Optics Communications 377 (2016) 52–58

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Mismatched front and back gratings for optimum light trapping in ultra-thin crystalline silicon solar cells

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ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
21 March 2016
Accepted 22 April 2016
Available online 20 May 2016

Keywords:
Light trapping
Double grating
Crystalline silicon
Solar cell
Thin absorber

ABSTRACT

The implementation of a front and back grating in ultra-thin photovoltaic cells is a promising approach towards improving light trapping. A simple design rule was developed using the least common multiple (LCM) of the front and back grating periods. From this design rule, several optimal period combinations can be found, providing greater design flexibility for absorbers of indirect band gap materials. Using numerical simulations, the photo-generated current (J_{ph}) for a 10-μm-thick crystalline silicon absorber was predicted to be as high as 38 mA/cm^2, which is 11.74% higher than that of a single front grating (J_{ph} $=34$ mA/cm^2).

1. Introduction

Solar photovoltaics (PV) technology has advanced considerably in recent years with current state-of-the-art single junction PV cells exhibiting efficiencies approaching the Shockley-Queisser limit [1]. The need to reduce costs have spurred the development of thin-film PV devices. Conventional bulk crystalline silicon (c-Si) PV cells typically have device thicknesses of 140–180 μm and require a 300-μm-thick wafer to produce one cell due to kerf losses associated with Si boules dicing. Including kerf losses, raw material costs have been shown to contribute over 30% of total module cost in conventional PV cells [2–4]. To produce thin c-Si cells without excessive material waste, new manufacturing technologies have been recently developed, including silicon epitaxial growth and direct wafering [5–8]. Despite the cost benefits, the combination of an indirect band gap and thinness of the absorber make thin c-Si cells a poor absorber of near-infrared light, leading to significant photocurrent losses. Therefore, light trapping is paramount for thin c-Si PV cells to approach the Shockley-Queisser limit [1].

In order to enhance light-trapping performance, a myriad of structures using surface plasmons [9–11], photonic crystals [12–14], or diffraction gratings [12–40] were proposed. In particular, diffraction gratings incorporated onto the front of PV cells have shown great potential by coupling incident light into guided modes in the thin film [16,18–20]. Additionally, recent studies have shown that triangular, pyramidal, or conical gratings exhibit higher absorption due to the impedance match from air to silicon [15–22,28,30,39]. To improve light trapping even further, the inclusion of a back grating structure has been studied as a means to better scatter near-infrared light into guided resonances [12–14,17,27–28,33]. By combining a front and back grating, recent studies have demonstrated enhancement to light trapping that outperforms absorbers that are textured only on one side [27–39]. Further improvements for these double grating structures have included the introduction of a phase shift through misalignment of two gratings and the use of blazed gratings to break symmetry [30,38–40]. To optimize the double grating structure, a general design strategy was proposed in which the front grating is treated as an anti-reflection layer to couple incident light while the back grating diffracts light into guided modes to trap it within the thin film [28,33]. The periodicities of both the front and back grating are therefore crucial to the overall performance. However, as these two gratings serve different purposes, they were typically optimized separately in prior studies. For instance, the optimization of the front grating requires striking a balance between larger in-coupling of incident sunlight and decreasing leakage of the guided

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http://dx.doi.org/10.1016/j.optcom.2016.04.055

modes [24–26,28,33]. The period of the back grating is then tuned to further improve light trapping. However, such an optimization can converge to a local maximum, which is determined by the choice of the front grating. To avoid this potential pitfall and simultaneously reduce computational costs of optimization, we propose a more general optimization approach that relies on tuning the periods of two gratings relative to each other, resulting in a simple rule that can be used to design double grating structures to achieve higher absorption in indirect band gap materials.

In this work, we focus on developing an optimized double grating light-trapping structure for a 10-μm-thick c-Si PV cell. Using numerical simulations to solve Maxwell equations, we demonstrate that when a mismatch is introduced between the periods of two gratings, the back grating will diffract incident light into guided modes that couple weakly to the diffraction orders of the front grating. This minimizes the number of incoming solar photons escaping solar cells without getting absorbed, thus improving photocurrent and cell conversion efficiency. By varying the degree of mismatch between the front and back gratings, the highest absorption occurs when the least common multiple (LCM) of the periods between the two gratings is large. This approach offers more design flexibility and *yields multiple near-optimum designs*, which can be chosen based on the material and fabrication processes. Interestingly, since our approach reveals that the mismatch between two gratings is the most important parameter, optimum designs can have back gratings with either larger or smaller periods than the front grating.

2. Principle

A simple one dimensional (1D) grating based on triangular grooves, in Fig. 1(a), is chosen in this study to act as a 2D analog of inverted nanopyramids or nanocones, which was shown in previous studies to exhibit good light-trapping performance [15–22,27–28]. By using this grating design, it is possible to apply well-established grating theory to better understand the underlying mechanisms and find a design rule to govern light trapping.

