European Journal of Scientific Research
ISSN 1450-216X Vol.24 No.3 (2008), pp.358-364

http://www.eurojournals.com/ejsr.htm

Enhancement of Optical Absorption in Thin-Film Silicon Solar Cells in Silicon-On-Insulator (SOI) Configuration

Kamaruzzaman Sopian
Solar Energy Research Institute, Universiti kebangsaan Malaysia
(National University of Malaysia), 43600 Bangi, Selangor Malaysia
Tel: +60-3-89214592; Fax: +60-3-89214593

Nilofar Asim
Solar Energy Research Institute, Universiti kebangsaan Malaysia
(National University of Malaysia), 43600 Bangi, Selangor Malaysia
E-mail: n_asim2001@yahoo.com
Tel: +60-3-89214592; Fax: +60-3-89214593

Nowshad Amin
Solar Energy Research Institute, Universiti kebangsaan Malaysia
(National University of Malaysia), 43600 Bangi, Selangor Malaysia
Tel: +60-3-89214592; Fax: +60-3-89214593

Saleem H. Zaidi
Gratings, Incorporated, Albuquerque, NM 87107
Tel: +60-3-89214592; Fax: +60-3-89214593

Abstract

High performance in crystalline thin (~ 10 μm) film silicon solar cells requires complete optical absorption over its spectral range. Geometrical schemes are ineffective due to their large feature dimensions. Enhanced optical absorption can be achieved through two mechanisms based on diffractive and physical optics. In diffractive approach, light confinement is achieved through obliquely propagating transmission orders that effectively fill the frequency space. In the physical optics approach, rigorous coupled wave analysis is used to calculate optical absorption in subwavelength grating structures based on wave guiding mechanism, A 10-μm thick Si film in SOI configuration was chosen to perform a comparative evaluation of these two approaches. Optical transmission of planar Si films was compared with randomly textured and deeply etched two-dimensional gratings structures. Transmission from random structures was diffuse and translucent, while that from gratings, was weak and wavelength-dependent. Although SOI substrates are not practical for large-scale manufacturing, they have been determined to highly effective for understanding and optimizing optical transmission and device performance.

Keywords: Optical absorption enhancement, Thin-film silicon solar cell

1. Introduction

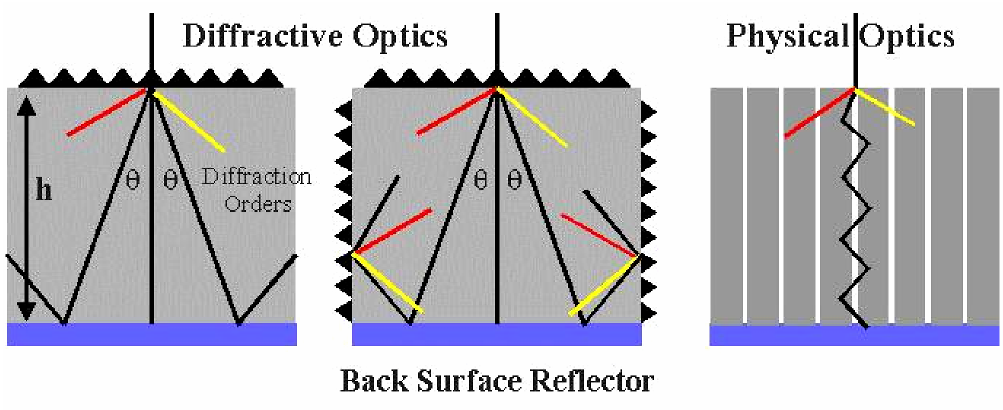
Thin-film crystalline Si solar cells are important because of their potential for significant cost savings relative to standard crystalline Si cells. These savings are achieved directly by reduced Si usage (Munzer et al., 1999), and are possible because thin film Si solar cells can be very efficient. For example, experimental and theoretical studies (Yamamoto, 1999; Yamamoto et al., 2000; Hebling et al., 1997; Iwata et al., 1995; Spitzer et al., 1980) have demonstrated that ~ 15 % efficiency can be realized in crystalline ~ 15 µm film solar cells (Faller and Hurrle, 1999). Approximately 19 % efficient thin film Si solar cells have been reported in 46-µm thick Si films in silicon-on-insulator SOI configuration (Hebling et al., 1997). To demonstrate high efficiency solar cells in thinner ~ 5-10-µm Si films, however, complete optical absorption is required over the entire spectral range. In the UV-visible region, Si has relatively high reflectance, but, it also absorbs strongly (Hebling et al., 1997). By contrast, in the near-IR (800-1100 nm) spectral region, particularly near the band edge, absorption is weak. For example, the absorption depth at $\lambda \sim 1$ µm is ~ 100 µm. This weak absorption fundamentally limits the efficiency of all Si solar cells. In thin films the limitation arises due to incomplete optical absorption, while in thick films the limitation is due to bulk recombination losses. Surface texturing mechanisms are principally aimed at reducing reflection as well as enhancing near IR absorption (Green and Keevers, 1995; Campbell and Green, 1987; Southwell, 1983; Zaidi et al., 2002). Yablonovitch in statistical analysis has shown that total absorption enhancement was $4n^2$ over that of a planar sheet, where n is the index of refraction of the collecting medium (Yablonovitch, 1982).

