Advances on the Applications of Nanostructured Composites Zinc Oxide (Zno) in Solar Energy Devices, And Photocatalysis: A Review

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ABSTRACT

Due to global efforts to achieve energy sustainability, researchers across the world are interested in new materials that can improve energy generation and storage, especially through the application of metal oxides. This review focuses on the recent advances in the applications of composite nanostructured ZnO in solar energy devices, and photocatalysis. Different solar energy generation and storage devices (dye-sensitized solar cells, perovskite solar cells, lithium-ion batteries, and supercapacitors) were studied. Among other metal oxides, the vast potential application of nanostructured ZnO in solar energy devices is due to its excellent bandgap energy, high level of electron mobility, measurable room-temperature, luminescence, low cost and non-toxicity. High theoretical capacity of ZnO makes it an outstanding material for fabrication of lithium-ion batteries. More so, the biocompatible, and environmentally friendly properties of ZnO enable it to have favorable applications in photocatalysis. Understanding the method of synthesizing ZnO nanostructures is important to optimize its applications in different areas; hence we briefly explained a few synthesis methods. Specifically, we discussed chemical vapor deposition, chemical bath deposition, electrodeposition, and hydrothermal methods. Though we suggested in this review that the gas phase method works better. This is because it produces layers and nanostructures of the best quality and device heterostructure, but it is expensive and requires high knowledge to operate. A table showing the pros and cons of all the methods discussed was presented to help researchers to decide on the method to use when synthesizing ZnO nanostructures. But regardless of the method used, the nature of ZnO nanostructures formed depends on the deposition temperature.

Key words: ZnO, Nanostructures, Solar Cells, Energy, Efficiency

INTRODUCTION

Recently, many researchers in the world have developed tremendous interest in Zinc oxide (ZnO) nanostructure due to its potential applications in many areas, including in the field of supercapacitors, batteries, biosensors, photocatalysis, and dye-sensitized solar cells. ZnO is used in these fields because of its wide and excellent bandgap, high electron mobility, luminescence, and biocompatibility properties. ZnO oxide is among the semiconductor compounds in group II-VI in which its bordering is between covalent and ionic semiconductor [1]. Some properties such as room-temperature, high transparency, wide bandgap and piezoelectricity have made ZnO to receive immeasurable attention in the past few years [2]. According to J. Theertagiri et al [3], ZnO nanostructure which is n-type semiconductor material, has application in supercapacitors, solar cells, biosensors, photocatalysis and biomedical devices because it is chemically and thermally stable. ZnO is synthesized in nanoscale forms and combined with other composite substances to form a new structure. ZnO has bandgap energy values in the range 3.1-3.3eV, and it absorbs light only in the UV region [4]. It has large exciton-binding energy of 60MeV [5], absorbs UV in the range 200-500nm and equally emits light in the region near UV and in the visible 500-600 and piezoelectricity [6]. The biocompatible properties of ZnO enable it to be a promising material in photocatalysis application. ZnO nanostructures in the recent time have been extensively studied by many researchers as gas [7, 8], and mechanical strain sensors [9].mi

Structures of Zinc Oxide

ZnO which belongs to group II-VI semiconductor materials crystallized in two ways: zinc blend and hexagonal wurtzite structure [10]. Anion is mainly enclosed by four cations in hexagonal structure or vice versa. The crystal structure of ZnO is classified into: (i) wurtzite (B4) (ii) zinc blende (B3) and (iii) rock salt (B1) [10]. These structures are shown in **fig.1** while **fig.2** is the wurtzite ZnO structure. The wurtzite crystal structure is a hexagonal structure that is closely packed in which each zinc atom is enclosed by an oxygen atom and thus creating an alternate combination of planes of oxygen and zinc atoms [8]. The wurtzite structures attain thermal stability under ambient conditions, the zinc blend attains its stability by growing it on substrates that are cubical in nature, while the rock salt is achieved when the pressure is too high. The space group for wurtzite (B4) structure is P63mc and its lattice parameters are a=0.3296nm and c= 0.52065nm [11]. The wurtzite is one of the important materials used in fabricating electronics devices, lasing, and piezoelectricity. Wurtzite crystal structure is mainly characterized as noncentral symmetry and polar surfaces [9]. Furthermore, zincite is name given to ZnO that occurs in mineral form, but its natural occurrence is very rare [8]. The shape of zincite is tetrahedral, while its structure is ZnO_4. Monocrystalline ZnO has interesting properties such as environmentally friendly, ability to withstand mechanical stress and biocompatibility [8].

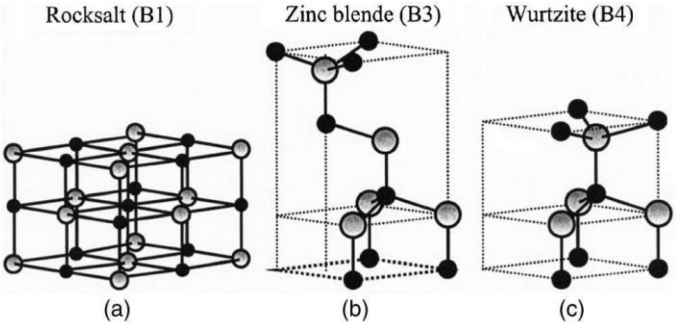

Fig.1: Structure of rocksalt (B1), zinc blende(B3), and wurtzite (B4) [12]

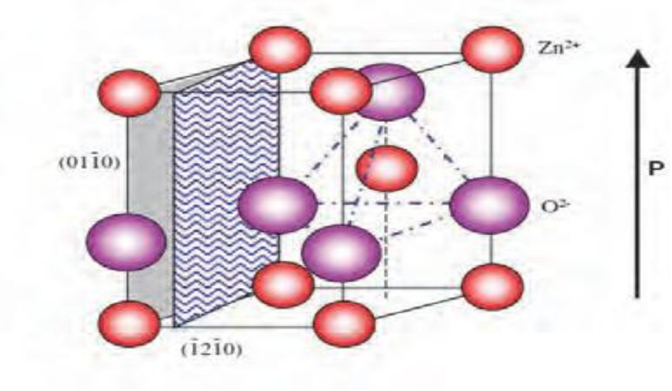

Fig.2: The wurtzite ZnO structure [13].

