

SILICON COMPOSITE FILMS AS AN ANTI-REFLECTION COATING LAYER FOR THIRD GENERATION PHOTOVOLTAIC

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Abstract

Anti-reflection coating (ARC) layer is a thin dielectric layer to be useful on the surface of photovoltaic cells due to its supportable reduced carrier recombination. The silicon composite film acts as an ARC layer that can collect the desired light wavelength. In this work, silicon composite ink (Si-ink) consisting of silicon powder and phospho-silicate glass solution (PSG-sol) was prepared by the sol-gel technique at the low temperature. Silicon powder at the average diameter of around 4 microns was produced in-house by grinding technique. Silicon composite films were formed on quartz substrates by spin coating technique. The effects of the varying Si concentrations on the electrical resistivity, and the optical, properties were studied to find the optimal Si dense. It is found that the Si composite films provide the basal absorption edge shifting to the higher energy along with the decrease of Si dense, and also the optical band gap of Si composite films computed by Tauc plot were shown the expanding value to the higher energy from 1.2 eV to 1.7 eV. The refractive index and extinction coefficient of the Si composite films are much lower than Si bulk. The refractive index of the Si composite film can be adjustable by varying the Si dense. The optimal Si composite conditions are in the ratio of PSG-sol:Si as 1:0.050 and 1:0.025 to provide good dielectric, low reflectance, high absorbance properties. The Si composite film with PSG matrix can be a promising approach for ARC layer in the third-generation solar cells.

Keywords: Anti-reflection coating, silicon ink, phosphosilicate glass, silicon composite film

Introduction

Solar cells have normally been used for generating electrical power from sunlight directly. They have many types such as crystalline silicon solar cell, amorphous silicon solar cell, GaAs solar cell, perovskite solar cell, organic solar cell, multijunction solar cell and etc (Glunz *et al.*, 2012;

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Amador-Bedolla *et al.* 2013; Battaglia *et al.*, 2016; Moon *et al.*, 2016; Qarony *et al.*, 2017; Philipps *et al.*, 2018; Sahoo *et al.*, 2018). Currently, crystalline silicon solar cells are the most popular and installed in many countries due to it provides the high-power conversion efficiencies (PCE), long lifespan and has lower prices than the other types. However, it was challenged to reach the maximum PCE due to the light losses from surface reflection, charge recombination in the material and temperature (Chee *et al.*, 2018). Hence Anti-reflection coating (ARC) layer is the essential element on the solar cell surface to reduce the light reflection and improve light absorption.

Silicon quantum dots (SiQDs) and Si nanocrystals (Si-nc) embedded in a dielectric matrix have been studied for tuning of energy bandgap (E_g) due to the use of quantum confinement effect (Cho *et al.*, 2007; Conibeer *et al.*, 2008; Bagher, 2016). The SiQDs have been able to be a heterojunction as an absorber layer in the tandem solar cell for further obtaining energy in the wider wavelength from the sunlight more than a single Si p-n junction solar cell (Dutta *et al.*, 2019; Kim *et al.*, 2019). Due to the properties of Si solar cell have the energy bandgap of the material of 1.1 eV and a limitation of light conversion under the detailed balance limit of efficiency of p-n junction solar cell by 30% (Shockley and Queisser 1961). However, theoretically, the tandem solar cell which absorbs more sunlight due to the arrangement of E_g series constrained tandem stacks can provide limiting efficiency to 86.8% (Brown and Green, 2002).

Past few decades, The SiQDs were embedded in the various dielectric matrix with high energy bandgaps such as silicon dioxide (SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4) and zinc oxide (ZnO) to improve the optical qualities of solar cell and optoelectronic devices (Hao *et al.*, 2009; Kim *et al.*, 2005; Higuera-Valenzuela *et al.*, 2018; Castaldo *et al.*, 2014; Kole and Chaudhuri, 2014), this matrix is able to be fabricated by sputtering technique (Lee *et al.*, 2016), plasma-enhanced chemical vapor deposition (PECVD) technique (Yu *et al.*, 2015), ion implantation (Karmouch *et al.*, 2013) and pulsed laser ablation (Gan *et al.*, 2011). Their E_g can expand depended on the number of layers of the film and the size of their Si nanocrystal. However, our previous work (Fangsuwannarak *et al.*, 2021) have used the micro-crystal sizes from waste silicon powder with embedded of nanocrystal grain boundary in ZnO doped with bismuth matrix to form a Si dot film. The film coated on solar cell can provide the gain of power conversion efficiency by 1.5% compared with a conventional silicon cell.

