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Asymmetric back contact nanograting design for thin c-Si solar cells

Inho Kim*, Doo Seok Jeong, Wook Seong Lee, Won Mok Kim, Kyeong-Seok Lee, Taek-Sung Lee

Center for Electronic Materials, Korea Institute of Science and Technology, Hwarang-ro 14-gil 5, Seongbuk-gu, Seoul, 136-791, Republic of Korea

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ABSTRACT

Texturing of silicon wafers with periodic gratings in submicron scale is one of effective light trapping routes especially for thin crystalline silicon solar cells. The grating can be very effective for trapping of photons near band gap of crystalline silicon when its period is suitably chosen. The asymmetric gratings provide higher light trapping efficiency than symmetric ones because the asymmetric one suppress the escape of internally reflected light in the silicon wafers. In this study, we conceptually show that asymmetric grating can be fabricated by simple stacking of a dielectric layer onto the symmetric silicon grating structures. Optical simulations were performed to calculate optical absorptions in thin crystalline silicon of a 5 μm thickness with symmetric and asymmetric grating structures. We demonstrate that with the asymmetric grating structures combined with highly efficient antireflection coating, optical absorptions in the thin silicon wafers can reach over 97% of the Lambertian absorption limit.

1. Introduction

The use of thinner silicon wafers is one of the most straightforward routes to reduce the cost of crystalline silicon solar cells [1]. However, the reduced wafer thicknesses lead to drastic decreases in optical absorptions especially for the thin silicon wafers thinner than 50 μm [2]. In order to compromise the optical absorption decreases, extensive research on light trapping technology has been performed [3–5]. Classical pyramidal texturing has been well studied and reported to be very efficient [6]. Randomly textured pyramids at both sides of the silicon wafers lead to the Lambertian absorption limit, which is the classical absorption limit [7]. However, the size of pyramids in the classical texturing generally ranges from a few micrometer to tens of micrometer; thus, this texturing scheme is hardly applicable to the thin silicon solar cells [8]. On the other hand, texturing in submicron scale of various shapes has been introduced and proved their performances [3,9]. Periodic nanostructures to exploit diffractive coupling into trapped modes in silicon wafers are very effective when optimally designed [10]. Interestingly, it is also reported that in narrow spectral ranges, the classical absorption limit can be surpassed with periodic nanostructures [11]. Periodic nanostructures of geometrical non-symmetry provide additional absorption enhancements compared with symmetric nanostructures when light is incident normally [12,13]. This is because normally incident light can couple to all the modes with even and odd modal amplitude profiles in films with symmetric gratings in contrast with the case in films with asymmetric gratings. Only the even modes can be excited in the case of the films with symmetric gratings [14]. Asymmetric grating with optimized Fourier series were reported to be even more effective than simple asymmetric gratings such as skewed triangle gratings [15]. Silicon nanostructures can be fabricated by various nano-lithography schemes such as nanoimprint, laser interference lithography, and colloidal lithography [16–18]. Although asymmetric nanostructures are well known to be more effective for light trapping, most experimental studies focus on symmetric ones because fabrication processes of asymmetric ones are more burdensome. In this regards, we conceptually propose a facile process to make asymmetric periodic nanostructures by simply stacking a dielectric layer asymmetrically onto symmetric nanostructures. The dielectric layer would be deposited directionally with oblique incidence by physical vapor deposition such as thermal evaporation or sputtering processes [19,20]. The oblique angle and thickness of the dielectric layers can be control parameters. In this study, we demonstrate numerically that asymmetrically modified periodic nanograting at back contact of thin crystalline silicon wafers with asymmetric deposition of dielectric layers can enhance optical absorptions greatly with an optimal design of asymmetric nanograting combined with nanocone

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* Corresponding author.
E-mail address: inhok@kist.re.kr (I. Kim).

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antireflection structures at the front side. Approximately 97% of the Lambertian absorption limit was able to be reached [21]. This scheme we propose would be a promising light trapping approach with low process burden.

2. Methods

The optical absorptances in the thin c-Si wafers of a 5 μm thickness with nanograting on the one side were calculated by the Rigorous Coupled-Wave Analysis (RCWA) method. The commercial software package (Gd-Calc, KJ Innovation) was used for all the three dimensional (3D) RCWA calculations. The thin c-Si wafer with rectangle nanograting in a square lattice was simulated for calculation of the optical absorptances. The double layer antireflection (DLARC) coating was adopted at the front side (the light incidence side) in order to suppress reflectances in broad spectral ranges.