Synthesis of Nanostructured Zno

Our review focuses mainly on the applications of ZnO in solar energy devices, and photocatalysis, but we briefly explained these synthesis methods below because understanding how ZnO nanoparticles are being synthesized will help to ensure that ZnO NPs of high quality are produced to optimize its applications in these areas. ZnO nanostructures are synthesized in two ways: gas-phase and liquid phase (chemical solution). In the chemical solution method, the cost of fabrication of nanostructures is extremely low and, it supports large-scale production [14]. The gas-phase method produces layers and nanostructures of the best quality and device heterostructure, but it is expensive and requires high knowledge to operate. Examples of gas-phase method include but not limited to the followings: chemical vapor deposition (CVD, vapor-liquid-solid (VLS), molecular beam epitaxy (MBE), e.t.c. Also, some examples of liquid phase are chemical bath deposition, electrodeposition, hydrothermal methods e.t.c. Four methods were discussed succinctly including some literature that support each method.

Chemical Vapor Deposition (CVD): Chemical bath deposition involves the decomposition of volatile precursors on the substrates to form thin films. CVD is the act of depositing solid material from vapor using chemical reaction which occurs in the vicinity of substrate surface heated at a certain temperature. The solid material formed using this method exist in either thin film powder or simple crystals [15]. In CVD, Zinc and Oxygen are transported in gaseous form with each other which results in creating zinc oxide (ZnO) nanostructures. CVD process requires high temperature, vacuum environment, and the precursors should be volatile. Liquid catalysts and other solid molecules are used in CVD to enhance the reaction which affects the properties of the resultant nanostructures. The morphology of ZnO nanostructures synthesized using CVD depend on so many parameters such as: catalyst, temperature of the deposition, and experimental configuration [16]. Other parameters like charged particles generated in the gas-phase and drag force contribute to nanostructure formation in chemical vapor deposition [17]. **Fig.3** is a simplified chemical vapor deposition reactor for carbon nanotubes synthesis (CNTs). Woo Kom et al [18] synthesized ZnO nanostructures using metalorganic chemical vapor deposition at relatively low growth temperature ($400-500^{o}$C) via assistance of colloidal gold (Au) nanoparticles dispersed on SiO_2/Si substrates. Their result indicates that the temperature of the deposition and the density of the Au nanoparticles are where the shape variation dependent on. Furthermore, from the observed result in photoluminescence measurements, the synthesized ZnO nanoparticles have zero week deep-level emission and as well have high optical properties. Thin layers of ZnO nanostructures can be excellently synthesized by growing it in sapphire substrates using CVD [19]. S.S Martin et al [20] revealed in their work that deposition temperature has the maximum effect on the ZnO film over other parameters. ZnO synthesized using chemical vapor deposition can be applied in the area of spintronics, gas-sensing devices, optoelectronics devices e.t.c.

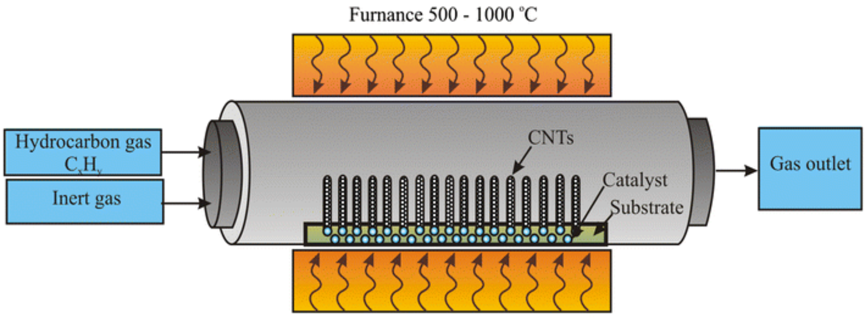

Fig.3: Simplified chemical vapor deposition reactor for carbon nanotubes synthesis (CNTs) [21]

Chemical Bath Deposition (CBD): Chemical bath deposition is the most convenient and simplest method of synthesizing ZnO nanostructures. Its simplicity, replicability, and commercial productions have made it the focal interest of researchers across the globe [22]. Chemical bath deposition on the other hand is regarded as chemical solution deposition. In this process, aqueous precursor solution is used in thin film deposition. Among other wet chemical deposition methods, chemical bath deposition has gained high momentum, and it is commonly used by the researchers [23]. This method of deposition is very simple and costs less because the process does not require high temperature. The anions and cations used in CBD are prepared in one solution and the whole deposition process takes place in a single bath. **Fig.4** is the diagram showing the chemical bath deposition setup.

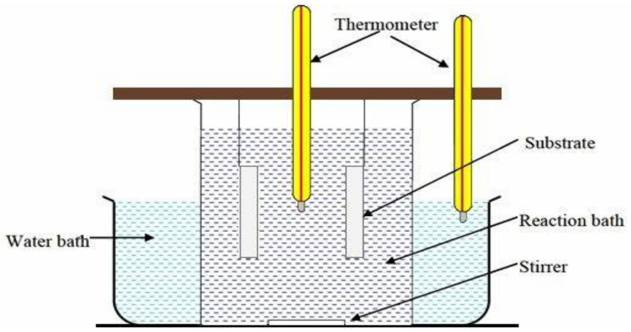

Fig.4: The diagram showing the chemical bath deposition setup [24].

