Review of Atomic Layer Deposition of Nanostructured Solar Cells

O.K. Ukoba[1*], and T-C. Jen[1]

,
[1]Mechanical Engineering Science Department, University of Johannesburg, South Africa.
Corresponding Author; ukobaking@yahoo.com

Abstract-
This study reviews atomic layer deposition technique with a special interest on solar cells applications. Atomic layer deposition is a vapour phase deposition technique used for producing thin films for several applications. This review focuses on the chemistry of Atomic Layer Deposition of solar cells, merits and demerits of ALD on thin film solar cells. Solar cells have attracted a lot of interest due to their potential for affordable, clean and sustainable energy. Solar cells can be deposited using different deposition techniques but Atomic layer deposition currently attracts attention owing to the merits. ALD has functional merit to bulk materials, great processing flexibility and affordability. The review examined the merits of ALD and solar cells and areas for future study. It offers affordability, ease of control of film growth, conformal and improvement on the deposition of solar cells. Despite few demerits, ALD is poised to be the deposition technique of choice for modifying interfaces of the film for improved performance.

Key words: Atomic Layer Deposition, Solar cells, Review, Thin films

1. Introduction

Clean, inexpensive and sustainable energy has been a keystone of increasing wealth and economic development of emerging economies. There is currently more investment in such technologies as alternate materials to meet global power needs of about 17 TW [1]. The emphasis is on the reduction of the cost and complexity of production of such technologies. About 120,000 TW of solar energy gets to the earth and only 600 TW is useful for consumption [2]. This makes solar energy the most abundant renewable and clean energy source. However, solar energy currently contributes just 1.1% of the total energy supply [3]. This low penetration may be attributed to several factors related to cultural, technology and economy. Sunlight is not evenly distributed globally and so is the level of acceptance/penetration of solar energy. Although, there is currently an increase in thin films solar cells research with emphasis on cost reduction for global consumption. Despite the decrease in solar cost in several developed countries, the same cannot be said of most developing countries. Domestication of solar energy technologies in all country will drastically reduce the cost and increase the acceptance globally. Module cost has been reduced but other factors still inhibit widespread of solar technology. The cost of solar is still unaffordable in several countries due to some factors. These factors include shipping, permits, labour and inspection cost incurred from importing solar in such countries [4-6]. A reduction in area per module and increased efficiency can crash the overall solar costs. This implies solar with theoretical efficiencies above the Shockley-Queisser limit with a cost less than $0.20 per watts [7, 8]. Thin film technology especially nanostructured metal oxide and scalable deposition like ALD can break the Shockley-Queisser limit [9, 10].

Thin films Materials can be deposited using various techniques [11]. There has been an attempt to review atomic layer deposition and its applications by some studies in the past [12-16]. Puurunen [17] did a review of the surface chemistry of ALD. Although, Parsons, Elam [18] gave a review of the history and origin of Atomic layer deposition science from the 1960s until 2013. Marin, Lanzutti [19] reviewed the ALD techniques, drawback and the instruments used for ALD analysis/characterization. Miikkulainen, Leskelä [12] reviewed the basics of ALD, the process of ALD reactant and ALD processing of ternary compounds. Kim [13] did a review of ALD processing of metals and nitride films and their areas of applications in semiconductor fabrication. Guo, Ye [14] reviewed the surface chemistry of ALD and its reaction mechanism for surface modification of polymeric materials. Tynell and Karppinen [20] did a comprehensive review of atomic layer deposition of ZnO and the applications. Kessels, Hoex [21] understudied the prospects of ALD for solar cells manufacturing. The study focused on the ALD deposition for first, second and third generation solar cells.
This study will explore the fundamentals, applications of ALD and examples of ALD deposited solar cells. This will open frontiers for more research on ALD deposition of thin film solar cells.

1.1 Deposition of Thin film

Thin film deposition is classified into three groups by means of its nature of deposition as illustrated in Figure 1 [22]. This classification is broadly grouped based on the chemical or physical process of the thin films [23]. Deposition of the thin film is done above the substrate surface. The material to be deposited is added to the substrate in layers. This layer can be structural or as a spacer that can be removed thereafter [24]. Chemical deposition occurs when the hot substrate and inert gases react chemically in a low atmospheric pressure chamber. Chemical deposition is divided into gas-phase and solution-processed. The gas-phase are atomic layer epitaxy, chemical vapour deposition and atomic layer deposition [25]. The solution-processed are spray pyrolysis, chemical bath deposition, screen printing, sol-gel, dip-coating and spin-coating [26-30]. Chemical deposition can also be sub-classified, based on precursor phase, into the spin coating, plating, atomic layer deposition, and chemical vapour deposition. The chemical vapour deposition (CVD) include plasma-enhanced CVD, low-pressure CVD and very low-pressure CVD [31].
However, physical deposition involves the physical movement of the material toward the substrate surface. This material can be liquid, solid or vapour. Physical deposition process includes sputtering (DC and RF), thermal evaporation, ion plating, pulsed laser deposition and Molecular Beam Epitaxy (MBE) [32-35].