The DLARC consists of layer 1(thickness: 45 nm, refractive index 2.72)/layer 2 (thickness: 104 nm, refractive index: 1.49) [22]. The nanogratings were placed at the back contact embedded with an optical spacer as shown in Fig. 1 (a). As a final layer, the ideal reflector which reflects all the incident light perfectly, was stacked. The grating width was set to be a half of the grating period. The refractive index of the silicon wafer is extracted from literature [23]. The refractive indices of the optical spacer and the dielectric layer are set for 1.45 and 2.9, respectively. The optical spacer is assumed to be silicon dioxide and the dielectric layer be silicon nitride of high refractive index with enriched silicon [24]. We calculated the optical absorptances and reflectances from the thin silicon wafers with varying the period and height of the nanogratings to find an optimal nanograting dimension. For fair comparisons of the optical absorptances from the silicon wafers with various dimensions of the nanogratings, the total mass of silicon was kept same by adjusting the thickness of the wafers. The symmetric nanogratings were modified by asymmetric coating of the dielectric layers onto the nanogratings in effort to find more effective light trapping structures as shown in Fig. 1 (b). The dielectric layers covers the nanogratings asymmetrically. These dielectric layers make the silicon nanogratings optically asymmetric. In the same manner, we calculated the optical absorptances and the reflectances in the asymmetric nanogratings with varying the dimensions of the silicon nanogratings. The thickness of the dielectric layers was adjusted to be a half of the height of the nanogratings. The dielectric layers on the bottom were extended by a half width of the silicon grating pillar in +x and −y directions. For further reduction in the reflectances, we introduced a dielectric nanocone structure on the front surface, and demonstrate the further enhancements in the optical absorptances were enabled [25].

3. Results and discussions

The optical absorptances in the thin silicon wafers with the symmetric gratings and the asymmetric ones were calculated and compared in Fig. 2. The heights of the silicon nanogratings were adjusted from 100 nm to 900 nm, and the periods were varied from

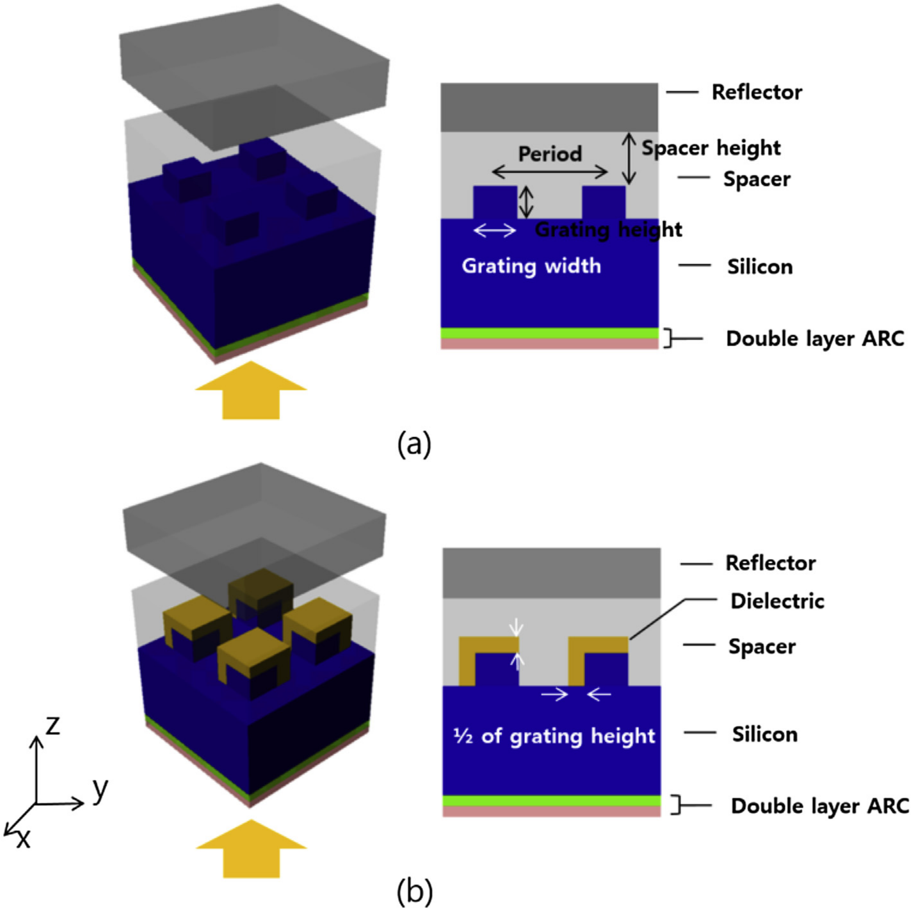

Fig. 1. Three dimensional and cross-sectional schematics of (a) the thin c-Si devices with symmetric and (b) asymmetric nanogratings. The reflectors in three dimensional schematics are intentionally displaced at both of the devices for a better visual understanding. The cross-sectional schematics are viewed in the z-y plane. Incident light (yellow arrow) comes from the bottom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)