The simulation study of ARC layer on solar cell surface was described by using PC1D

simulation application (Hashmi *et al.*, 2018). The report showed the reflectance the solar cell with and without ARC layer with different types of ARC layer such as zinc sulphide (ZnS), silicon carbide (SiC), silicon dioxide (SiO_2), titanium dioxide (TiO_2), zinc oxide (ZnO) and silicon nitride (Si_3N_4). The results were revealed the lowest light reflection for solar cell with the ARC layer at wavelength of 600 nm which place is the highest intensity irradiance located. Moreover, the double-layer antireflection coatings (DLARC) of $\text{SiO}_2/\text{SiN}_x\text{:H}$ on solar cell surface also have been reported that it assists the decrease of light reflection at UV and IR wavelength and it can provide the PCE more than single layer of $\text{SiN}_x\text{:H}$ by 0.32% (Li *et al.*, 2014).

As a wide bandgap of dielectric matrix materials, these thin ARC films have been attracting attention for opto-electronic devices, in the particular crystalline silicon solar cells. However, the commercial ARC as SiO_2 or Si_3N_4 film on the p-n junction Si cells has been produced by using plasma enhanced chemical vapor deposition (PECVD) technique with such high purity of the chemical-gases between silane (SiH_4) and ammonia (NH_3) for silicon nitride ARC layer (El amrani *et al.*, 2008). The aim of this work is to study the silicon composite film consisting of Si powder in a phospho-silicate (PSG) matrix at the comparatively low temperature and to utilize Si powder by recycling waste-Si wafers mixed PSG-sol for transmogrifying into Si composite ink as the main source of Si composite thin films. The various densities of Si composite have induced the changes in the electrical resistivity, optoelectrical properties and absorbance mechanism.

Experimental Details

Si ink was composed of tetraethyl orthosilicate (TEOS, $\text{Si}(\text{OC}_2\text{H}_5)_4$, ethanol (EtOH , $\text{C}_2\text{H}_5\text{OH}$), orthophosphoric acid (H_3PO_4 , 85%), hexadecyltrimethyl ammonium bromide (CTAB, $\text{C}_{19}\text{H}_{42}\text{BrN}$), DI water (DI, H_2O), and silicon powder from grinding technique in previous work (Laohawiroj *et al.*, 2018). First, prepared 5 millimolar of CTAB solution (CTAB-Sol) by dissolving CTAB with DI at room temperature. the volume ratio of TEOS: EtOH :CTAB-Sol of 5:10:1.5 was a precursory substance that mixed on a hot plate stirrer at a temperature of 70°C for 5 min. After that, H_3PO_4 was added into the mixture to obtain the phosphorus atom of 0.5% in the solution. Then the mixture was continued stirring for 30 min and following aged for 48 h in order to obtain a clear PSG solution. After that, the various amount of Si powder was added in the PSG solution to acquire the Si-ink which has the

concentration between Si powder and PSG sol in range of 0:1 to 0.075:1, respectively. Then the Si-inks were blended by ultrasonic to disperse the accumulated Si powder for 10 min. The Si ink was instantaneously spun on quart substrates with a spin rate of 2,500 rpm for 30 sec and baked at 50°C for 1 h. The thickness of the film was measured by an optical surface profiler (Bruker).

The optical microscope was used to observe the dispersion of silicon powder. The electrical properties of the film for getting the relationship between the current density and voltage curve were analyzed by two probe methods (Lataste, 2010; Singh, 2013), which have 0.05 cm diameter of silver metal contacts for becoming electrical current pass through the film. And the intensity of the light for the illumination test is about 1.77 mW/cm². The resistivity (ρ) can be calculated by using the Equation (1) (Kaewphoka *et al.*, 2014).

$$\rho = \frac{R \times A}{l} = \frac{R \times (t \times D)}{l} \quad (1)$$

where R is the electrical resistance (Ω)
 A is the cross section area of the electrical measurement (cm²)
 l is the length between metal contact (cm)
 t is the thickness of the PSG thin film with Si concentration (cm)
 D is the diameter of the electrode (cm)