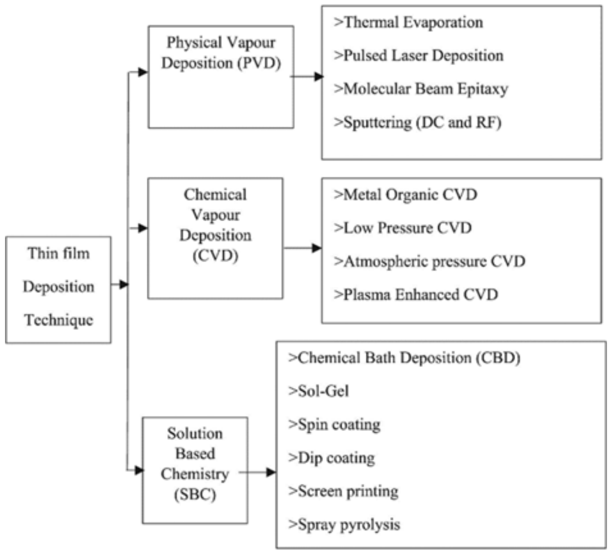


Figure 1: Classification of thin film deposition methods

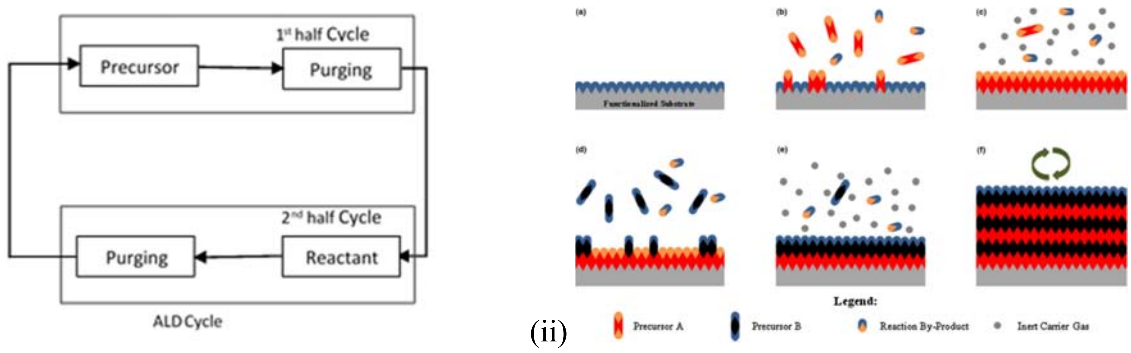
2. Introduction to Atomic Layer Deposition basics

The emerging and future directions of ALD is geared towards energy applications. This includes energy conversion, energy conservation and energy storage. The main focus of energy conversion ALD studies is on fuel cells, solar cells and photo-electrochemical cells. However, energy conservation researches are towards improved catalysts. ALD study for energy storage tends to gravitate towards lithium and ultra-capacitors. The focus of ALD studies on energy applications stern from the interest in nanostructured materials. Nanostructured material is believed to be a global solution for low-cost and eco-friendly energy [36-39]. ALD is a viable tool for growing nanomaterials and deposition of nanostructured materials. This is in addition to the vast merit of the technique.

ALD is a vapour phase deposition technique used for the deposition of different categories of thin films materials [40]. It is based cyclic use of self-limited chemical reactions for adjusting of the layer thickness. ALD has shown tremendous potential for deposition of novel semiconductors and other energy conversion processes [41-43]. The quest for efficient and affordable thin-film solar cells have shifted research focus to the atomic level control of thin film thickness, uniformity and maintains quality. ALD appears to be deposition technique of choice due to the simplicity, reproducibility, conformal, and uniform nature of the as-deposited thin films [44, 45]. Also, films deposited with ALD are continuous and pin-hole free [46]. The ALD was originally known as atomic layer epitaxy (ALE) by Suntola and Antson in 1977 [47]. ALD evolved from a couple of ALE processes of incorporating metals and metal oxides deposited non-epitaxial.

2.1 Chemistry of ALD

ALD is similar to chemical vapour deposition. However, ALD comprises of chemical reactions in which the precursors react with the surface successively but the reactants are kept apart at lower temperature [48]. During this reaction, the precursor is pulsated into a vacuum chamber of about <1 Torr for a specified amount of time to enable the precursor to react with the surface. The surface reaction is disconnected using nitrogen or argon purging. This purging ensures that unreacted precursor and by-product are removed. The purging and self-limited reactions create the ALD cycle which is shown in Figure 2i. A detailed schematic of the ALD cycle is depicted in Figure 2ii [49]. The amount of film thickness deposited in one complete cycle is known as growth per cycle (GPC). The final thickness is not dependent on the duration of the reaction but a number of the cycle. Individual layer thickness can be optimized with great accuracy.



