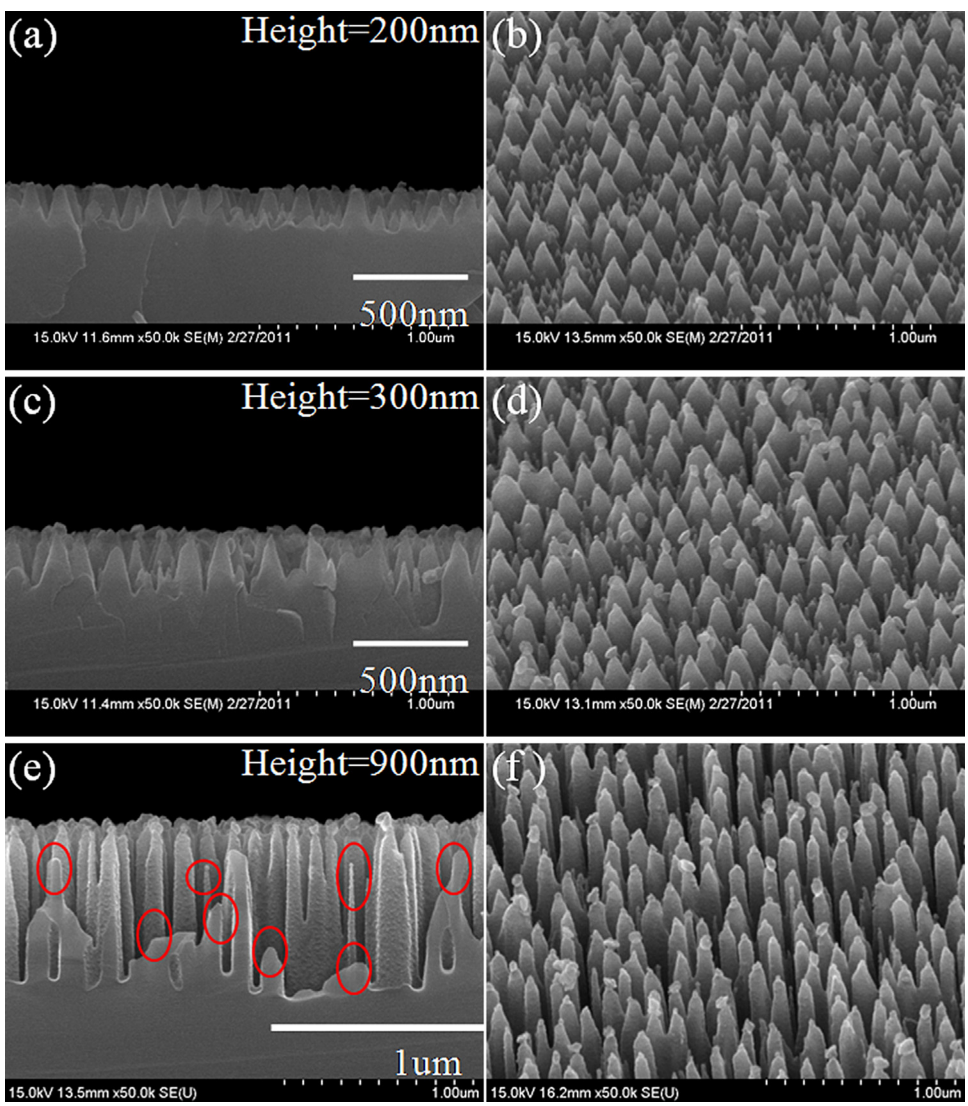


**Fig. 2.** SEM images of cross sectional silicon moth eye patterns with different heights in (a, c, e); and the corresponding top view images in (b, d, f) respectively.