The optical properties of the film were analyzed by UV VIS spectrophotometer (PerkinElmer Inc.,

series LAMDA 950) for observing the light transmittance (T) and reflectance (R) with the wavelength of 200-1,250 nm. We have calculated the absorption coefficient from Equation (2) to observe the light absorption and used the Tauc plot to estimate E_g of the PSG film with various Si concentration from Equation (3) (Pankove, 1976; Aziz *et al.*, 2016). Moreover, the extinction coefficient and refractive index were also calculated by using the Equations (4) and (5) (Pankove, 1976; Abdullah *et al.*, 2017), respectively.

$$\alpha = \frac{1}{t} \ln \left(\frac{\sqrt{(1-R)^4 + 4T^2 R^2} - (1-R)^2}{2TR} \right) \quad (2)$$

$$\alpha h\nu = C(h\nu - E_g)^N \quad (3)$$

$$k = \frac{\alpha \lambda}{4\pi} \quad (4)$$

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \quad (5)$$

where α is an absorption coefficient (cm⁻¹)
 t is the thickness of the film (cm)
 R is the reflectance of light
 T is the transmittance of light
 $h\nu$ is the photon energy
 C is a constant for an allowed indirect transition
 E_g is the bandgap energy
 N is equal to 2 for an allowed indirect transition
 k is an extinction coefficient
 n is the refractive index

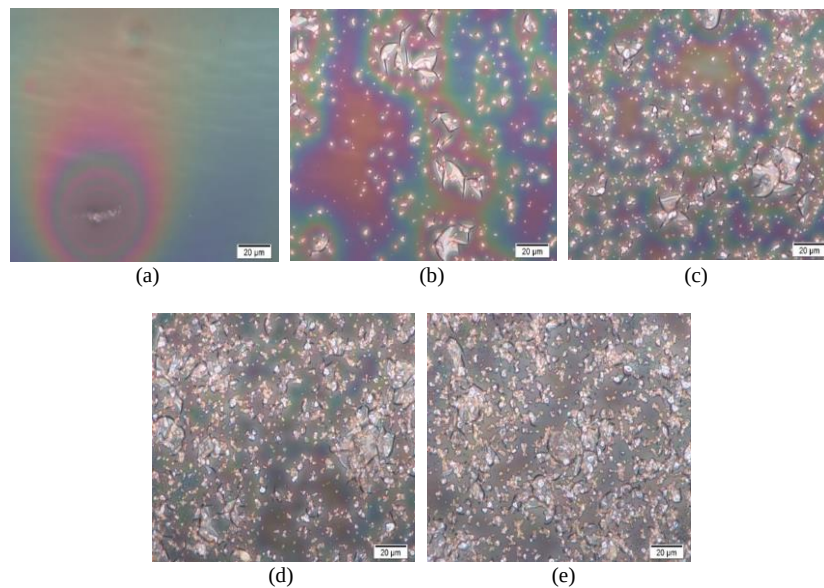


Figure 1. Shows illustration from the optical microscope with a magnification of 1000x of the a) PSG thin film and PSG thin film with Si in a concentration of Si powder : PSG of b) 0.015 : 1, c) 0.025 : 1, d) 0.05 : 1 and e) 0.075 : 1

Results and Discussion

Figure 1 shows the surface morphology of PSG thin films with varying Si concentration ratios of Si powder and PSG-sol from the fraction of 0:1 to 0.075:1. For PSG film, it reveals the smooth surface and some defects in the film, whereas the increase in the concentration of Si powder obviously revealed the dense existences of silicon particles in the film. An optical surface profiler was used for measuring the average thickness of the film and the films have the thickness in a range of 390 – 600 nm as shown in Table 1.

Figure 2 shows the result of current density (J) with an increase of voltage (V) for PSG thin film and PSG thin film with Si powder by using the 2-probe method. The linear relationship of the J-V curve in both dark and illumination tests were expressed the Ohmic behavior between a silver metal contact and PSG film as shown in Figures 2(a) and 2(b). The comparison of J-V curves under dark test and illumination test was described in Figures 2(c) and 2(d). They revealed the PSG thin film with a Si concentration of 0.025:1 that has the current density higher than bare PSG film, on the other hand, the current density of the other films is lower. The PSG thin films with Si in various concentration provided the current density in dark test in the range of 10^{-2} to 10^{-3} A/cm² at 10 V. However, the illumination test indicated the light-induced degradation from the

decrease of current density, it is due to the defect in the impurity of PSG and Si powder (Dhamrin *et al.* 2002; Lindroos and Savin, 2016; Meyer *et al.*, 2019). Table 1 shows the result of resistivity from computing with Equation (1) and expressed the increase of resistivity in illumination test.