(i) (ii)

Figure 2: ALD cycle (i) summarized the ALD cycle (ii) Schematic of the ALD process. (a) Substrate surface has natural functionalization or is treated to functionalize the surface. (b) Precursor A is pulsed and reacts with the surface. (c) Excess precursor and reaction by-products are purged with an inert carrier gas. (d) Precursor B is pulsed and reacts with the surface. (e) Excess precursor and reaction by-products are purged with an inert carrier gas. (f) Steps 2–5 are repeated until the desired material thickness is achieved.

As seen in figure 2, a typical ALD cycle comprises four steps. The first step is the introduction of the reactants. This is followed by purging using inert gas to eliminate surplus reactants. The third step involves the addition of counter-reactants. The last step is purging of the unused reactants and by-product of the reaction. The anticipated thickness determines the amount of the cycle is repeated.

ALD operates at a lower temperature of <350°C compared to CVD. Atomic layer deposition temperature window is the temperature where the growth is saturated and is dependent on the specific ALD process. A poor growth rate is obtained when the deposition is done outside of the ALD window.

3. Atomic Layer deposition for thin film solar cells

Material Solar energy has been identified as an emerging energy source due to the clean and sustainable nature [50]. Electricity is generated using a photovoltaic effect when solar cells convert sunlight into electricity [51]. A lot of solar cells have been developed over the last decades. However, efficiency and affordability still hinder the uniform domestication of solar energy across the globe [52]. The uniform and affordable deposition of metal oxides (TiO, ZnO, SnO_2, HfO_2, Al_2O_3), nitrides (TaN, TiN, WN, NbN), metals (Ru, Ir, Pt) and sulphides (ZnS) can be achieved using Atomic layer deposition. A metal oxide thin film is formed when a metal complex (e.g metal halide, metal alkoxide, etc.) and an oxygen source reacts [17]. The metal oxide is obtained via hydrolysis and condensation steps. Although, research is still on for atomic layer deposition of Ge, Si, Si_3N_4 and other multicomponent oxides. Table 1 outline an overview of major atomic layer deposition in solar cells.

Table 1. Summary of major ALD applications in solar cells.

Author	Material	Application	Thickness (nm)	Solar Cells Classification
[53-56]	Cu_xS	Absorber	unspecified	Nanostructured heterojunction
[57, 58]	$CuInS_2$			
[59]	ZnO	TCO		
[60, 61]	Al_2O_3	Barrier Layer	0.1–25	Dye-sensitized
[62]	TiO_2			
[63]	HfO_2			
[64]	ZrO_2			
[65]	AZO	Photoanode	5–90	
[66]	TiO_2			
[65]	SnO_2			
[67, 68]	ZnO			
[69]	TiO_2: Ta			
[61, 69-	TiO_2	Blocking	7-20	
71]	SnO_2	Layer		
[60]				
	HfO_2			
[72]		Compact		
	In_2O_3:	layer	7	
[73]	Sn			
		TCO		
[74]	Pt			
			5	
[75]	In_2S_3			
		Sensitizer		
[76]	ZnSe	Buffer layer	10 - 70	CIGS
[77]	ZnS			
[78-80]	O (Zn,			
[81-84]	Mg)			
[85]	Zn (O,			
[86-88]	S)			
[85]	TiO_2			
[77]	In_2S_3			
[89, 90]	Al_2O_3			
	GaS			
[91]	Zn-Sn-O	Diffusion barrier layer	100 – 300	
[92]	Al_2O_3	Encapsulation layer	10 – 55	
	Al_2O_3			

[93]	ZnO: B	TCO	400	a-Si: H
[94-96]	Al_2O_3	Surface passivation layer	5-30	c-Si
[97]	AlAs	Absorber	30 - 400	AlGaAs/GaAs multijunction
[97, 98]	AlGaAs			
[97, 98]	GaAs			

Atomic layer deposition can be used in several aspects of solar cells. ALD provides better control over CBD, PVD and CVD in terms of material growth and conformality. Material growth and conformality are vital for the development of new and low-cost solar cells. Atomic layer deposition has shown an advantage over other techniques for solar cells deposition. Atomic layer deposition technique has been established for forming barrier layers [99], an absorber layer and a passivation layer in crystalline silicon cells [100]. This has been shown in different categories of emerging solar cells especially nanostructured metal oxide solar cells.

Banerjee, Lee [64] did ALD deposition of Al-doped ZnO films. The film thickness was ~100 nm and deposited at 150 °C on a quartz substrate. The study observed 17.7 $cm^2V^{-1}s^{-1}$ maximum mobility and 4.4 x 10^{-3} Ωcm resistivity. The carrier concentration was obtained to be 1.7 x 10^{20} cm^{-3} at 3% Al. A band gap of 3.23 eV and optical transmittance of 80% was achieved.

