Highly Efficient Dome Shaped Nanowires Solar Cell

R. El-Bashar,[1] Mohamed Farhat. O. Hameed,[2*] S. S. A. Obayya [2*]

[1]National Institute of Laser Enhanced Sciences (NILES), Cairo University, Giza 12613, Egypt
[2]Center for Photonics and Smart Materials, Zewail City of Science and Technology, October Gardens, 6th of October City, Giza, 12578 Egypt. *E-mail: mfarahat@zewailcity.edu.eg, sobayya@zewailcity.edu.eg

Abstract— The optical characteristics of Si dome-tapered nanowires (NWs) solar cell (SC) are reported and analyzed by using finite difference time domain method. The geometrical parameters are studied to maximize the light absorption and hence the ultimate efficiency and short circuit current density of the reported NWs SC. The dome-shaped NWs show better absorption enhancement than the conventional conical design especially in the longer wavelength range. This is due to the better tapering gradient of the active material compared to the conventional conical-NWs. Therefore, the light reflection is reduced from the proposed NWs while the absorption is improved. The ultimate efficiency of the dome and conical shaped NWs are equal to 38% and 34.9%, respectively. Further, the achieved short circuit current density is equal to 33.6 mA/cm^2 with an improvement of 12.5% compared to the conical-NWs.

***Index Terms*— Plasmon surface resonance, Solar cell, Periodic boundary condition, Perfect matched layer.**

There is growing global demand for low cost solar cells (SCs) with high efficiency [1]. The 1st generation of bulk Si solar cell has high cost and it is still nearly 85% of the worldwide market. Thin-film (TF) based SC has been presented as a 2nd generation to reduce the cost. However, the power conversion efficiency has been reduced [2]. Over the past decade, nanowires (NWs) nanostructures [3]–[5] have been suggested to replace the thin film (TF) active material with better performance and low cost [6], [7]. The conventional cylindrical NWs array was proposed with an ultimate efficiency (η) of 12.5% [8]. In order to boost the efficiency of the NWs SC, different geometries are studied such as conical NWs [6] and nanohole (NH) NWs [9]. It has been shown that the NHs array exhibits a higher power absorption compared to the conventional NWs [10]. The conical nanostructure offers a superior top surface antireflection capabilities owing to the smaller Si volume of top nanocone surface [11]. It has been shown that conical NWs offer an ultimate efficiency of 36.3% with an improvement of 16.5% compared to the conventional NWs [6]. Tapered NWs SC also improved the photovoltaic characteristics by 23 % in the short circuit current compared to the bunched NWs array[12]. Further, dome-textured SC has a light absorption of 94% over wavelength range from 400 to 800 nm compared to 65% absorption of the flat films SC [13]. To further increase the light harvesting, the dome-tapered NWs is optically studied in this paper compared to conventional conical NW.

In this work, the dome-tapered NWs arranged in hexagonal lattice are studied to maximize the light absorption. Figure 1 shows the 3D diagram and the unit cell of the studied dome-tapered NWs. A logarithmic gradient factor (m) of the NW tapering is defined to govern the NW tapering in the longitudinal direction which equals to unity for perfect conical NW. The total length of the studied SC is taken by 2330 nm to be comparable to the thickness of the typical planar TF SC [8]. In this study, the NW thickness (T_w) is taken by 2000 nm and thus the substrate length is equal to 230 nm. Similar to structure of the Moth-eye insect [14], the NW array is set in hexagonal lattice. The bottom NW radius (R_o) is taken as 300 nm as suggested in [15] while the periodicity is equal to 600 nm.

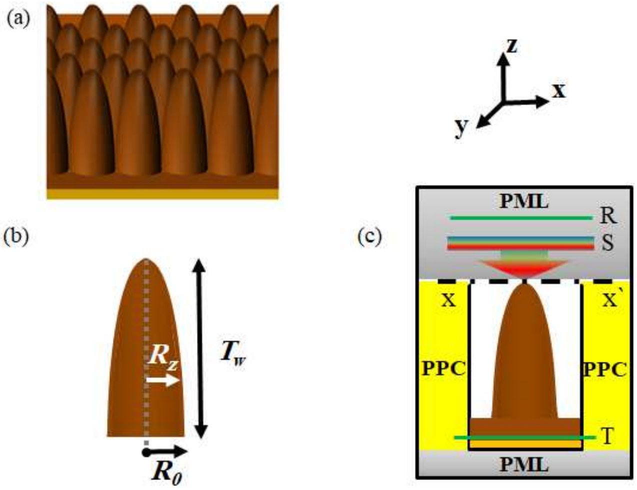

Fig. 1. (a) 3D view of dome-tapered NW array architecture, (b) the corresponding single NW in 2D and (c) the side-view in x-z plane of the studied unit cell with a bottom Si substrate and metal contact.