In general, gratings are characterized by their dispersion of light into discrete diffraction orders. These orders are determined by adding a characteristic grating momentum, which depends on the period, to the parallel momentum of incoming light [40],

$$\vec{k}_{2\parallel}=\vec{k}_{1\parallel}+\vec{G}_m \tag{1}$$

where $k_{1\parallel}$ and $k_{2\parallel}$ are parallel wavevectors of the incident and diffracted light respectively, and $\vec{G}_m$ is grating momentum. The subscript $\parallel$ corresponds to the in-plane direction and m is the index for the diffraction order. For the 1D grating in Fig. 1(a), the momentum equation can be simplified as

$$n_2\frac{2\pi}{\lambda}\sin\beta_m=n_1\frac{2\pi}{\lambda}\sin\theta+m\frac{2\pi}{W} \tag{2}$$

where λ is wavelength of light, θ is incident angle, β_m is the diffraction angle for order m, W is the period of the grating, and n_1 and n_2 are refractive indices of air and silicon, respectively. Each diffraction order corresponds to a particular β_m and depends on θ, W, λ, m, and n_2. A drawing of each grating order is shown in Fig. 1 (a).

By using a grating to diffract incident light, the addition of the grating momentum along the film plane direction will lead to an increase in the optical path length of light in PV cells as waves propagate more parallel to the film. In addition, for thin c-Si cells, which support guided modes, the diffraction of light also provides greater opportunities to couple into these modes over a broad wavelength range, resulting in improvements in absorption.

In order to further improve light trapping, a second grating is introduced on the back of the PV cell with a period of W_{2d}, as shown in Fig. 1(b). The purpose of the back grating is to add additional momentum to the diffracted light such that light reflected by the back metal reflector cannot couple back to air through the same diffraction channel. However, it is crucial to note that the addition of a second grating by itself may not lead to better light trapping as improvements will depend on the difference in grating periods, W_{1d} and W_{2d}. For example, if $W_{1d}=W_{2d}=700$ nm, which corresponds to the optimal grating period in the front single grating (SG) case, [41] the front and back gratings support the

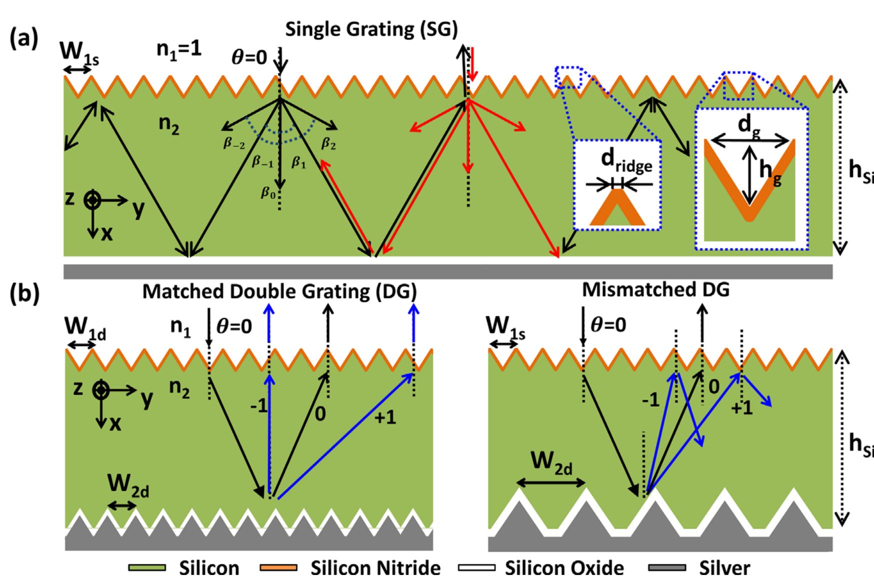

Fig. 1. A schematic of (a) the single grating (SG) case and (b) the double grating case illustrating the design of ultrathin c-Si PV cells. In SG cases, the black and red arrows indicate different diffraction orders of light coupled into c-Si by the front grating for the case where $W_{1s}=700$ nm and $\lambda=1000$ nm. In DG cases, two grating periods are considered and denoted as W_{1d} and W_{2d} for the front and back gratings, respectively. The black and blue arrows correspond to the diffraction orders at the wavelength of 1000 nm. *Two cases are considered: the matched DG case where* $W_{1d}=W_{2d}=700$ nm *and a mismatched DG case where* $W_{1d}=700$ nm *and* $W_{2d}=3100$ nm. The blue arrows represent light at normal incidence diffracted into the 1st diffraction order ($m=+1$) by the front grating. The black arrows represent light diffracted by the back grating. Only the first three diffraction orders ($m=-1,0,+1$) are shown for both cases; however, there are 11 available diffraction orders ($m=-5,-4,-3,-2,-1,0,+1,+2,+3,+4,+5$) for this grating structure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)