Nguyen, Resende [101] deposited Al-doped ZnO films on borosilicate glass substrate using atmospheric pressure spatial ALD. A transparency of 90% and a tunable band gap in the range of 3.30 and 3.55eV was achieved. Also, the electron mobility of 5.5 cm^2 $V^{-1}s^{-1}$ was recorded. A resistivity of 5.57 x 10^{-3} Ωcm was achieved which compared favourably with 3.0 x 10^{-3} Ωcm obtained using RF Sputtering [102]. Also, a carrier density of 4.25 x 10^{20} cm^{-3} was recorded.

Also, Muñoz‐Rojas, Sun [71] used atmospheric pressure spatial ALD to deposit TiO_2 as a hole blocking layers for P3HT-PCBM-based solar cells. Glass and ITO substrates were used for the films deposition. The longest deposition took 50cycles and the thinnest took 10cycles at 100 ºC in 37 s. The study concluded that fast deposition, low processing temperature, material usage, and condensed energy input makes ALD effective method for layer blocking [103, 104].

Muñoz-Rojas, Jordan [105] deposited Cu_2O films on both glass and polymer substrate at 225 ºC using rapid atmospheric ALD. The study achieved a carrier concentration of ~10^{16} cm^{-3} and mobility of 5 $cm^2V^{-1}s^{-1}$ with a thickness in the range of 50 – 120 nm using area >10 cm^2.

Poodt, Cameron [106] did an overview of spatial ALD. The study summarized the concept of spatially separating the half-reactions, with separate precursor inlets and exhausts. Several applications of spatial ALD was mentioned with thin film encapsulation and light management for PV explained. The process is an improvement on conventional ALD where the use of shields of inert gas to separate the half-reaction zones. The gas shield width is designed wide to avert diffusion and cross-reactions between the precursors. Quantum dot sensitizers with precise size have been grown using ALD [107]. The absorption coefficient of about 1.7 x 10^7 cm^{-1} has been achieved on plasmonic nanostructures using ALD.

4. Atomic Layer Deposition Demerit

There are a couple of demerits associated with Atomic layer deposition of solar cells. A major demerit is the temperature range of 80 – 300 ºC of most ALD. The elevated surface-volume ratio causes nanostructured materials to have substantial melting point depression when combined with the vacuum in the atomic layer deposition reactor chamber [108]. Also, the formation of the nanostructured firm at low temperature causes quantum dot solar cells to lose their quantum confinement. This demerit can be overcome by depositing at a low temperature. A different solution is deposition of barrier layer material grown at low temperature around the quantum dot and the second material at elevated temperature.
Also, the non-uniformity of ALD deposition of some porous structure of the thin film is a demerit. A third demerit is the inadequate commercial precursors for ALD deposition in existence. This continues to restrict the deposition for targeted material and application [49].

5. Conclusion

This review successful shed light on Atomic layer deposition, the chemistry of ALD, previous ALD deposition of solar cells and demerit of ALD. Atomic layer deposition has been shown to be the solution for conformal, precise thickness control and barrier layer formation for thin film solar cells, especially nanostructured solar cells. It offers affordability, ease of control of film growth and improvement on the deposition of solar cells. Despite the demerits, ALD is poised to be the deposition technique of choice for modifying interfaces of the film for improved performance.

Acknowledgements
The authors wish to acknowledge the financial support offered by NRF of South Africa and the PDRF and UROC support from the University of Johannesburg in actualization of this research work for publication

Reference

1. Hosenuzzaman, M., et al., *Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation.* Renewable and Sustainable Energy Reviews, 2015. **41**: p. 284-297.
2. Lewis, N.S. and G. Crabtree, *Basic research needs for solar energy utilization: report of the basic energy sciences workshop on solar energy utilization, April 18-21, 2005*. 2005, US Department of Energy, Office of Basic Energy Science.
3. Fahrenbruch, A. and R. Bube, *Fundamentals of solar cells: photovoltaic solar energy conversion*. 2012: Elsevier.
4. Feldman, D., et al., *Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections 2015 Edition.* 2015.
5. Ardani, K., et al., *Benchmarking Non-Hardware Balance of System (Soft) Costs for US Photovoltaic Systems Using a Data-Driven Analysis from PV Installer Survey Results*. 2012, National Renewable Energy Lab.(NREL), Golden, CO (United States).
6. Feldman, D., *Photovoltaic (PV) pricing trends: historical, recent, and near-term projections.* 2012.
7. Green, M.A., *Third generation photovoltaics*. 2006: Springer.