Table 1. Shows the resistivity of the PSG film and PSG film with various Si concentration

Si:PSG	Thickness (nm)	Resistivity (Ωcm)	
		Dark test	Illumination test
PSG	606	4.05×10^2	3.15×10^3
0.015:1	515	9.91×10^3	3.60×10^4
0.025:1	548	1.18×10^2	1.49×10^3
0.05:1	390	3.51×10^2	1.24×10^3
0.075:1	478	4.12×10^2	3.17×10^3

Figures 3 and 4 show the reflectance and transmittance spectra in the wavelength range of 200-1,200 nm for PSG thin films composed of the different Si fraction ratios, respectively. It is found that the Si composite films present the minimum reflectance of 5-8% in the wavelength range of 450-550 nm. The wider range of minimum reflectance found in the Si composite film is very effective ARC requirement in the solar cell, while commercial ARC film provide the minimum %R at the one wavelength. It is indicated that the Si composite films can be an effective candidate for an ARC

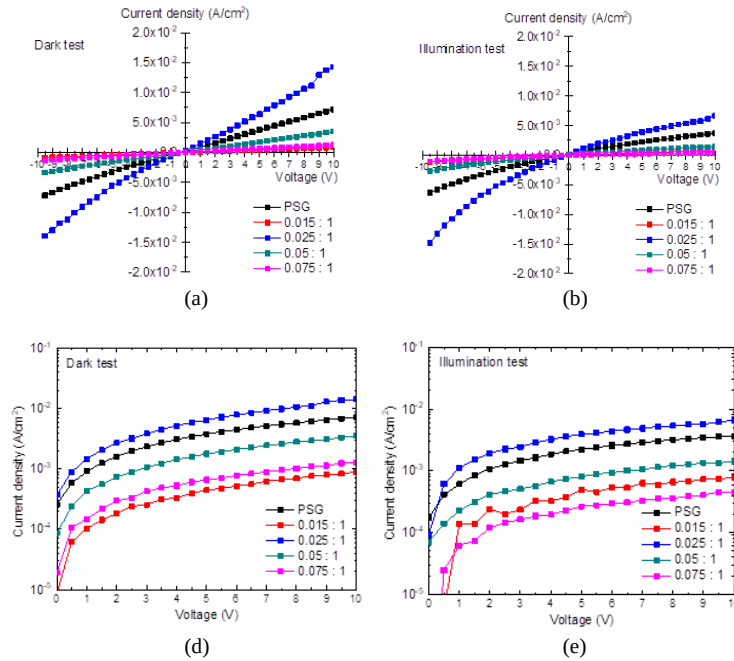


Figure 2. Relationship between current density and voltage of PSG thin film and PSG thin film with various concentration of Si powder in dark and illumination test for (a) (b) linear graph and (c) (d) semi-log graph, respectively

layer due to presence of the potential to trap the high photon energy (Tang *et al.*, 2014) and reduce the optical loss for the window layer of solar cells. Furthermore, all transmittance spectra of the film are higher than 60% which indicates that the remaining light can penetrate through to the other active layer of the underneath films. For considering the light absorption of the film, the Equation (2) was used and plotted as shown in Figure 5.

From Figure 5, the PSG thin film and Si composite film with condition of 0.015:1 revealed the high absorption coefficient in the range of 200-225 nm wavelength, which can imply that an absorbance edge is in only the high photon energy in UV region. Meanwhile, the increasing concentration of Si composite from 0.025:1, 0.05:1 and 0.075:1 present an extended absorption edge to 720, 840, and 890 nm, respectively, which can indicate that these films can improve the light absorption ability from the UV through the IR wavelength. The absorbance edge implying to the optical band gap (E_g) of Si composite shift into the lower photo energy near at 1.1eV (E_g of a Si bulk) when the Si concentration is denser.