A tapering parameter (m) is defined to control the NW dome tapering from the conventional cone-shaped NW. The NW radius at a certain z-position (R_z) from the Si substrate-top can be given by

$$R_z = R_o[1 - \frac{z}{T_w}]^{1/m} \qquad (1)$$

where T_w is the NW length, R_o is the NW bottom-radius of the NW and z is the distance from the substrate top. In this study, the taper order is taken as 3 while m=1 for conventional cone-NW. The finite-difference time-domain (FDTD) method is utilized to study the optical characteristics of the reported design via FDTD Lumerical software package [16]. To mimic the open boundaries and absorbing the outgoing field waves, a perfect matched layer (PML) is used in z-direction as shown in Fig. 1(b). In addition, to reduce the computational time, a periodic boundary condition (PBC) layer is taken in the 2D lateral direction (*x*- and *y*- planes) [5]. The optical absorption (A) of the studied NW structure is investigated by evaluating the reflectance (R) and transmittance (T) though a frequency domain field monitor as shown in Fig. 1 (c). The material permittivity of the Si material and the Ag metal constant are evaluated based on Palik model [17]. In this study, the geometry of the proposed NWs is swept to maximize the ultimate efficiency (η) and then the short circuit current density *(J_{sc})*. To evaluate the useful absorption capabilities of the reported nanostructure, the ultimate η is weighed which is identified by [8]:

$$\eta = \frac{\int_{300nm}^{\lambda g} I(\lambda) * \frac{\lambda}{\lambda_g} * A(\lambda) d\lambda}{\int_{300nm}^{4000nm} I_G(\lambda) d\lambda} \times 100 \ (\%) \qquad (2)$$

where $I_G(\lambda)$ is the global solar irradiance (AM-1.5G) well-defined by the American Society for Testing and Materials (ASTM) with an average solar power of 100 mW/cm^2 [5]. The minimum and maximum of the solar spectra have wavelengths of 300 nm and 4000 nm, respectively and $\lambda_g = 1100$ nm is the bandgap wavelength of Si corresponding to bandgap energy of 1.12 eV [18]. Regarding to the optical investigation, every absorbed photon (i.e. $\lambda \leq$ bandgap wavelength) creates only one electron-hole (e-h) carrier. Consequently, the ideal J_{sc} can be estimated from the ultimate η as given in [19]

Figure 2 shows the absorption of the studied NWs design with tapering factor of 3 compared to the conventional cone-NWs structure with m=1. It may be seen that the suggested design has better absorption than the conventional conical NWs for longer wavelength than 600 nm. The achieved light absorption enhancement is due to the increase of the tapering gradient of the active material compared to conventional conical-NWs design. Such gradual volume growth lessens the light reflected and enhance internal light reflections inside the active material of the suggested dome-tapered NW structure [15]. Further, the waveguide modes coupling through the suggested tapered NW are increased which increase the light absorption. The ultimate η of the suggested and conventional NWs are equal to 38% and 34.9%, respectively. The superior J_{sc} and of the optimized-dome-NW design are equal to 33.6 mA/cm^2 with an improvement of 12.5% compared to the reported conical-NW designs.

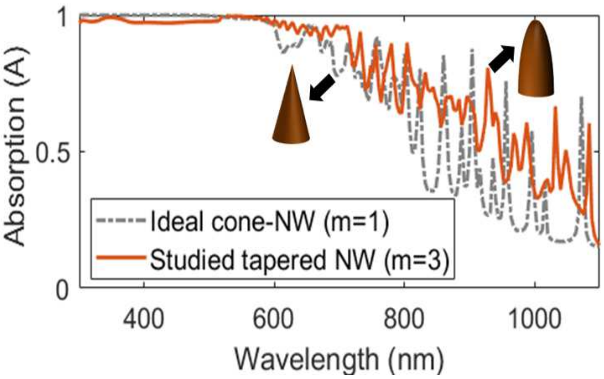

Fig. 2. Absorption spectra for the dome and conical NWs.

ACKNOWLEDGMENT

The authors acknowledge the financial support by Academy of Scientific Research and Technology (ASRT) at Egypt under the South Africa-Egypt Cooperation.