P.B. Taunk et al [25] revealed in their study of optical properties of ZnO nanostructure deposited using chemical bath deposition that ZnO thin film deposited using CBD has an optical bandgap energy of 2.59-3.57eV. In the visible and infrared region of electromagnetic spectrum, the deposited ZnO film shows maximum transmittance. Kathalingam et al [26] noted that crystallite size and bandgap energy of ZnO thin film deposited using chemical bath deposition entirely depend on the temperature of the deposition, otherwise known as the bath temperature. Crystallite size and bath temperature have inverse relationship with the bandgap energy, which means that increase in the crystallite size and bath temperature lead to decrease in the bandgap. Also, the PH values were found to have major effect on the deposited ZnO film, and the most favorable PH range for the synthesis of ZnO film using CBD is 9.5-10.5. Fu Yen Pei et al [27] used zinc acetate to synthesize ZnO film using chemical bath deposition and the result of their study shows that ZnO film is hexagonal in shape. The analysis result from the scanning electron microscopy (SEM) shows that heterogeneous nucleation occurs at the bottom of the film. Also, the synthesized ZnO film can be used in thin film solar cells as conductive layers. Sreedev et al [28] noted in their work that UV-visible spectral analysis revealed the dependence of transmittance, extinction co-efficient, reflectance and refractive index decrease and on the other hand, extinction coefficient and refractive index increase with the time of deposition for all wavelengths from 350nm to 700nm. Though the CBD method costs less, more convenience, and environmentally friendly, it has one major drawback. Its major setback is that it involves constant changing of solution, which makes it impossible to use this method to fabricate nanowires of length (20–30μm) [23].

Electrochemical deposition or Electrodeposition: This is the process by which conducting and semiconducting materials are deposited in a substrate using electric field or redox reaction. The simplicity, high rate of deposition, and low cost of electrodeposition technique has made it to be considered as the most effective method of synthesizing ZnO thin film [29]. In electrodeposition method, some factors such as the time of the deposition, current density and amount of the electrolytic bath help to control the film thickness, morphological and optical properties. Zinc nitrate solutions [30], and chloride solutions [31] are used as precursors in the electrochemical deposition. Electrodeposition helps to ensure excellence in the coating of different geometries of substrates and equally permits the control of the size of the crystallite, morphology and thickness [32]. The formation of either nanowalls, nanorods or platelets using electrodeposition method depends on how the deposition potential is varied and the bath temperature [33]. Electrodeposition solution consists of Zn^{2+} cations and nitrate ions [34]. The deposition of ZnO using electrodeposition is carried at similar temperature and pressure as that of CBD [23]. **Fig.5** is the schematic view of the electrodeposition setups. Electrodeposition allows the formation of substrates of different shapes and film thickness due to its low deposition temperature [35]. Also, electrodeposition technique does not permit the use of vacuum systems, which encourages the synthesis of nanoparticles [36]. ZnO nanostructure fabricates using electrodeposition have many applications including batteries, electrolytes, solar cell, magnetic devices and sensors. A well-defined nanorod, nanowire, and cauliflower-like nanostructures were formed when ZnO nanostructure was synthesized using electrodeposition [37].

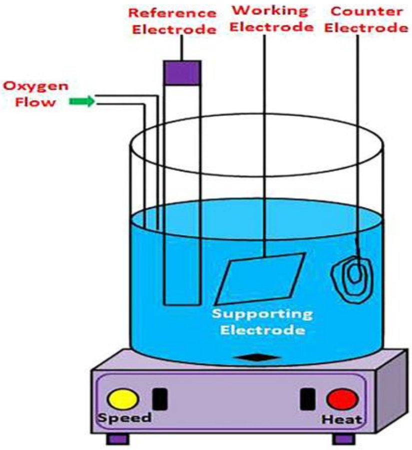

Fig.5: The schematic view of the electrodeposition setup [37].

Hydrothermal Method: This is the most used method to synthesize ZnO nanomaterials, and it has gained immeasurable interest from the researchers in the last fifteen years [38]. Hydrothermal is the term used to describe any heterogeneous reaction that takes place in the presence of aqueous solvents at a high temperature and pressure [38]. This synthesis method involves chemical reaction of substance in a thermal closed aqueous solution at a high temperature and pressure i.e temperature and pressure that is above the ambient values [10]. Hydrothermal method ensures the synthesis of ZnO nanomaterials that have definite structure, morphology and assembly [10]. Hour Krajian et al [39] revealed that ZnO film synthesized using hydrothermal method has big grain size and preferential orientation and can be used in fabricating optical and optoelectronics devices. ZnO synthesized using this method also has a good application in LED, gas sensors and solar energy devices such as photovoltaic cells [40]. Sonima Mohan et al [41] noted that some parameters such as temperature and reaction time affect the hydrothermal method of synthesis of ZnO nanoparticles. Increase in the temperature of the reaction leads to a decrease in the size of the crystalline and as well results in blue shift. While, as the reaction time increases, grain size increases and red shift is observed. The hydrothermal method in general is considered as the best synthesis method for various nanomaterials with defined optical properties [41].

Table 1. The comparison of the synthesis method of ZnO nanostructures.

Synthesis	Advantages	Disadvantages
Chemical vapor deposition	Simple and effective.	It requires high temperature, vacuum environment and the precursors should be volatile.
Chemical bath deposition	It is less expensive, more effective, and the deposition of sample occurs at any substrates.	It causes waste of solution.
Electrodeposition	It costs less, the synthesis temperature or deposition temperature is very low, some deposition parameters help to control the structure and morphology of ZnO.	It involves the use of conductive substrates.
Hydrothermal	It does not require complicated equipment, less expensive.	High pressure and as well as high reaction temperature are required.