Figure 6 shows the optical energy bandgap estimation from Tauc plot Equation (3). When the Si concentration is decreased in the PSG thin film, it presents the blue shifted spectra (higher photon energy) from 1.1 eV, which is original energy band gap of Si bulk into 1.4eV, 1.5eV, and 1.7eV for the sample conditions of 0.075:1, 0.05:1 and 0.025:1, respectively. It is most probable due to the increase of localized states within the forbidden band gap of the film (Abdullah *et al.*, 2017). Meanwhile, PSG film as a doped-silica material indicates the wide bandgap replied from the absorption edge at 5.7eV relating to E_g about 5-9 eV of silica materials. It is noticed that the absorption edge of the lowest Si dense (0.015:1 sample) is close to that of PSG film. A few increasing Si concentration of 0.025:1 indicates the 2-seperating curve that behaves the 2 roles of silicon composite and silica materials.

In addition, other composite films consisting of silicon in various matrix can also occur the phenomenal blue shifting of the energy band gap, such as silicon nanocrystals embeded in SiC matrix, silicon quantum dot in silicon rich oxide (SRO), Si quantum dots in a hydrogenated SiN_x and silicon dot in ZnO as shown in Table 2. However, their thin films were fabricated with high temperature and high pressure to obtain the nano sized silicon.

The curves of extinction coefficient and refractive index in Figures 7 and 8 were computed by relationship in Equations (4) and (5), respectively. The evaluation of the optical losses in Figure 7 as the result of optical absorption and light scattering were described. From the optical loss

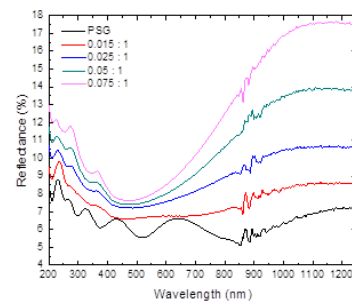


Figure 3. Reflectance of PSG thin film and PSG thin film with various Si concentration

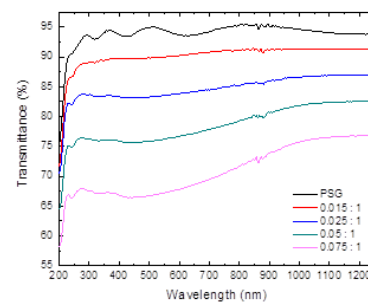


Figure 4. Transmittance of PSG thin film and PSG thin film with various Si concentration

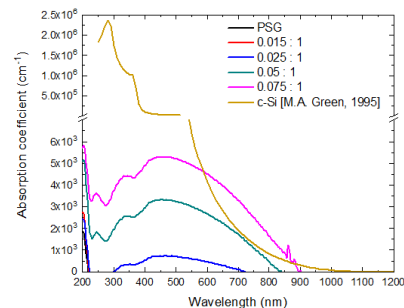


Figure 5. Absorption coefficient of PSG thin film and PSG thin film with various Si concentration

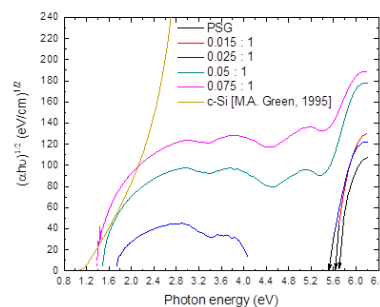


Figure 6. Optical bandgap estimation at the absorbance edge curve of films with various Si concentration

results, the PSG thin film and low Si concentration film of 0.015:1 indicated the amount of light losses in only UV wavelength region, while the higher Si concentration films provide the optical losses to dominant IR region. It is noticeable that the extinction coefficient increased along the higher Si concentration film to have relative agreement with a silicon bulk property. Figure 8 showed the refractive index curve of the PSG film which have the value that alter along the wavelength of the light incident. However, the refractive index value increases with the increase of concentration of Si in the film. Moreover, the PSG films with various Si powder ratio have values of refractive index lower than crystal silicon (c-Si) (Green and Keevers, 1995) which indicated that the film can apply to be a window layer of the solar cell application.