We propose application of sub-wavelength periodic structures to achieve complete optical absorption in thin Si films beyond the $4n^2$ optical limit through creation of deeply-etched three-dimensional cavity structures. Two optical configurations have been investigated. In the first approach, light confinement is achieved by using diffractive optics. The second approach, based on physical optics, combines low-cost interferometric lithography (Zaidi and Brueck, 1993) with advanced deep reactive ion etching (DRIE) technology (Alcatel Micro Machining Systems website, 2008)to couple light into waveguides perpendicular to film. Rigorous coupled wave analysis (Grating Solver Development Company website, 2008) is used to calculate optical absorption in grating structures. Absorption in such structures can best be understood if each grating structure is considered as waveguide running perpendicular to the surface, as opposed to conventional horizontal, thin-film waveguide structures such as those proposed by Sheng (1984). These highly advanced 3D optical structures are in many ways similar to photonic crystals used for applications such as narrow band filters, resonant cavities and waveguides (Joannopoulos et al., 1995)

2. Optical Absorption based on Diffractive and Physical Optics

Fig. 1(a) shows three configurations used to calculate optical absorption in thin Si films. An Al reflector is used at the backside to enhance optical confinement. In the diffractive optics case; enhanced optical absorption is achieved by coupling the incident beam into obliquely propagating diffraction orders. Here the path length enhancement is $h/\cos\theta$, where h is the film thickness, and θ is the diffraction order propagation angle. Sidewall textured surfaces can create additional diffraction orders to more effectively populate the frequency space. In general, for the diffractive optics mechanism to be effective, surface features must be efficient in bending light obliquely, and deeply etched surfaces to enhance internal diffraction.

Figure 1: Optical absorption in three thin film configurations front surface texture, front surface/sidewall texture, and deeply etched structures through the entire film.



In the physical optics case, the absorption takes place primarily within the grating structures. For the deeply (>>λ) etched structures, a grating line can be considered as a symmetric waveguide supporting an increasing number of modes as its thickness and depth are increased. Optical absorption A_g in grating structures only is given by:

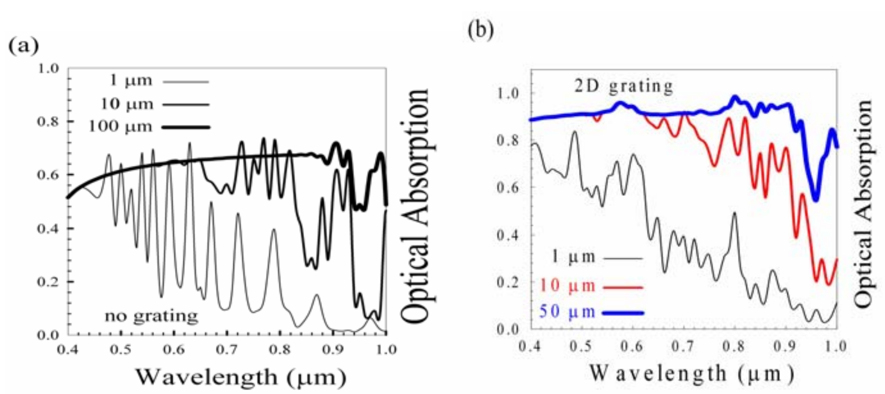
$$Absorption, A_g = 1 - \sum_i R_i - \sum_j T_j \tag{1}$$

where the summation indices i & j include all the radiative and evanescent diffraction orders in air and Si.

With rigorous coupled wave analysis software, we calculated optical absorption for a wide parameter space of subwavelength 1D and 2D structures with Si film thickness in ~ 0-100 µm range for three optical configurations described in Fig. 1. For simplicity, no anti-reflection films are included, and absorption in planar films was calculated without any diffractive structure on the front surface. Fig. 2 plots optical absorption as a function of wavelength for planar films (Fig. 2-a) and for 1-µm period grating structures (Fig. 2-b) for several film thicknesses.