Application of Nanostructured Zno

Among the semiconductor metal oxides, ZnO is identified to have wider application in optoelectronics, solar energy system, biosensors devices, photocatalysis, batteries and supercapacitors. These potential applications of ZnO nanomaterials in many areas are owing to its excellent bandgap, luminescence, high rate of electron mobility and debatable room-temperature [42]. Energy generation and storage devices covered are dye-sensitized solar cells (DSSCSs), perovskite solar cells (PSCs), quantum dot sensitized solar cells (QDSSCs), lithium-ion battery, and supercapacitor. Also, its applications in photocatalysis and biosensors were reviewed.

Dye-Sensitized Solar Cells (DSSCs): Dye-sensitized solar cell (DSSC) is one of the thin-film solar cells. Dye-sensitized solar cell was invented by Michal Gratzel and Brian O'Regan [43]. It is more economical than the popular p-n junction photovoltaic cells, and it is called DSSCs or DYSC in short forms. It has some interesting properties such as semi-flexible, semi-transparent, easy to fabricate and low cost. **Fig.7** is a diagram of dye-sensitized solar cells. Semiconductors are not used in absorption of light and charge carrier in dye-sensitized solar cells [43]. A sensitizer in DSSC absorbs all the lights on the surface and the separation of charge occurs at the gap from the molecule of dye into the conduction band of the solar cell through a light induced (photoinduced) electron injection [43]. The conduction band semiconductor, otherwise known as the charge collector, will then receive these charge carriers. Its mechanism of operation is based on the photoelectrochemical process [44]. **Fig.8** shows the energy diagram of DSSCs, and its working principles.

In the past fifteen years, the application of ZnO nanomaterials in the dye-sensitized solar cells has acquired momentum owing to its high rate of electron mobility and electron diffusion coefficient [45]. Zinc oxide is among the first metal oxide used in fabricating dye-sensitized solar cells (DSSCs) [46]. It has many interesting properties such as high electron mobility, easy to synthesize and most abundant nanostructures [46]. There is a notable similarity between the energy levels of ZnO and that of TiO_2, but ZnO has higher carrier mobility which makes the collection of light induced (photoinduced) electrons more favorable [47]. One of the issues that affects dye-sensitized solar cell fabricated using ZnO nanostructure is “dye aggregation”, which tends to increase current recombination [45]. The conversion efficiencies of ZnO are 0.4-5.8% while that of TiO_2 is 11%, yet ZnO is a good alternative to TiO_2 because of its ease of crystalline and anisotropic growth [48]. The efficiency of dye-sensitize solar cells fabricated using ZnO is the second after TiO_2 [47]. ZnO nanoparticle is one of the emerging materials used in creating photoanode in DSSCs [49]. P Sudhargar et al [50] studied the application of jack-like ZnO nanorod architecture as a photoanode in dye-sensitized solar cells, their result shows that ZnO nanorod has excellent conversion efficiency of 1.82%. M. Thambidurai et al [51] synthesized ZnO nanorods for dye-sensitized solar cells application using chemical bath deposition method. They conducted their experiment by preparing different moles (0.03M, 0.05M and 0.07M). The power conversion efficiency of the dye-sensitized solar cell designed using 0.03M concentration is 0.07%. Also, the efficiency of dye-sensitized solar cells fabricated using ZnO nanorod with concentration 0.05M is 0.51% while the efficiency of the fabricated dye-sensitized solar cells using ZnO nanorod prepared at 0.07M is 0.71%. Their experimental result shows that ZnO nanorod synthesized via chemical bath deposition is a prominent electrode material in dye-sensitized solar cells and the efficiency of the solar cells increases as the molecular concentration increases. O. Lupan et al [52] revealed in their work that ZnO nanowire synthesized by the method of electrodeposition using ITO substrate has an efficiency of 0.66% when used in photovoltaic cells. ZnO nanowires synthesized using PVD method has a good repeatability and efficiencies of 0.1% and 0.5% when used in fabricating dye-synthesize solar cell [53]. Also, an overall efficiency of 3.5% was obtained when ZnO nanowire synthesized by combining the methods of co-precipitation and electrodeposition are used in dye-sensitized solar cells [47]. Xi Y.Y et al [54] revealed that the efficiency of dye-sensitized solar cells fabricated using ZnO nanoporous depend on the morphology of the ZnO film. Yongming Meng et al [55] noted that the efficiency of dye-sensitized solar cells when ZnO nanosheets are used as photoanode is 1.82%. Also, 3D-ZnO nanosheet shows an efficiency of 1.59% when used in dye-sensitized solar cells [56].

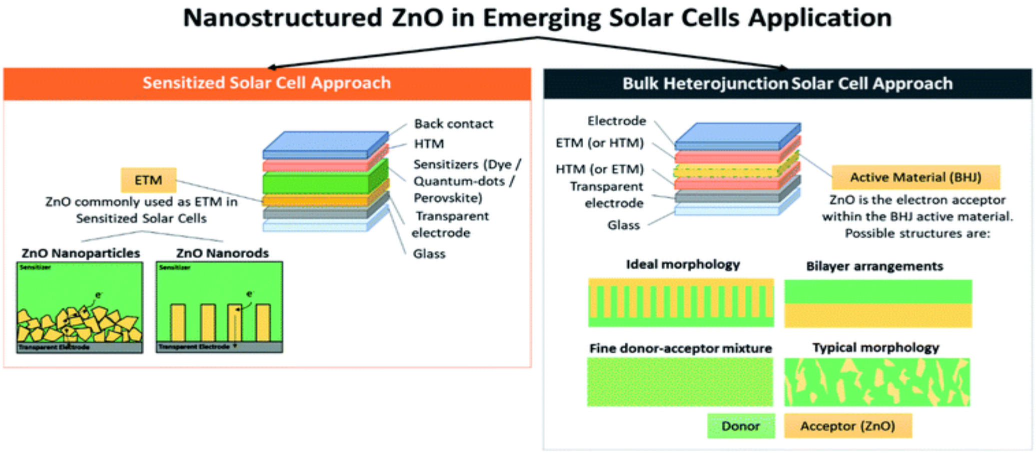

Fig.6: Nanostructured ZnO in emerging solar application [4]

