Renewable and Sustainable Energy Reviews 66 (2016) 380–398

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Research and development efforts on texturization to reduce the optical losses at front surface of silicon solar cell

M.F. Abdullah [a], M.A. Alghoul [b,c,*], Hameed Naser [d], Nilofar Asim [e], Shideh Ahmadi [f], B. Yatim [d], K. Sopian [e]

[a] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, Kuala Lumpur 54100, Malaysia
[b] Energy and Building Research Center, Kuwait Institute for Scientific Research, P.O. Box 24885, Safat 13109, Kuwait
[c] Center of Research Excellence in Renewable Energy (CoRe-RE), Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[d] The School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Malaysia
[e] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
[f] NOVITAS, School of Electrical and Electronic Engineering, Nanyang Technological University, 639798, Singapore

ARTICLE INFO

Article history:
Received 26 July 2015
Received in revised form
22 June 2016
Accepted 15 July 2016

Keywords:
Silicon solar cell
Optical loss reduction
Role of texturization
Side effect of texturization
Power conversion efficiency

ABSTRACT

Silicon wafer-based solar cell contributes to about 92% of the total production of photovoltaic cells. An average of 30% of the incident light is lost via reflection from the front surface of the silicon solar cell, thus reducing the cell's power conversion efficiency. Texturization is a process of producing the desired unevenness on the surface of solar cell. It is well known as a practical solution to the limitation. Front surface texture reduces cell reflectivity and contributes to more photocurrent generation within active materials. The research and development efforts to reduce the optical losses via texturization are reviewed in this paper. The mechanisms of optical loss reduction, desirable texture feature, methods of texturization, side effects of texturization, and its compatibility with other optical enhancements for crystal silicon cell are elaborated upon. Front surface texture is associated with minimizing optical loss, and negatively affecting carrier and electrical losses. The importance of texturization for crystalline silicon is briefly related with thin film amorphous silicon solar cell to fully encompass this topic. Lesson learned and conclusion is highlighted in the last section.

Contents

Abbreviations: μc-Si, Microcrystalline silicon; a-Si, Amorphous silicon; $AgNO_3$, Silver nitride; AR, Anti-reflection; Ar, Argon gas; AZO, Aluminum-doped zinc oxide; CH_3COOH, Acetic acid; CH_3COONa, Sodium acetate; c-Si, Monocrystalline silicon; Cl_2, Chlorine gas; ClF_3, Chlorine trifluoride; Cr, Chromium; DIW, De-ionized water; H_2O, Water; H_2O_2, Hydrogen peroxide; H_2SO_4, Sulfuric acid; HF, Hydrofluoric acid; HNO_3, Nitric acid; I-V, Current-voltage; IPA, Isopropyl alcohol; J_{sc}, Short circuit current; KOH, Potassium hydroxide; mc-Si, Multicrystalline silicon; N_2H_4, Hydrazine; Na_2CO_3, Sodium carbonate; $Na_2S_2O_8$, Sodium persulfate; Na_3PO_4, Sodium phosphate; $NaHCO_3$, Sodium bicarbonate; NaOCl, Sodium hypochlorite; NaOH, Sodium hydroxide; O_2, Oxygen gas; PDMS, Polydimethylsiloxane; PECVD, Plasma-enhanced chemical vapor deposition; PERL, Passivated emitter and localized; R&D, Research and development; RF, Radio frequency; RIE, Reactive ion etching; SEM, Scanning electron microscopy; SF_6, Sulfur hexafluoride; Si, Silicon; Si_3N_4, Silicon nitride; SDE, Saw damage etchings; SnO_2, Tin oxide; TBA, Tertiary-butyl alcohol; TCO, Transparent conducting oxide; TMAH, Tetramethyl-ammonium hydroxide; V_{oc}, Open circuit voltage; ZnO, Zinc oxide; ZrO_2, Zirconium dioxide

* Corresponding author at: Energy and Building Research Center, Kuwait Institute for Scientific Research, P.O. Box 24885, Safat 13109, Kuwait.
E-mail address: dr.alghoul@gmail.com (M.A. Alghoul).