It was found that optical absorption is much stronger in grating structures. This trend is clearly seen in Fig. 3, where the total absorption in 0.4-1.0-µm range is plotted as a function of grating depth. We notice that absorption increase is rapid for depths in ~ 0-10 µm range, after which the absorption increase is very slow. These simulations indicate that with optimized grating structures (period, depth, and duty cycle); almost complete optical absorption would be achievable in ~ 10-µm thick Si films.

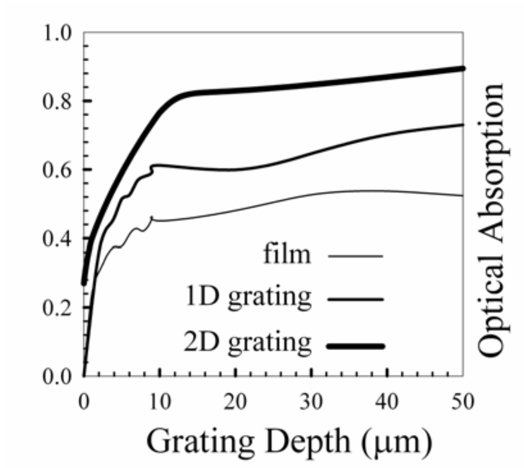
Figure 2: Calculated optical absorption in planar (a) and grating structures (b); back surface Al reflector is used in all cases for light confinement.



3. Experimental Work

Conventional and interferometric lithography techniques were combined with deep reactive ion etching methods to fabricate 10-µm deep structures at 20 µm and 1 µm periods (Zaidi, Brueck, 1997; Zaidi et al., 2000 and 2002)

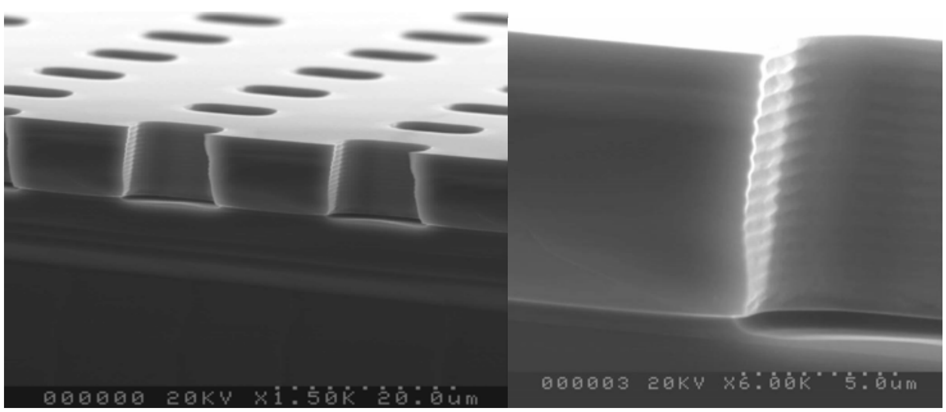
Figure 3: Wavelength-integrated total absorption (over the 0.4-1 um range) variation as a function of grating depth for 1-µm grating period.



4. Results and Discussion

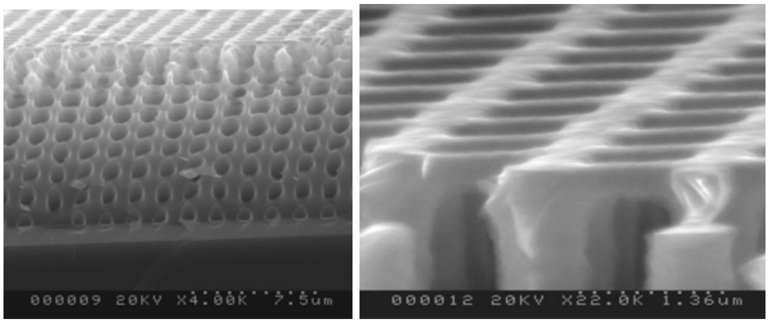
Fig. 4 shows scanning electron microscope (SEM) pictures of two-dimensional (2D) 20-µm period grating etched in 10-µm thick Si in SOI configuration. The sidewall grating structure at a period of ~ 1 µm and the buried oxide layer were found.

Figurer 4: SEM pictures of 2D, 20-µm period gratings etched into 10-µm Si film in SOI configuration.



The sidewall oxide structure is typical of DRIE etching process and can be used for enhanced diffractive coupling. Fig. 5 shows SEM pictures of 2D, 1-µm period grating etched to a depth of 10 µm in the same substrate. The gratings lines were thinner at the top due to lateral undercutting. The linewidths varied from ~ 0.1 µm at the top to ~ 0.4 µm at the bottom of the grooves; the vertical hole pattern is an artifact of the cleavage process.