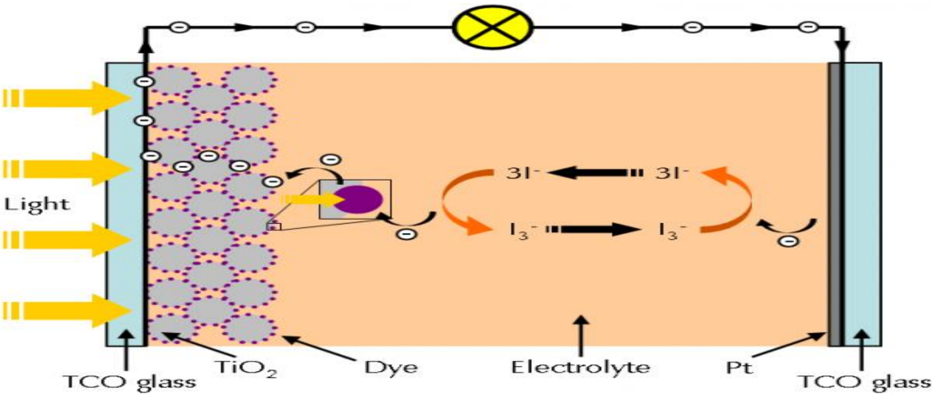

Fig.7: Diagram of dye-sensitized solar cells [44]

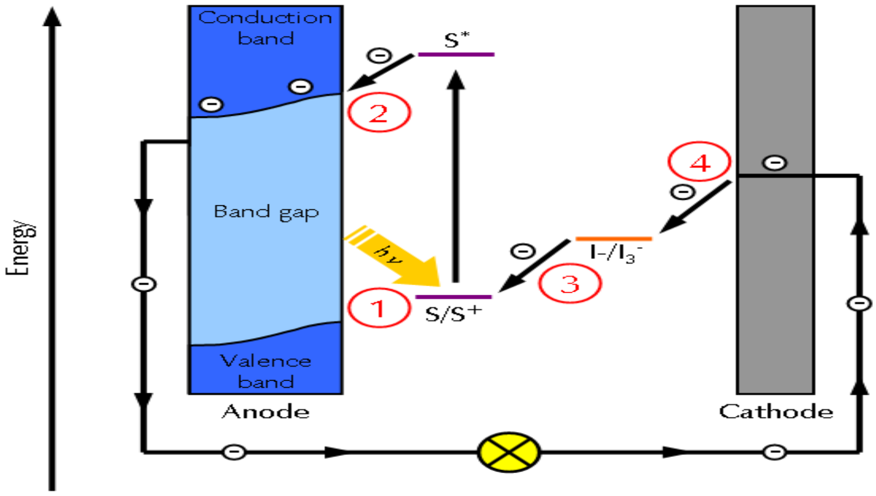

Fig.8: Energy diagram of DSSCs, and its working principles [44].

Perovskite Solar Cells: Perovskite solar cells (PSCs) are photoelectrochemical systems, which consist of a mesoporous metal oxide film which adsorbed perovskite sensitized materials [57]. Perovskite solar cells have gained significant attention owning to their versatility in application, low cost of production and high efficient. They are cheaper to produce than the traditional silicon-based solar cells, and one of the method used to manufacture PSCs is by using simple solution-based process, such as spin coating. Perovskite solar cells have the same working principle as dye-sensitize solar cells [57]. **Fig.9** is the schematic diagram of perovskite solar cells and its mechanism for energy generation. At the center of the cell, the perovskite is situated. When light is absorbed, the electrons will jump to a higher energy level, leaving the holes behind [58]. If the electrons and holes are separated further, it will result in the generation of current. Shahinuzzaman et al [59] revealed in their work that the power conversion efficiency (PCE) of perovskite solar cells synthesized using ZnO and tungsten doped ZnO (W-ZnO) has been found to be 21.16% for ZnO and 23.61% for W-ZnO. Fan et al [60] studied the application of ZnO in perovskite solar cells by incorporating polyvinyl alcohol (PVA) into ZnO NPs. The power conversion efficiency of perovskite solar cells with PVA has been found to increase from 17.59% to 19.89% and 15.03% to 16.56% for $CsFAPb_3$ and $MAPbl_3$ perovskite structures respectively. The power conversion efficiency perovskite solar cells with 40nm ZnO Nanoparticles is 15.92% [61]. ZnO NRs perovskite solar cells with Au NPs have an efficiency of 16.77% while without Au NPs, the efficiency is 14.51% [62]. Li et al [63] revealed in their work that the uniform-core shell $ZnO@SnO_2$ nanoparticles has favorable application in inorganic perovskite films. The power conversion efficiency of inorganic perovskite solar cells is 14.35% [63] while the perovskite solar cells with dual sensitization architecture show a high-power conversion of efficiency over 21% [64]. Cao et al [65] noted in their work that the PCE of perovskite solar cells is up to 21.1% when the electron transport layer is ZnO. To improve the stability and performance of perovskite solar cells. According to Tavakohi et al [66], the PCE of PCS is 19.8% when monolayer graphene (MLG) is introduced at the interface of the ZnO electron transport layers.