REFERENCES

[1] H. A. Aribisala, "Improving the efficiency of solar photovoltaic power system," 2013.

[2] U. W. Paetzold, *Light trapping with plasmonic back contacts in thin-film silicon solar cells*. Forschungszentrum Jülich, 2013.

[3] G. Y. Abdel-Latif, M. F. O. Hameed, M. Hussein, M. A. Razzak, and S. S. A. Obayya, "Electrical characteristics of funnel-shaped silicon nanowire solar cells," *J. Photonics Energy*, vol. 7, no. 4, p. 47501, 2017.

[4] M. Hussein *et al.*, "Ultra-high efficient solar cell based on decagonal arrays of silicon nanowires," *spiedigitallibrary.org*, 2014, doi: 10.1117/1.OE.53.11.117105.

[5] R. El-Bashar, M. Hussein, S. Hegazy, Y. Badr, M. Hameed, and S. Obayya, "Analysis of Highly Efficient Quad-Crescent-Shaped Si Nanowires Solar Cell," *Opt. Express*, vol. 29, no. 9, pp. 13641--13656, 2021, doi: 10.1364/oe.417652.

[6] B. Wang, E. Stevens, and P. W. Leu, "Strong broadband absorption in GaAs nanocone and nanowire arrays for solar cells," *Opt. Express*, vol. 22, no. S2, p. A386, 2014, doi: 10.1364/OE.22.00A386.

[7] S.-K. Kim, J. F. Day R. W. andCahoon, T. J. Kempa, K. D. Song, H.-G. Park, and C. M. Lieber, "Tuning Light Absorption in Core/Shell Silicon Nanowire Photovoltaic Devices through Morphological Design," *Nano Lett.*, vol. 12, p. 4971−4976, 2012.

[8] L. Hu and G. Chen, "Analysis of optical absorption in silicon nanowire Arrays for photovoltaic applications," *Nano Lett.*, vol. 7, pp. 3249–3252, 2007, doi: 10.1021/nl071018b.

[9] G. Attolini, F. Rossi, F. Fabbri, M. Bosi, G. Salviati, and B. E. Watts, "Cubic SiC nanowires: growth, characterization and applications," in *Nanowires*, IntechOpen London, 2010.

[10] A. Shang, X. Zhai, C. Zhang, Y. Zhan, S. Wu, and X. Li, "Nanowire and nanohole silicon solar cells: a thorough optoelectronic evaluation," *Prog. Photovoltaics Res. Appl.*, vol. 23, no. 12, pp. 1734–1741, 2015.

[11] B. Wang and P. W. Leu, "Enhanced absorption in silicon nanocone arrays for photovoltaics," *Nanotechnology*, vol. 23, no. 19, 2012, doi: 10.1088/0957-4484/23/19/194003.

[12] J.-Y. Jung, Z. Guo, S.-W. Jee, H.-D. Um, K.-T. Park, and J.-H. Lee, "Optically improved solar cell using tapered silicon nano wires," in *10th IEEE International Conference on Nanotechnology*, 2010, pp. 1163–1166.

[13] S. Joseph and J. Joseph, "PDF- Influence of periodic texture profile and parameters for enhanced light absorption in amorphous silicon ultra-thin solar cells," *Appl. Opt.*, vol. 56, no. 17, p. 5013, 2017, doi: 10.1364/ao.56.005013.

[14] R. H. Siddique, G. Gomard, and H. Hölscher, "The role of random nanostructures for the omnidirectional anti-reflection properties of the glasswing butterfly," *Nat. Commun.*, vol. 6, no. 1, pp. 1–8, 2015.

[15] M.-D. Ko, T. Rim, K. Kim, M. Meyyappan, and C.-K. Baek, "High efficiency silicon solar cell based on asymmetric nanowire," *Sci. Rep.*, vol. 5, no. 1, pp. 1–8, 2015.

[16] "Ansys / Lumerical Inc.," *Lumerical*, 2015. https://www.lumerical.com/ (accessed Feb. 02, 2020).

[17] E. D. Palik, *Handbook of optical constants of solids*, vol. 3. Academic press, 1998.

[18] B. G. Streetman and S. Banerjee, *Solid state electronic devices*. Prentice-Hall of India, 2001.

[19] & O. El-Bashar, R., Hussein, M., Hegazy, S. F., Badr, Y., Hameed, M. F. O., "Efficient Silicon Nanowires Solar Cell," 2021.