Conclusions

The Si composite film consisting of such Si powder dispersed into the phospho-silicate matrix was deposited on quartz substrate by spin coating technique to observe the electrical and optical properties. The decrease of current density of the Si composite film with various Si concentrations in illumination test expressed the appearing of light induced degradation. Therefore, the film thickness around 400-500 nm in this study is considered for solar cell application. The Si composite films have the minimum reflection around 6-8% at the wavelength range of 450-550 nm and 50% higher light transmission in visible region of the Si composite films have been observed. This is attributed to that the optical band gap values of the Si composite films shifts toward the higher photon energy from 1.1 eV (Si bulk) to 1.7 eV for decreasing Si concentration ratios from 1:0.075 to 1:0.025, which implying the increase of blue-light absorption. However, too low dense of Si concentration can obtain the very low light absorption and the optical property similar to PSG film. Therefore, the optimal Si composite ratios at the range 1:0.050 to 1:0.025 are considered in the functions of good dielectric, low reflectance, high absorbance properties. These property contributions of the Si composite film with PSG matrix can be a promising approach for efficiency improvement of third-generation solar cells.

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Table 2. Blue shifting of energy bandgap of silicon composite film

Matrix	Estimation of E_g of composite film (eV)	Reference
SiC	1.52-2.45	(Kole and Chaudhuri, 2014)
SRO	1.98-2.35	(Hao <i>et al.</i> , 2009)
SiN _x	2.2-4.3	(Goncharova <i>et al.</i> , 2015)
ZnO	1.7-3.8	(Castaldo <i>et al.</i> , 2014)
PSG	1.4-5.7	This work

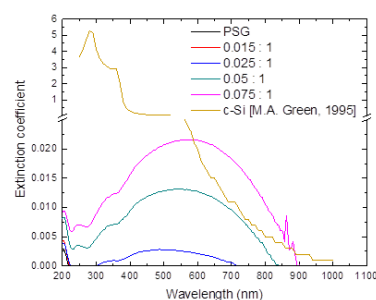


Figure 7. Extinction coefficient curve of PSG thin film with various Si concentration

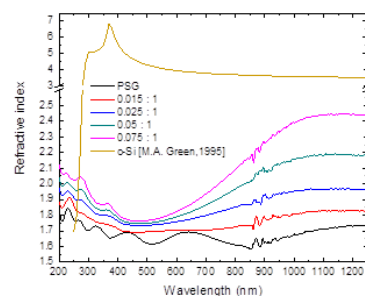


Figure 8. Refractive index curve of PSG thin film with various Si powder concentration

References

- Abdullah, O.G., Aziz S.B., and Rasheed M.A. (2017). Effect of silicon powder on the optical characterization of Poly(methyl methacrylate) polymer composites. *J. Mater. Sci.: Mater. Electron.*, 28(5):4,513-4,520.
- Amador-Bedolla, C., Olivares-Amaya R., Johannes H., and Aspuru-Guzik A. (2013). Chapter 17 - Organic Photovoltaics. In: *Informatics for Materials Science and Engineering*. Krishna, R. (ed.). Butterworth-Heinemann, Oxford, p. 423-442.
- Aziz, B.S., Rebar, A., Hazhar, R., and Hameed, A. (2016). In situ synthesis of CuS nanoparticle with a distinguishable SPR peak in NIR region. *J. Mater. Sci. Mater. Electron.*, 27:4,163-4,171.