Figure 5: SEM pictures of 2D, 1-µm period gratings etched into 10-µm Si film in SOI configuration



Preliminary optical absorption and device fabrication results are reported here. In order to qualitatively measure optical transmission, planar and textured SOII substrates were attached to a glass slide and Si was etched from the back side to the from buried oxide layer. A simple CCD camera was used to take pictures with planar, randomly textured, and periodically structured Si films placed in front of it. Fig. 6 shows the pictures with three respective configurations. As shown, there is orange transmission from planar Si, translucent yellowish transmission from randomly-textured film, and weak coherent transmission from gratings pattern.

These measurements, although not precise, nevertheless demonstrate the different optical mechanisms at work. Random structures promote three-dimensional scattering with the results that a coherent image outline is not transmitted. The periodic structure does not scatter light, instead it behaves as an absorptive filter as predicted by first principles calculations. Spectrophotometer measurements are required to determine absorption precisely.

Fabrication of devices was done using interdigitated patterns with $POCl_3$ diffusion, Al-diffused front surface p-contact, and thermally grown oxide films for surface passivation. Fig. 7 shows LIV measurements from planar and 20-µm period structures.

Figure 6: Optical transmission measurements from 10-mm thick Si films in planar (a), randomly-textured (b), and periodically structured (c) configurations

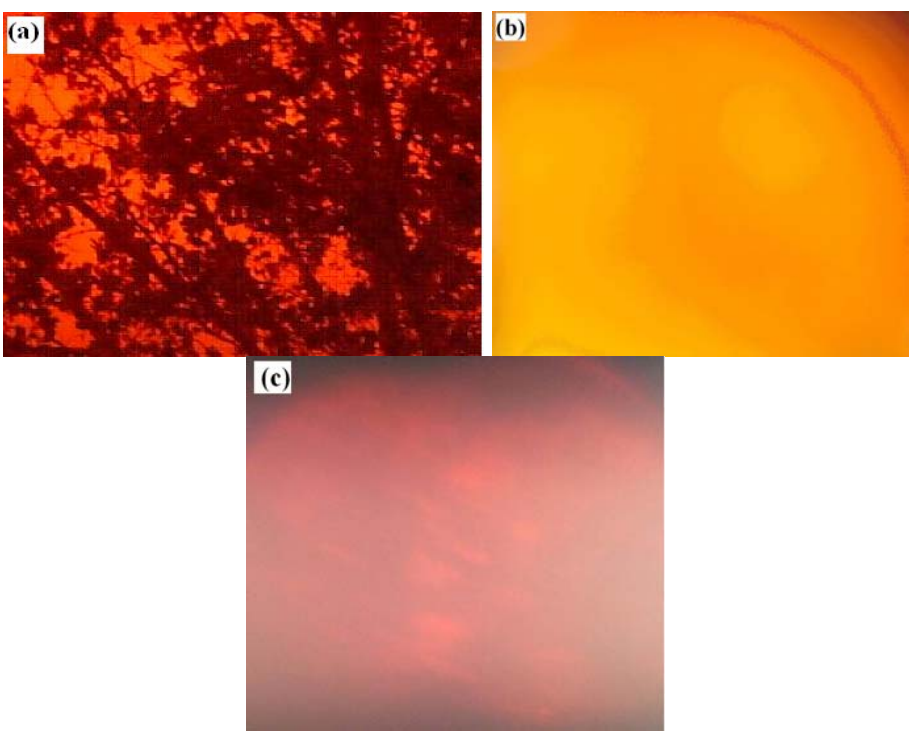
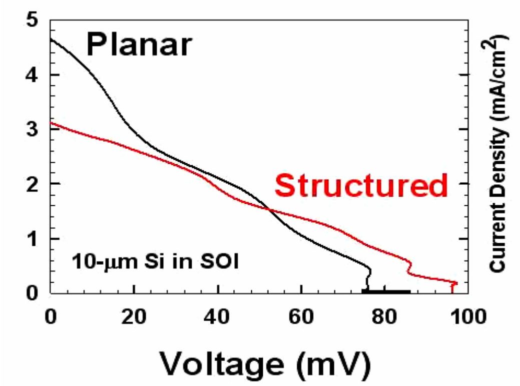


Figure 7: LIV measurements from 10-µm Si thick Si films in SOI configuration.



