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NANOCRYSTAL ARCHITECTURES FOR ENHANCED OPTOELECTRONIC PROPERTIES: A PARADIGM SHIFT IN ENERGY HARVESTING AND STORAGE

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Abstract

The nanocrystal architecture has revolutionized the field of optoelectronics, offering innovative solutions for energy harvesting and storage applications. This review examines the important role of optoelectronics devices in modern technology and highlights the limitations of traditional materials and introduces nanocrystal architecture as a promising solution. Nanocrystals are synthesized using various colloidal synthesis techniques and template assisted methods. The control on size, shape and composition of nanocrystal is very crucial to maximize the optoelectronic properties. In comparison to conventional materials, nanocrystals perform more efficiently due to key phenomena such the quantum confinement effect, which improves the tunability of bandgaps, absorption coefficients, and charge transport efficiency. Energy harvesting applications are also being investigated, such as the incorporation of nanocrystals into thin-film solar cells, extremely sensitive photodetectors, and photocatalytic devices for water splitting and solar-powered fuel cells. The review also discusses developments in energy storage, with particular attention on lithium-ion battery technology and nanocrystal-based supercapacitors, as well as hybrid devices that combine several other functions. The emerging field of 4D printing has a great potential to produce responsive material for adaptive energy solutions. The potential approaches including interface engineering and sophisticated packing control are discussed, along with the difficulties in creating high-efficiency nanocrystal-based systems. Finally, this review provides an outlook on the future of nanocrystal based optoelectronic devices emphasizing their transformative potential in energy harvesting and energy storage applications.

1. INTRODUCTION

Functional optoelectronic devices are the basis of artificial intelligence (AI) optoelectronic sensing technology and are made of a range of materials such as 2D materials, organic optoelectronic materials, semiconductors and some other common materials represented by carbon materials. Photoelectric sensors are getting popular as they are digital, small and intelligent [1]. Optoelectronic technology integration is becoming more important, with key roles being played in vital areas including energy sensing, communication, imaging and harvesting [2].

The discovery of innovative materials like nanocrystals has the potential to drastically alter the landscape of modern optoelectronics, redefining its possibilities. The researchers from all around the world have been fascinated by two-dimensional marvels like graphene and transition metal dichalcogenides. Due to remarkable optical and electronic properties, these materials have become pivotal platforms for the production of optoelectronic devices. Graphene has high transparency and conductivity which increases the speed of response and sensitivity [3]. Unique bandgap properties of transition metal dichalcogenides make them ideal for quantum devices [4]. These nanocrystal architecture plays important role to enhance efficiency of optoelectronic devices

Optoelectronic devices play pivotal role in high-speed communication networks. Optical fibers are used for travelling of lights to long distances with minimum signal loss. Lasers are used to produce signals of light which are then converted into electrical signals again by photodiodes. This technique is used in TV, phone lines and internet. These devices are also used to get high resolution images of internal structures. Optical coherence tomography (OCT) is one of such techniques. Light emitting diodes (LEDs) and organic light emitting diodes (OLEDs) are optoelectronic devices which are used in display of computer, television and smartphones [5].

For energy harvesting, solar cells are the devices which use the process known as photovoltaic effect to convert sunlight into electricity. These are renewable energy source and are used for the production of electricity on every scale from small devices to homes and industrial scale [6]. Different types of solar cells are silicon crystal solar cells, thin-film solar cells, organic solar cells, tandem solar cells, multi-junction solar cells, etc. Every type has its own advantages and limitations. The research remains continue in this field to increase the efficiency, lower the cost and expand the applications to produce electricity by environment friendly methods [7].