- Bagher, A.M. (2016). Solar Cell Quantum Dots. *American J. Renew. Sustain. Ener.*, 2:1-5.
- Battaglia, C., Andres C., and Stefaan D.W. (2016). High-efficiency crystalline silicon solar cells: status and perspectives. *Energy Environ. Sci.*, 9:1,552-1,576.
- Brown, A.S. and Green, M.A. (2002). Detailed balance limit for the series constrained two terminal tandem solar cell. *Physica E Low Dimens. Syst. Nanostruct.*, 14(1):96-100.
- Castaldo, A., Alessandro, A., and Maria, L.A. (2014) Synthesis of silicon quantum dots in zinc silicate matrix by low-temperature process: Optical, structural and electrical characterization. *Thin Solid Films*, 562:172-180.
- Chee, K.W.A., Ziqiang, T., Hong, L., and Feng, H. (2018). Anti-reflective structures for photovoltaics: Numerical and experimental design. *Energy Rep.*, 4:266-273.
- Cho, E.C., Green, M.A., Gavin, C., Dengyuan, S., Cho, Y.H., Giuseppe, S., Shujuan, H., Sangwook, P., Hao, X.J., Yidan, H., and Lap, V.D. (2007). Silicon Quantum Dots in a Dielectric Matrix for All-Silicon Tandem Solar Cells. *Adv Optoelectron.*, p. 11.
- Conibeer, G., Green, M., Cho, E.C., Dirk, K., Cho, Y.H., Fangsuwannarak, T., Giuseppe, S., Edwin, P., Yidan, H., Tom, P., Shujuan, H., Dengyuan, S., Chris, F., Sangwook, P., Xiaojing, H., and Daniel, M. (2008). Silicon quantum dot nanostructures for tandem photovoltaic cells. *Thin Solid Films*, 516(20):6,748-6,756.
- Dhamrin, M., Akihito, T., Hashigami, H., and Saitoh, T. (2002). Light-induced lifetime degradation of commercial multicrystalline silicon wafers. *Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference*; May 19-24, 2002; Naka-cho, Koganei, Tokyo, Japan, p. 395-398.
- Dutta, S., Somenath, C., Kumar, M., Cho, Y.H., and Junsin, Y. (2019). Control of size and distribution of silicon quantum dots in silicon dielectrics for solar cell application: A review. *Renew. Energy*, 144:2-14.
- El amrani, A., Menous, I., Mahiou, L., Tadjine, R., Touati, A., and Lefgoum, A. (2008). Silicon nitride film for solar cells. *Renew. Energy*, 33(10):2,289-2,293.
- Fangsuwannarak, T., Laohawiroj, S., Rattanawichai, P., Mekmork, K., Limsiri, W., and Phatthanakun, R. (2021). Silicon dots films deposited by spin-coating as a generated carrier addition layer of third generation photovoltaics. *Prog. Nat. Sci. PROG NAT SCI-MATER.* "In press"
- Gan, J., Li, Q., Hu, Z., Yu, W., Gao, K., Sun, J., Xu, N., and Wu, J. (2011). Study on phase separation in a-SiO_x for Si nanocrystal formation through the correlation of photoluminescence with structural and optical properties. *Appl. Surf. Sci.*, 257(14):6,145-6,151.
- Glunz, S.W., Preu, R., and Biro, D. (2012). 1.16 - Crystalline Silicon Solar Cells: State-of-the-Art and Future Developments. In: *Comprehensive Renewable Energy*. Sayigh A. (ed.). Elsevier, Oxford p. 353-387.
- Goncharova, L.V., Nguyen, P.H., Karner, V.L., D'Ortenzio, Chaudhary, R.S., Mokry, C.R. and Simpson P.J. (2015). Si quantum dots in silicon nitride: Quantum confinement and defects. *J. Appl. Phys.*, 118: 224302.
- Green, M.A., and Keevers, M.J. (1995). Optical properties of intrinsic silicon at 300 K. *Progress in Photovoltaics: Research and Applications*, 3:189-192.
- Hao, X.J., Podhorodecki, A.P., Shen, Y.S., Zatyryb, G., Misiewicz, J. and Green, M.A. (2009). Effects of Si-rich oxide layer stoichiometry on the structural and optical properties of Si QD/SiO₂ multilayer films. *Nanotechnology*, 20(48):485703.
- Hashmi, G., Rashid, M.J., Mahmood, Z.H., Hoq, M., and Rahman, M.H. (2018). Investigation of the impact of different ARC layers using PC1D simulation: application to crystalline silicon solar cells. *J. Theor. Appl. Phys.*, 12(4):327-334.
- Higuera-Valenzuela, H.J., Romo-García, F., Cabrera-German, D., Ramos-Carrazco, A., Rosas-Burgos, R., García-Gutierrez, R., Contreras, O.E., and Berman-Mendoza, D. (2018). Novel two-stage method for the synthesis of silicon quantum dots embedded on ZnO matrix. *Mater. Lett.*, 228:157-159.