8. Beard, M.C., et al., *Third generation photovoltaics based on multiple exciton generation in quantum confined semiconductors.* Accounts of chemical research, 2012. **46**(6): p. 1252-1260.
9. Brown, G.F. and J. Wu, *Third generation photovoltaics.* Laser & Photonics Reviews, 2009. **3**(4): p. 394-405.
10. Ukoba, O., A. Eloka-Eboka, and F. Inambao, *Influence of concentration on properties of spray deposited nickel oxide films for solar cells.* Energy Procedia, 2017. **142**: p. 236-243.
11. Seshan, K. and D. Schepis, *Handbook of thin film deposition*. 2018: William Andrew.
12. Miikkulainen, V., et al., *Crystallinity of inorganic films grown by atomic layer deposition: Overview and general trends.* Journal of Applied Physics, 2013. **113**(2): p. 101.
13. Kim, H., *Atomic layer deposition of metal and nitride thin films: Current research efforts and applications for semiconductor device processing.* Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena, 2003. **21**(6): p. 2231-2261.
14. Guo, H.C., et al., *Recent progress of atomic layer deposition on polymeric materials.* Materials Science and Engineering: C, 2017. **70**: p. 1182-1191.
15. Biyikli, N. and A. Haider, *Atomic layer deposition: an enabling technology for the growth of functional nanoscale semiconductors.* Semiconductor Science and Technology, 2017. **32**(9): p. 093002.
16. Niu, W., et al., *Applications of atomic layer deposition in solar cells.* Nanotechnology, 2015. **26**(6): p. 064001.
17. Puurunen, R.L., *Surface chemistry of atomic layer deposition: A case study for the trimethylaluminum/water process.* Journal of applied physics, 2005. **97**(12): p. 9.
18. Parsons, G.N., et al., *History of atomic layer deposition and its relationship with the American Vacuum Society.* Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2013. **31**(5): p. 050818.
19. Marin, E., et al., *Atomic layer deposition: state-of-the-art and research/industrial perspectives.* Corrosion Reviews, 2011. **29**(5-6): p. 191-208.
20. Tynell, T. and M. Karppinen, *Atomic layer deposition of ZnO: a review.* Semiconductor Science and Technology, 2014. **29**(4): p. 043001.
21. Kessels, W., B. Hoex, and M. van de Sanden. *Atomic layer deposition: prospects for solar cell manufacturing*. in *Photovoltaic Specialists Conference, 2008. PVSC'08. 33rd IEEE*. 2008. IEEE.
22. Freund, L.B. and S. Suresh, *Thin film materials: stress, defect formation and surface evolution*. 2004: Cambridge University Press.
23. Kern, W., *Thin film processes II*. Vol. 2. 2012: Elsevier.
24. Madou, M.J., *Pattern transfer with additive techniques.* Fundamentals of Microfabrication and Nanotechnology: Manufacturing Techniques for Microfabrication and Nanotechnology, 1997.
25. Ahvenniemi, E. and M. Karppinen, *Atomic/molecular layer deposition: a direct gas-phase route to crystalline metal–organic framework thin films.* Chemical Communications, 2016. **52**(6): p. 1139-1142.

26. Ukoba, O., F. Inambao, and A. Eloka-Eboka, *Influence of annealing on properties of spray deposited nickel oxide films for solar cells.* Energy Procedia, 2017. **142**: p. 244-252.
27. Sta, I., et al., *Structural, optical and electrical properties of undoped and Li-doped NiO thin films prepared by sol–gel spin coating method.* Thin solid films, 2014. **555**: p. 131-137.
28. Zhang, W., et al., *Ultrasmooth organic–inorganic perovskite thin-film formation and crystallization for efficient planar heterojunction solar cells.* Nature communications, 2015. **6**: p. 6142.
29. Chaki, S.H., M. Deshpande, and J.P. Tailor, *Characterization of CuS nanocrystalline thin films synthesized by chemical bath deposition and dip coating techniques.* Thin Solid Films, 2014. **550**: p. 291-297.
30. Akhtar, M.S., et al., *Structural, optical, magnetic and half-metallic studies of cobalt doped ZnS thin films deposited via chemical bath deposition.* Journal of Materials Chemistry C, 2015. **3**(26): p. 6755-6763.
31. Morosanu, C.E., *Thin films by chemical vapour deposition*. Vol. 7. 2016: Elsevier.
32. Zawadzka, A., et al., *Linear and nonlinear optical properties of ZnO thin films deposited by pulsed laser deposition.* Journal of Luminescence, 2016. **169**: p. 483-491.
33. Raj, P.D., S. Gupta, and M. Sridharan, *Studies on Nanostructured V 2 O 5 Deposited by Reactive DC Magnetron Sputtering*, in *Physics of Semiconductor Devices*. 2014, Springer. p. 573-576.
34. Vanalakar, S., et al., *A review on pulsed laser deposited CZTS thin films for solar cell applications.* Journal of Alloys and Compounds, 2015. **619**: p. 109-121.
35. Harzer, T.P., et al., *Nanostructure and mechanical behavior of metastable Cu–Cr thin films grown by molecular beam epitaxy.* Acta Materialia, 2015. **83**: p. 318-332.
36. Guo, K.W., *Green nanotechnology of trends in future energy: a review.* International journal of energy research, 2012. **36**(1): p. 1-17.
37. Mandizadeh, S., M. Bazarganipour, and M. Salavati-Niasari, *A low-cost and eco-friendly viable approach for green synthesis of barium haxaferrite nanostructures using palm oil.* Ceramics International, 2014. **40**(10): p. 15685-15691.
38. Gund, G.S., et al., *Low-cost flexible supercapacitors with high-energy density based on nanostructured MnO 2 and Fe 2 O 3 thin films directly fabricated onto stainless steel.* Scientific reports, 2015. **5**: p. 12454.
39. Yuan, C., et al., *Mixed transition‐metal oxides: design, synthesis, and energy‐related applications.* Angewandte Chemie International Edition, 2014. **53**(6): p. 1488-1504.
40. Elam, J., M. Groner, and S. George, *Viscous flow reactor with quartz crystal microbalance for thin film growth by atomic layer deposition.* Review of Scientific Instruments, 2002. **73**(8): p. 2981-2987.
41. Richter, A., J. Benick, and M. Hermle, *Boron Emitter Passivation With Al $ _ {\bf 2} $ O $ _ {\bf 3} $ and Al $ _ {\bf 2} $ O $ _ {\bf 3} $/SiN $ _ {\bm x} $ Stacks Using ALD Al $ _ {\bf 2} $ O $ _ {\bf 3} $.* IEEE Journal of Photovoltaics, 2013. **3**(1): p. 236-245.
42. Hwang, C.S., *Erratum to: Atomic Layer Deposition for Semiconductors*, in *Atomic Layer Deposition for Semiconductors*. 2014, Springer. p. E1-E1.