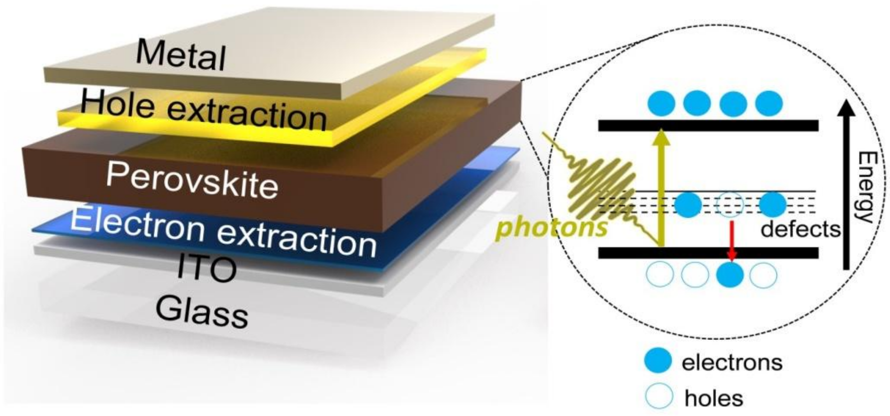

Fig.9: The schematic diagram of perovskite solar cells and its mechanism for energy generation [58].

Lithium-ion Battery: Due to the increase in world populations and industrialization, numerous interests have been placed on the environment and energy. The development of renewable energy storage and generation devices have gained momentum due to their importance in societal sustainability. Lithium-ion batteries are one of the major devices used in energy storage. The high density and ability of lithium-ion battery to produce power has made it to be considered as prominent power source. Also, its high specific capacity, extend lifetime and high electrochemical performance enable it to be an excellent device used in energy generation [67]. Regardless of its prominent application in energy storage, it can also be used in electronics devices and hybrid/electric vehicles. **Fig.10** is the schematic diagram of Lithium-ion battery. An ideal lithium-ion battery system is made up of separator, cathode, anode and electrolyte. During the charging process, the Li ion at the cathode migrates to the anode through the electrolyte and charges (electrons) pass through an outer circuit following the same direction, while discharging is the reverse of the charging process [68]. The anodes materials have a tremendous effect on the efficiency of lithium-ion battery. For instance, graphite anode has a specific capacity of 372 mA·h·g−1, which is very low and could not be applied in many areas [69]. To improve the efficiency of this battery, metal oxides are used as anode materials. Metal oxides are mainly used to enhance their performance because they have higher theoretical capacity and are safer than conventional materials like carbon materials. Among many metal oxides in use, nanostructured zinc oxide is a good material for anode owing to its non-toxicity, low costs, and its high theoretical capacity. ZnO has many interesting properties like high theoretical capacity, very ease to synthesize, environmentally friendly and less expensive [68]. When compared to other metal oxides, zinc oxide does not only have a higher theoretical capacity, but it is as well less expensive, very ease to synthesize and has different morphologies [67]. The theoretical capacity of ZnO is 978mAhg^{-1} [67]. **Table.2** shows the theoretical capacity of different metal oxides used in fabricating lithium-ion batteries. Compounds of Zn atom have the highest capacity. Redox reaction is used to achieve high theoretical capacity Li [68], and the redox equations are shown below.

Conversion reaction: $ZnO + 2Li + 2e^- \rightarrow Zn + Li_2O$ ……………………. (1)

Alloying-de-alloying reaction: $Zn + xLi^+ + xe^- \rightarrow Li_xZn$ ………………... (2)

The process in equation 1&2 is reversible process which involves two different steps. Lithium oxide and zinc metal formed in the first step are through conversion process while in the second step, lithium zinc alloy is formed by the process of alloying dealloying reaction. Nadia Garino at al [70] synthesized spong-like nanostructure ZnO using sputtering deposition, the result shows that spong-like nanostructure ZnO has a stable specific capacity that is above 50иAhCm^{-2}. According to Samapti Kundu et al [71], zinc oxide nanorods synthesized using a chemical method at room-temperature without addition of any template is a good anode material in lithium-ion battery. Vu Khac Hoang Bui et al [67] revealed that the performance of lithium-ion battery can be enhanced when ZnO is used as the anode.

Though ZnO has features that made it an interesting material to be used in lithium-ion batteries, but it suffers from three major problems: slow chemical reaction kinetics, intense capacity fading on potential cycling and low-rate capacity [68]. To overcome issues in ZnO, many approaches such as nanostructuring and formation of composition with various materials have been employed by researchers [68]. Also, according Xiaoliang Wang et al [69], 3D ZnO hierarchical nanostructures can be used to improve the lithium storage properties of zinc oxide anodes.

Table.2: The comparison of theoretical capacity of some metal oxides used in lithium-ion batteries [67].

Metal oxides	Lithium intercalation method	Theoretical capacity(mAhg^{-1})
Co_3O_4	Conversion	890
CoO	Conversion	716
CuO	Conversion	674
Fe_2O_3	Conversion	1006

NiO	Conversion	718
RuO_2	Conversion	806
SnO_2	Alloying	740
TiO_2	Intercalation	335
$ZnCo_2O_4$	Conversion	903
$ZnFe_2O_4$	Conversion	1000
ZnO	Alloying	978