- Kaewphoka, J., Fangsuwannarak, T. and Rattanachan, S.T. (2014). Synthesis of surfactant-assisted nanostructured Bi-doped Zinc oxide for photo-sensing application. In: *2014 11th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*; May 14-17, 2014, p. 1-4.
- Karmouch, R., G. Savard, D. Barba, D. Koshel, F. Martin, and Ross, G.G. (2013). Investigation of electrical and optical measurements of silicon nanocrystals embedded in SiO₂ matrix. *J. Mater. Sci.: Mater. Electron.*, 24(6):1,837-1,841.
- Kim, B.H., Cho, C.H., Kim, T.W., Park, N.M., Sung, G.Y., and Park, S.J. (2005). Photoluminescence of silicon quantum dots in silicon nitride grown by NH₃ and SiH₄. *Appl. Phys. Lett.*, 86(9):091908.
- Kim, T.G., Kwak, G.Y., Do, K., and Kim, K.J. (2019). High efficiency Si quantum dot heterojunction solar cells using a single SiO_x:B layer. *Nanotechnology*, 30(32):325404.
- Kole, A., and Chaudhuri, P. (2014). Growth of silicon quantum dots by oxidation of the silicon nanocrystals embedded within silicon carbide matrix, *AIP Adv.*, 4(10):107106.
- Laohawiroj, S., Mangkornkaew, A., Maneedaeng, A., and Fangsuwannarak, T. (2018). Silicon composite ink for advanced photovoltaic generation prepared by low-cost technique. *J. Renew. Energy Smart Grid Technol.*, 13(2).
- Lataste, J.F. (2010). 12-Electrical resistivity for the evaluation of reinforced concrete structures. In: *Non-Destructive Evaluation of Reinforced Concrete Structures*. Maierhofer, C., Reinhardt, H.W., and Dobmann, G. (eds.). Woodhead Publishing, France, p. 243-275.
- Lee, S.H., Kwak, G.Y., Hong, S., Kim, C., Kim, S., Kim, A., and Kim, K.J. (2016). Ultraviolet responses of a heterojunction Si quantum dot solar cell. *Nanotechnology*, 28(3):035402.
- Li, M., Shen, H., Zhuang, L., Chen, D., and Liang, X. (2014). SiO₂ Antireflection Coatings Fabricated by Electron-Beam Evaporation for Black Monocrystalline Silicon Solar Cells. *Int. J. Photoenergy*, 2014:670438.
- Lindroos, J., and Savin, H. (2016). Review of light-induced degradation in crystalline silicon solar cells. *Sol. Energy Mater. Sol. Cells*, 147:115-126.
- Meyer, A.R., LaSalvia, V., Nemeth, W., Page, M., Young, D., Agarwal, S., and Stradins, P. (2019). Mitigating Process Induced Degradation in p- and n-Czochralski Silicon Wafers with Tabula Rasa. In: *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*; June 16-21, 2019, p. 0068-0071.
- Moon, S., Kim, K., Kim, Y., Heo, J., and Lee, J. (2016). Highly efficient single-junction GaAs thin-film solar cell on flexible substrate. *Sci. Rep.*, 6(1):30107.
- Pankove, J.I. (1976). *Optical Processes in Semiconductors*. Dover publications, New York.
- Philipps, S.P., Dimroth, F., and Bett, A.W. (2018). Chapter I-4-B - High-Efficiency III-V Multijunction Solar Cells. In: *McEvoy's Handbook of Photovoltaics (3rd Ed)*. Kalogirou S.A. (ed.). Academic Press, p. 439-472.
- Qarony, W., Hossain, M.I., Hossain, M.K., Uddin, M.J., Haque, A., Saad, A.R., and Tsang, Y.H. (2017). Efficient amorphous silicon solar cells: characterization, optimization, and optical loss analysis. *Results Phys.*, 7:4,287-4,293.
- Sahoo, S., Manoharan, B., and Sivakumar, N. (2018). Chapter 1 - Introduction: Why Perovskite and Perovskite Solar Cells?. In: *Perovskite Photovoltaics*. Thomas, S. and Thankappan, A. (eds.). Academic Press, p. 1-24.

- Shockley, W. and Hans, J.Q. (1961). Detailed Balance Limit of Efficiency of p-n Junction Solar Cells, *J. Appl. Phys.*, 32(3):510-519.
- Singh, Y. (2013). Electrical resistivity measurements: a review. *Int. J. Mod. Phys.: Conf. Ser.*, 22:745-756.
- Tang, Z., Tress, W., and Inganäs, O. (2014). Light trapping in thin film organic solar cells. *Mater. Today.*, 17(8):389-396.
- Yu, X., Yu, W., Wang, X., Zheng, Y., Zhang, J., Jiang, Z., and Fu, G. (2015). Effects of phosphorus doping on the optical and electronic properties of Si-quantum-dots/SiO₂ multilayer films. *Superlatt. Microstruct.*, 78:88-96.