43. Kang, S.-B., et al., *Method of forming metal layer using atomic layer deposition and semiconductor device having the metal layer as barrier metal layer or upper or lower electrode of capacitor*. 2001, Google Patents.
44. Knez, M., K. Nielsch, and L. Niinistö, *Synthesis and surface engineering of complex nanostructures by atomic layer deposition.* Advanced Materials, 2007. **19**(21): p. 3425-3438.
45. Leskelä, M. and M. Ritala, *Atomic layer deposition chemistry: recent developments and future challenges.* Angewandte Chemie International Edition, 2003. **42**(45): p. 5548-5554.
46. George, S.M., *Atomic layer deposition: an overview.* Chemical reviews, 2009. **110**(1): p. 111-131.
47. Suntola, T. and J. Antson, *Method for producing compound thin films*. 1977, Google Patents.
48. Ritala, M., et al., *Chemical vapour deposition: precursors, processes and applications*. 2008: Royal Society of Chemistry.
49. Johnson, R.W., A. Hultqvist, and S.F. Bent, *A brief review of atomic layer deposition: from fundamentals to applications.* Materials today, 2014. **17**(5): p. 236-246.
50. Ukoba, K., A. Eloka-Eboka, and F. Inambao, *Review of nanostructured NiO thin film deposition using the spray pyrolysis technique.* Renewable and Sustainable Energy Reviews, 2017.
51. Lu, L., et al., *Recent advances in bulk heterojunction polymer solar cells.* Chemical reviews, 2015. **115**(23): p. 12666-12731.
52. Ukoba, K.O., F.L. Inambao, and A.C. Eloka-Eboka, *Fabrication of Affordable and Sustainable Solar Cells Using NiO/TiO2 PN Heterojunction.* International Journal of Photoenergy, 2018. **2018**.
53. Reijnen, L., et al., *Atomic layer deposition of CuxS for solar energy conversion.* Chemical Vapor Deposition, 2003. **9**(1): p. 15-20.
54. Dasgupta, N.P., et al., *Atomic layer deposition of metal sulfide materials.* Accounts of chemical research, 2015. **48**(2): p. 341-348.
55. Johansson, J., et al., *Growth of conductive copper sulfide thin films by atomic layer deposition.* Journal of Materials Chemistry, 2002. **12**(4): p. 1022-1026.
56. Reijnen, L., et al., *Comparison of Cu x S films grown by atomic layer deposition and chemical vapor deposition.* Chemistry of materials, 2005. **17**(10): p. 2724-2728.
57. Nanu, M., J. Schoonman, and A. Goossens, *Inorganic Nanocomposites of n ‐ and p ‐ Type Semiconductors: A New Type of Three ‐ Dimensional Solar Cell.* Advanced Materials, 2004. **16**(5): p. 453-456.
58. Lenzmann, F., et al., *Substantial improvement of the photovoltaic characteristics of TiO2/CuInS2 interfaces by the use of recombination barrier coatings.* Thin Solid Films, 2004. **451**: p. 639-643.
59. Garcia-Alonso, D., et al., *Atomic layer deposition of B-doped ZnO using triisopropyl borate as the boron precursor and comparison with Al-doped ZnO.* Journal of Materials Chemistry C, 2015. **3**(13): p. 3095-3107.
60. Prasittichai, C. and J.T. Hupp, *Surface modification of SnO2 photoelectrodes in dye-sensitized solar cells: significant improvements in photovoltage via Al2O3 atomic*

layer deposition. The Journal of Physical Chemistry Letters, 2010. **1**(10): p. 1611-1615.