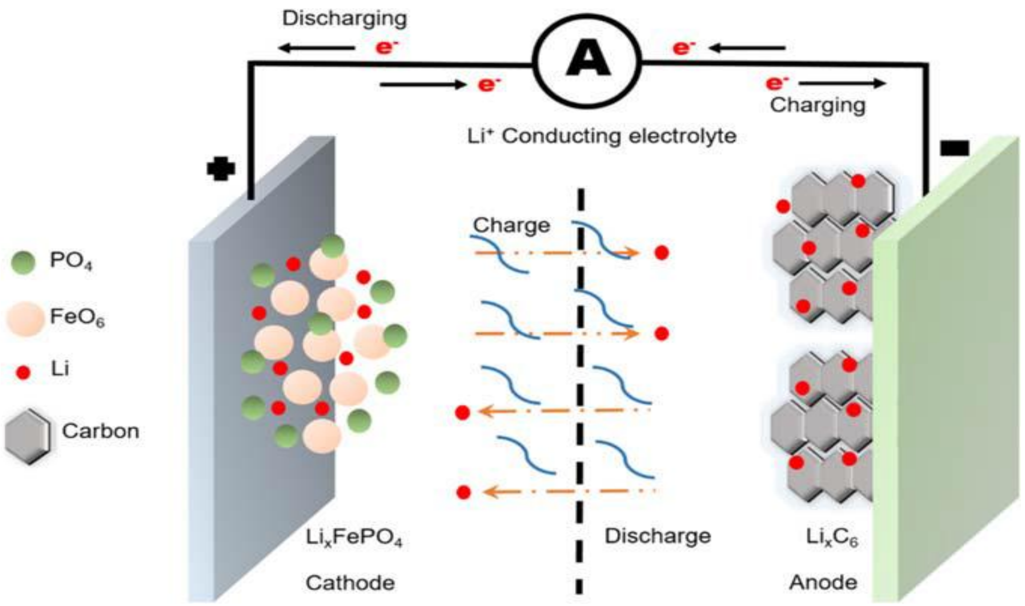

Fig.10: The schematic diagram of Lithium-ion battery [68]

Supercapacitor: With the global efforts to move into a low carbon economy and ever-increasing demand for energy in the world, supercapacitor has received immeasurable attention. Energy development is one of the key sustainable development goals, and electrochemical energy storage devices such as supercapacitors, batteries, and fuel cells have been in the forefront of this development. Among other electrochemical energy storage devices, supercapacitor has gained momentum because of its ability to generate high amounts of energy. **Fig.11** is the Schematic view of supercapacitor. The energy density of supercapacitor is low when compared to those of other electrochemical devices like batteries and fuel cells, but it has higher power density. The relationship between the energy density and power density of supercapacitors and other electrochemical energy storage devices is shown in **Fig.12** [72]. The plot is known as Ragone plot. In designing and fabricating supercapacitor, ZnO nanostructures have been extensively used due to its remarkable energy density of 650Ang^{-1} and electrical conductivity of 230SCm^{-1} [73]. Great potential electrode material has been recognized to be ZnO nanostructure. According to Ding et al [74], ZnO nanomaterials with excellent theoretical specific capacity have been considered as a good supercapacitor's materials, but the application of these materials is limited due to their poor active site and conductivity which tend to increase the electrode's internal resistance and lowers the supercapacitor's capacity. L. Goswami et al [75] noted that the amazing properties of ZnO nanostructure made it to be a promising material for electrode in supercapacitors. Also, ZnO nanostructure is made up of different nanocarbons such as nanofiber, nanorods, activated carbon graphene e.t.c. M. Selvakumar et al [76] stated that composites Zn-AC has excellent application in supercapacitors.

Advantages of the SCs over other electrochemical energy devices

1. It discharges and charges easily.

2. Its life cycles can be more than 100,000 charge-discharge cycles
3. Good reversibility
4. The capacitance ranges in the value 0.043-2700F

Disadvantages of Supercapacitors:

1. It has low energy density.
2. The internal resistance of supercapacitor is low.
3. The materials used in fabricating supercapacitors are very expensive.

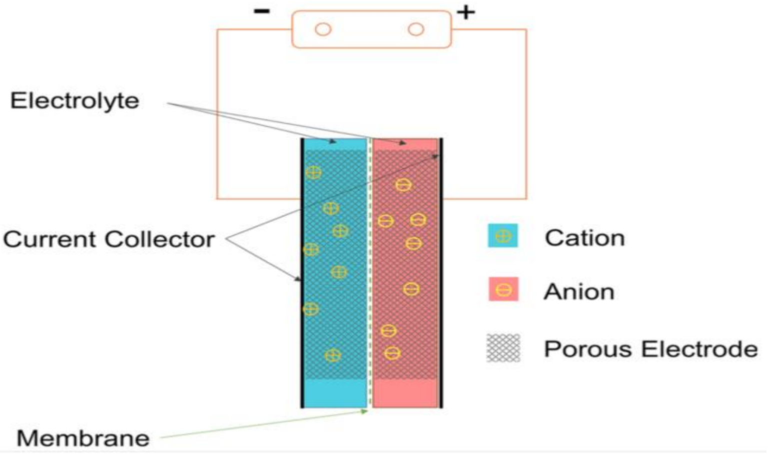

Fig.11: The Schematic view of supercapacitor [77]

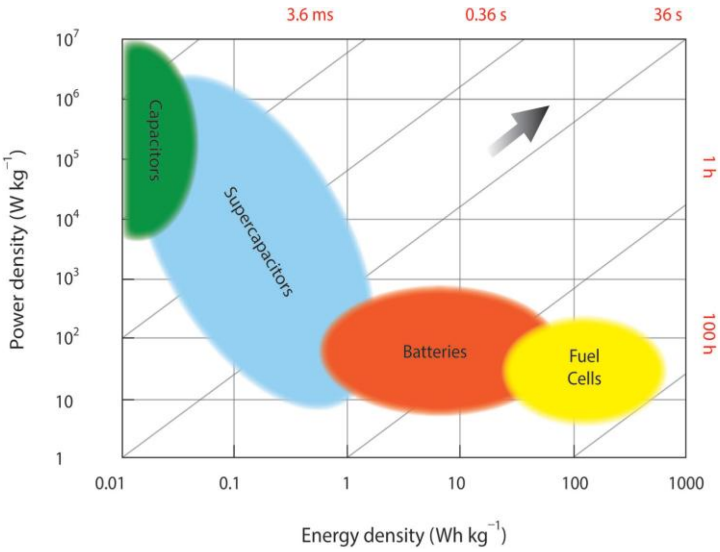

Fig.12: The relationship between the energy density and power density of supercapacitors and other electrochemical energy storage devices [72]