http://dx.doi.org/10.1016/j.rser.2016.07.065
1364-0321/

1. Introduction

Silicon (Si) wafer-based solar cell contributes to approximately 92% of the total photovoltaic cells production in 2014, while the remaining ~9% are contributed by thin films [1]. According to Saga [2], research and development (R&D) efforts on enhancing the efficiency of Si solar cell are focused on reducing the optical loss using several methods as detailed in Table 1. These include studies on the front surface texture, application of anti-reflection (AR) coating on the front surface, attaining high reflectivity and low light absorption on the rear surface, and back contact cell design to avoid shadow on the front surface. The front surface texture is applicable for both conventional crystalline and thin film amorphous Si solar cell. In this study, we cover topics on textured Si solar cell from multiple perspectives based on various research articles. A critical review is performed on the R&D aspects of textured Si solar cell and the associated issues on texturization. There are five main R&D aspects to be highlighted on Si solar cell texturization, which are the optical loss reduction mechanisms, desirable texture features, methods of texturization, side effects of texturization, and texture compatibility with other optical enhancements. Fig. 1 is an important figure illustrating the overall progress in improving the solar cell performance.

Table 1
Key technologies for highly-efficient crystalline Si solar cells [2].

Aspect	Techniques of improvement
Minimizing photon loss	• Textured front surface • Anti reflection coating • Back-contact cell structure • High reflectivity via flat rear surface • Rear surface reflector of thin metal with dielectric layer
Minimizing carrier loss	• Passivation of (under) front electrode • Shallow-doped p-n junction with front surface dielectric passivation layer • Locally p+-doped back surface field and point contact structure • Back surface passivation by a dielectric layer
Minimizing electrical loss	• Fine front contact gridline • Selective emitter of deep and highly doped emitter under the contact • n-type or p-type Si substrates with minority carrier diffusion lengths that are longer than the base thickness

Earlier on, Green and Keevers [3] studied the optical properties of intrinsic Si and tabulated the absorption coefficient as a function of wavelength. The data which is later being updated as in Ref. [4] indicates that Si is a poor light absorber especially at longer wavelength approaching near infra-red, supported as in Fig. 2(a). Around 1 cm thick Si wafer is needed to successfully absorb the light energy at wavelength close to 1150 nm. The reflection of Si in the visible wavelength range can be obtained in the manner shown in Fig. 2(b) based on the value of real refractive index and extinction coefficient.

More than 30% of the incident light is lost via reflection and this is more pronounced in short wavelength or blue light range. Thus, the optical loss by low absorption in long wavelength and high reflection in short wavelength limit the amount of light that can be converted into electricity in a Si-based solar cell. A technique that addresses both the limitations is the front surface texturization, as mentioned previously, which is our focus of discussion in this article. The mechanism of optical loss reduction in textured Si solar cell can be summarized as in Fig. 3, which are:

i. The presence of front surface texture increases the chance for short wavelength absorption by increasing the surface area, which results in carrier generation and collection closer to the junction.
ii. Multiply the external reflectance of light onto neighboring inclined surface, promotes neighboring light bouncing instead of outside of the solar cell.
iii. Diffraction of the incident light is more than just the zeroth order (happens on planar surface). First and second diffraction orders are promoted into the Si depending on the texture.
iv. Lengthen the optical path for long wavelength to more than double of Si thickness to compensate for its low light absorption coefficient.
v. Light trapping by total internal reflection of the reflected long wavelength from the rear surface. This occurs when light reaches the internal side of the textured surface with an angle exceeding the critical value.

The mechanism of optical loss reduction is initiated once the feature size of the texture reaches its minimum. According to a two dimensional surface grating model and numerical simulation, negligibly very small the texture does not significantly modify the reflectance value. In fact, the reflectance value is similar to that of polished surface if the feature size is not sufficiently big [5] or does not have inappropriate width/height ratio [6]. The reduction of