61. Hamann, T.W., O.K. Farha, and J.T. Hupp, *Outer-sphere redox couples as shuttles in dye-sensitized solar cells. Performance enhancement based on photoelectrode modification via atomic layer deposition.* The Journal of Physical Chemistry C, 2008. **112**(49): p. 19756-19764.
62. Park K, et al., Adv. Mater., 2010 **22** p. 2329-32.
63. Shanmugam M, B.M. F, and G. D, Thin Solid Films 2010 **518**: p. 2678–82.
64. Banerjee, P., et al., *Structural, electrical, and optical properties of atomic layer deposition Al-doped ZnO films.* Journal of Applied Physics, 2010. **108**(4): p. 043504.
65. Tétreault, N., et al., *Atomic layer deposition for novel dye-sensitized solar cells.* ECS Transactions, 2011. **41**(2): p. 303-314.
66. Williams, V.O., et al., *Fast transporting ZnO–TiO2 coaxial photoanodes for dye-sensitized solar cells based on ALD-modified SiO2 aerogel frameworks.* ACS nano, 2012. **6**(7): p. 6185-6196.
67. Martinson, A.B., et al., *Planar dye-sensitized photovoltaics through cavity mode enhancement.* Energy & Environmental Science, 2011. **4**(8): p. 2980-2985.
68. Hamann, T.W., et al., *Aerogel templated ZnO dye‐sensitized solar cells.* Advanced Materials, 2008. **20**(8): p. 1560-1564.
69. Choi, J.-H., et al., *Atomic layer deposition of Ta-doped TiO2 electrodes for dye-sensitized solar cells.* Journal of the Electrochemical Society, 2011. **158**(6): p. B749-B753.
70. Klahr, B.M. and T.W. Hamann, *Performance enhancement and limitations of cobalt bipyridyl redox shuttles in dye-sensitized solar cells.* The Journal of Physical Chemistry C, 2009. **113**(31): p. 14040-14045.
71. Muñoz‐Rojas, D., et al., *High‐speed atmospheric atomic layer deposition of ultra thin amorphous TiO2 blocking layers at 100 °C for inverted bulk heterojunction solar cells.* Progress in Photovoltaics: Research and Applications, 2013. **21**(4): p. 393-400.
72. Bills, B., M. Shanmugam, and M.F. Baroughi, *Effects of atomic layer deposited HfO2 compact layer on the performance of dye-sensitized solar cells.* Thin Solid Films, 2011. **519**(22): p. 7803-7808.
73. Martinson, A.B., et al., *Radial electron collection in dye-sensitized solar cells.* Nano Letters, 2008. **8**(9): p. 2862-2866.
74. Garcia‐Alonso, D., et al., *Atomic Layer Deposition of Highly Transparent Platinum Counter Electrodes for Metal/Polymer Flexible Dye‐Sensitized Solar Cells.* Advanced Energy Materials, 2014. **4**(4): p. 1300831.
75. Sarkar, S.K., et al., *In2S3 atomic layer deposition and its application as a sensitizer on TiO2 nanotube arrays for solar energy conversion.* The Journal of Physical Chemistry C, 2010. **114**(17): p. 8032-8039.
76. Ohtake Y, et al., Japan. J. Appl. Phys. , 1995. **34**: p. 5949–55.
77. Genev´ee P, et al. in *25th European Photovoltaic Solar Energy Conf. and Exhibition*. 2010. Valencia.