Photocatalysis: When a chemical reaction accelerates in the presence of light and catalyst, photocatalysis is said to have taken place. ZnO nanmaterials have gained immeasurable attention in the field of photocatalysis owing to its biocompatibility, non-toxicity and its natural abundance [69]. The ability of ZnO to remove chemical and biological contaminant from water makes it a suitable choice for photocatalysis [78]. A satisfactory photocatalyst should be one that can efficiently absorb light in the visible region [69] or close ultraviolet part of the electromagnetic spectrum. The process associated with photocatalysis are grouped into four steps, which are (a) absorption of light (b) production and demarcation of photoinduced electrons and holes (c) carrier migration, transport, and recombination (d) oxidation and reduction of surface electrocatalytic reactions. Photoinduced process to split down organic contaminants and inactive microorganisms (bacterial) using photocatalyst from semiconductor is done through photocatalysis. **Fig.13** is schematic illustration of photocatalytic process in ZnO. The formation of a positive hole (h^+) in the valance band and electron (e^-) in the conduction band [79] as shown in **Fig.13** results from a photocatalytic surface with enough photo-energy. The positive hole can either oxidize organic contaminants directly or form hydroxyl (OH*) that will be reactive in nature [79]. Research proves that the bandgap value of ZnO is not equivalent in comparison with other semiconductor materials such as TiO_2, this can be linked to diverse degree of O vacancy in ZnO [80]. Even though, the commonly under seek photocatalysis is TiO_2, ZnO has not been left out as a suitable substitute for TiO_2 because of uniformity in its bandgap energy with TiO_2 and its low cost of production [81]. There is also a tendency for ZnO to be more photoactive than TiO_2 because of its ability to sufficiently generate and disintegrate photoinduced electrons and holes [81]. According to Chin Boo Ong et al [82], ZnO nanostructure is an outstanding photocatalyst used in photodegradation owing to its low cost of production, environmentally friendly and ability to absorb light across a large fraction of the electromagnetic spectrum compared to TiO_2. Jin SE et al [83] suggested that the next-generation photocatalytic antibiotics disinfection system can be favorable with zinc oxide nanoparticles and their networks. In addition, ZnO nanoparticles have some applications in industries and as well can be used as efficient and safe photocatalytic antibiotics. Biabara et al [84] noted that increase in the reactivity of the ZnO nanoparticle surface makes it a good photocatalytic and antibacterial material. The higher the surface area of ZnO nanoparticle, the higher the removal rate of different pollutants. Minh Tan Man et al [85] found that precipitated zinc oxide nanorods show amazing performance in the absorption and photocatalytic decomposition of dye. Nai-Feng Hsu et al [86] synthesized dandelion-like zinc oxide nanostructures on Si substrates using thermal oxidation approach in two steps. The synthesis was conducted at different thermal oxidation temperatures which range from 400℃-700℃, using the decomposition of methyl orange (MO) dye under ultraviolet illumination to test the photocatalytic effect of the synthesized nanoparticles. Their plot of wavelength against absorbance shows that the absorption intensity of the solution decreases as the synthesized temperature increases, and the highest absorbance value corresponds to 461nm wavelength. Furthermore, the degradation of solutions shows a degree of enhancement from 0.4% -90% with nanostructures Zinc oxide. Hence, their experimental result revealed that dandelion-like zinc oxide nanostructures synthesized at 700℃ shows an excellent photocatalytic effect.

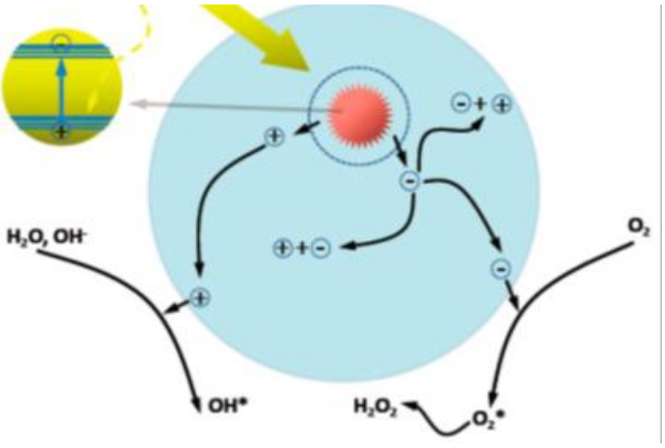

Fig.13: Schematic illustration of photocatalytic process in ZnO [69].

CONCLUSIONS

This research was carried out to contribute to the recent development in the applications of new materials in solar energy generation and storage devices, and photocatalysis. Among other metal oxides, ZnO nanostructures have been found to be a good substitutes for TiO_2 in fabricating solar energy devices owing to its high theoretical capacity, and electron mobility. More so, the biocompatibility, non-toxicity, and abundance of ZnO nanostructures make them favorable materials for photocatalysis. While other reviews focus only on the applications of ZnO nanostructures in solar cells, we ensured that lithium-ion batteries and supercapacitors, which are emerging solar energy storage devices, are discussed. Also, environmental degradation is seriously impacting the ecosystem; therefore, our review covered the photocatalytic application of ZnO nanostructures to address these environmental challenges.

Conflicts of Interest

We declare that there are no conflicts of interest.

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