The devices at 1-µm period exhibited no optical response. Several conclusions can be drawn:

- The V_{OC} values are very low indicating defective emitter and contacts,
- The short-circuit current compares well with bulk (~ 500 µm thickness) or even 100-µm thick devices when volume considerations are considered
- The poor current response of structured device may be attributed to plasma-induced surface damage, and finally
- The 1-µm devices may have been completely diffused due to their fine dimensions.

5. Conclusion

Enhancement of optical absorption in thin film solar cells will increase performance. We have investigated two alternative mechanisms aimed at enhanced absorption in thin Si films. Qualitative measurements indicate higher absorption in periodically structured surfaces. Solar cell fabrication in such structures must address surface damage removal during plasma etching and aim at sub-100 nm junction formation using such methods as ion or plasma implantation.

References

[1] Campbell, P. and Green, M.A., 1987. "Light Trapping Properties of Pyramidally Textured Surfaces", *Journal of Applied Physisc*, 62, pp. 243-249

[2] Faller, F.R. and Hurrle, A., 1999. “High-Temperature CVD for Crystalline-Silicon Thin-Film Solar Cells” *IEEE Transaction on Electron Devices, 46,* pp. 2048-2054

[3] Green, M.A. and Keevers, M.J., 1995. “Optical Properties of Intrinsic Silicon at 300K”, *Progress in Photovoltaics Research and Applications*, 3, pp. 189-192

[4] Hebling, C., Glunz, S.W., Schumacher, J.O. and Knobloch, J.,1997. “High-efficiency (19.2\%) silicon thin-film solar cells with interdigitated emitter and base front-contacts”, Proceedings of the 14th European Photovoltaic Solar Energy Conference, pp.2318-2321

[5] Iwata, H., Ohzone, T. and Takakura, H., 1995. “Numerical simulation of silicon-on-insulator thin-film solar cells”, Japanese journal of applied physics, 34 (1), pp. 4055-4061

[6] Joannopoulos, J.D., Meade, R.D. and Win, J.N., 1995. Photonic Crystals: Molding the Flow of Light, Princeton University Press

[7] Munzer, A.A., Holdermann, K.T., Schlosser, R.E. and Sterk, S.,1999.“ Thin Monocrystalline Silicon Solar Cells”, *IEEE Transaction on Electron Devices,* 46, pp.2055-2061

[8] Spitzer, M., Shewchum, J., Vera, E.S. and Lofenski, J.J., 1980. “Ultra High Efficiency Thin Silicon P-N Junction Solar Cell Using Reflecting Surfaces”, I4th IEEE Photovoltaic Specialists Conference, pp. 375-380

[9] Southwell, W.H., 1983. "Gradient-index antireflection coatings", *Optics Letters,* 8, pp.584-586

[10] Sheng, P., 1984. “Optical absorption of thin film on a Lambertian reflector substrate”, *IEEE Transaction on Electron Devices,* 31, pp.634-636

[11] Website of the Alcatel Micro Machining Systems, www.alcatelmicromachining.com

[12] Website of the Grating Solver Development Company,www.gsolver.com

[13] Yablonovitch, E.,1982. “ Statistical ray optics”, *Journal of the Optical Society of America*, 72(7), pp.899-907

[14] Yamamoto, K., 1999. “Very Thin Film Crystalline Silicon Solar Cells on Glass Substrate Fabricated at Low Temperature” *IEEE Transaction on Electron Devices*, 46, pp. 2041-2047

[15] Yamamoto, K., Yoshini, M., Suzuki, T., Nakata, T., Swada, T. and Hagashi, K., 2000. *28^{th} IEEE PVSC,* pp. 1428

[16] Saleem H. Zaidi and Brueck, S.R.J., 1993. “Multiple-Exposure Interferometric Lithography” *Journal of Vacuum Science & Technology B, Second Series*, 11, pp. 658-666

[17] Saleem H. Zaidi, Brueck, S.R.J., 1997. “Si texturing with sub-wavelength structures”, 26^{th} *IEEE photovoltaic specialists conference*, pp. 171-174

[18] Saleem H. Zaidi, Gee, J.M. and Ruby, D.S., 2000. “Diffraction grating structures in solar cells”, 28^{th} *IEEE photovoltaic specialists conference*, pp.395-398

[19] Saleem H. Zaidi, Marquardt, R., Minhas, B., and Tringe, J.W., 2002. “Deeply etched grating structures for enhanced absorption in thin C-Si solar cells”, 29^{th} *IEEE photovoltaic specialists conference*, pp.1290-1293

[20] Saleem H. Zaidi, Ruby, D.S., Dezetter, K., and Gee, J.M., 2002. “Enhanced near IR absorption in random, RIE textured silicon solar cells: the role of surface profiles”, Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE, pp.142-145