78. Pettersson, J., C. Platzer‐Björkman, and M. Edoff, *Temperature‐dependent current‐voltage and lightsoaking measurements on Cu (In, Ga) Se2 solar cells with ALD‐Zn1‐xMgxO buffer layers.* Progress in Photovoltaics: Research and Applications, 2009. **17**(7): p. 460-469.
79. Platzer‐Björkman, C., et al., *Improved fill factor and open circuit voltage by crystalline selenium at the Cu (In, Ga) Se2/buffer layer interface in thin film solar cells.* Progress in Photovoltaics: Research and Applications, 2010. **18**(4): p. 249-256.
80. Törndahl, T., et al., *The effect of Zn1‐xMgxO buffer layer deposition temperature on Cu (In, Ga) Se2 solar cells: A study of the buffer/absorber interface.* Progress in Photovoltaics: Research and Applications, 2009. **17**(2): p. 115-125.
81. Paire, M., et al., *Chalcogenide thin-film solar cells.* Solar Cell Materials, 2014: p. 145-215.
82. Hultqvist, A., et al., *Experimental investigation of Cu (In1− x, Gax) Se2/Zn (O1− z, Sz) solar cell performance.* Solar Energy Materials and Solar Cells, 2011. **95**(2): p. 497-503.
83. Westin, P.-O., P. Neretnieks, and M. Edoff. *Damp heat degradation of CIGS-based PV modules*. in *21st European Photovoltaic Solar Energy Conference*. 2006.
84. Yousfi, E., et al., *Cadmium-free buffer layers deposited by atomic later epitaxy for copper indium diselenide solar cells.* Thin Solid Films, 2000. **361**: p. 183-186.
85. Yousfi E B, et al., Thin Solid Films, 2000. **361**: p. 183–6.
86. Sterner, J., J. Malmström, and L. Stolt, *Study on ALD In2S3/Cu (In, Ga) Se2 interface formation.* Progress in Photovoltaics: Research and Applications, 2005. **13**(3): p. 179-193.
87. Spiering, S., et al., *Stability behaviour of Cd-free Cu (In, Ga) Se2 solar modules with In2S3 buffer layer prepared by atomic layer deposition.* Thin Solid Films, 2005. **480**: p. 195-198.
88. Spiering, S., et al., *Large-area Cd-free CIGS solar modules with In2S3 buffer layer deposited by ALCVD.* Thin Solid Films, 2004. **451**: p. 562-566.
89. Hultqvist A, E. M, and T.o. T, Prog. Photovolt. Res. Appl. , 2011. **19**: p. 478–81.
90. Hultqvist, A., et al., *Growth kinetics, properties, performance, and stability of atomic layer deposition Zn–Sn–O buffer layers for Cu(In,Ga)Se2 solar cells.* Progress in Photovoltaics: Research and Applications, 2012. **20**: p. 883–891.
91. Bae, D., et al., *37th IEEE Photovoltaic Specialists Conf.* 2011, Seattle.
92. Carcia, P., R. McLean, and S. Hegedus, *Encapsulation of Cu (InGa) Se2 solar cell with Al2O3 thin-film moisture barrier grown by atomic layer deposition.* Solar energy materials and Solar cells, 2010. **94**(12): p. 2375-2378.
93. Sang, B., et al., *High-efficiency amorphous silicon solar cells with ZnO as front contact.* Japanese journal of applied physics, 1999. **38**(9R): p. 4983.
94. Schmidt, J., et al., *Advances in the surface passivation of silicon solar cells.* Energy Procedia, 2012. **15**: p. 30-39.
95. Wang, J., S.S. Mottaghian, and M.F. Baroughi, *Passivation properties of atomic-layer-deposited hafnium and aluminum oxides on Si surfaces.* IEEE transactions on Electron Devices, 2012. **59**(2): p. 342-348.

96. Sun, W., et al., *High efficiency silicon solar cells with bilayer passivation structure.* Electrochemical and Solid-State Letters, 2009. **12**(10): p. H388-H391.
97. Hayafuji N, et al., Appl. Surf. Sci. , 1994. **82**(3): p. 18–22.
98. Al Dallal G M, et al., Renewable Energy 1995. **6**: p. 713–8.
99. Carcia, P., et al., *Gas diffusion ultrabarriers on polymer substrates using Al 2 O 3 atomic layer deposition and SiN plasma-enhanced chemical vapor deposition.* Journal of Applied Physics, 2009. **106**(2): p. 023533.
100. Bakke, J.R., et al., *Nanoengineering and interfacial engineering of photovoltaics by atomic layer deposition.* Nanoscale, 2011. **3**(9): p. 3482-3508.
101. Nguyen, V.H., et al., *Deposition of ZnO based thin films by atmospheric pressure spatial atomic layer deposition for application in solar cells.* Journal of Renewable and Sustainable Energy, 2017. **9**(2): p. 021203.
102. Lyubchyk, A., et al., *Mapping the Electrical Properties of ZnO‐Based Transparent Conductive Oxides Grown at Room Temperature and Improved by Controlled Postdeposition Annealing.* Advanced Electronic Materials, 2016. **2**(1): p. 1500287.
103. García‐Valverde, R., J.A. Cherni, and A. Urbina, *Life cycle analysis of organic photovoltaic technologies.* Progress in Photovoltaics: Research and Applications, 2010. **18**(7): p. 535-558.
104. Espinosa, N., et al., *Solar cells with one-day energy payback for the factories of the future.* Energy & Environmental Science, 2012. **5**(1): p. 5117-5132.
105. Muñoz-Rojas, D., et al., *Growth of∼ 5 cm2V− 1s− 1 mobility, p-type Copper (I) oxide (Cu2O) films by fast atmospheric atomic layer deposition (AALD) at 225° C and below.* AIP Advances, 2012. **2**(4): p. 042179.
106. Poodt, P., et al., *Spatial atomic layer deposition: A route towards further industrialization of atomic layer deposition.* Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2012. **30**(1): p. 010802.
107. Palmstrom, A.F., P.K. Santra, and S.F. Bent, *Atomic layer deposition in nanostructured photovoltaics: tuning optical, electronic and surface properties.* Nanoscale, 2015. **7**(29): p. 12266-12283.
108. Goldstein, A., C. Echer, and A. Alivisatos, *Melting in semiconductor nanocrystals.* Science, 1992. **256**(5062): p. 1425-1427.