Modern information and communication, display, optical imaging, and energy technologies all depend on optoelectronic devices. Photodetectors (PDs) are vital optoelectronic devices that are used in nighttime surveillance, industrial production, environmental monitoring, and optical communication [8]. Conventional photodetectors need energy to operate but now self-powered photodetectors (PDs) are used which in conjunction with a straightforward device design require little to no maintenance, have a long lifespan and can operate wirelessly. Stated differently, autonomous, wireless power devices (PDs) hold great potential for improving human well-being and advancing economic and technical developments [9]. PDs are also already used in modern fields like video tracking, scene reconstruction, visual prosthesis and visual serving [10].

Conventional materials often face difficulties such as poor solubility, reduced structural integrity, and performance inefficiencies in many applications. Conventional energy storage systems, for instance, sometimes have trouble scaling efficiently and exhibit uneven performance, which makes them less dependable for wider usage [11]. Nanocrystals enhance the transfer of charge in electrochemical devices, which leads to improved overall energy storage efficiency. In resistive memory devices, the presence of nanocrystals stabilizes the voltages and ensures reliable data retention [11,[12].

There are several problems with the use of traditional materials for optoelectronic devices. III-V semiconductors, although largely used, are expensive and complex in terms of processing [13]. Organic semiconductors have an advantage in terms of flexibility, and their manufacturing is cost-effective. They also need significant improvement in material properties and the efficiency of the devices. The research has now found a rhythm in developing innovative methods, such as tailoring the optical environment of active layers and designing two-dimensional organic hybrid heterostructures to improve performance [14, 15].

Modern nanocrystal technology can also be used to cope with water pollution. The public has long been concerned about environmental degradation, especially water pollution. The environment and public health have always been threatened by metal-contaminated wastewater that comes from human activity in a variety of sectors, including agriculture, industry and home sewage [14]. Heavy metals, such as Cd, Zn, Pb, Fe, Cu, Hg, Ni, Mn, Co, etc., are generally found at small levels but are believed to be the most toxic and frequent substances present in wastewater effluent [15]. Several methods have been proposed for effective removal of heavy metals from aqueous medium, which include solvent extraction, coagulation, ion exchange, chemical precipitation, membrane filtration, and electrochemical technologies [16].

Activated carbons (ACs) are widely utilized in water treatment facilities as adsorbents for the purpose of adsorbing heavy metals because of their chemical complexity, huge surface area, and microporous structure. Variable functional groups, such as phenol, carbonyl, lactone, carboxyl, quinone, and others, are present on their exterior surface [17]. Other options must be explored due to the expensive manufacture and renewal of activated carbon. Furthermore, due to their limited metal adsorption capability, traditional materials often cannot provide the desired removal efficiency for the heavy metals in wastewater treatment. The researchers have been working on creating new adsorbents in the past few years, focusing on nanostructured materials such MXene, graphene, fullerene, and carbon nanotubes [18].

Metal oxides have been regarded as one of the most promising classes of adsorbent materials because of their exceptional adsorption performance, simplicity of synthesis and modification, low cost, and mass-produced nature. When used in wastewater treatment, zinc oxide nanoparticles made from Phoenix dactylifera waste demonstrate effective suppression of microbes [19]. Large specific surface area, excellent chemical stability, and improved functional and active sites on its surface are only a few of graphene exceptional qualities. Graphene is a more promising adsorbent than activated carbon for wastewater treatment because of its chemical characteristics that may be adjusted and its mainly delocalized π electrons [20].

Other novel materials produced for better water treatment are Graphitic carbon nitride, metal organic framework, etc. Their attributes include superior electrical conductivity, great chemical stability, and environmental friendliness. 2D nanomaterials are ideal for wastewater treatment applications because of their huge specific surface area, large lateral dimensions, and nanoscale thickness [18].

Electricity has attained great importance in modern society. It is used in every field of life and its consumption is increasing day by day. Conventional methods of producing electricity like fossil fuels can cause environmental pollution and many other issues. The development of next-generation energy conversion and storage technologies that are affordable, highly efficient, and environmentally benign is essential [21]. Renewable sources can be used for energy production like solar energy, wind energy, etc. These energy sources also have some drawbacks as solar radiations are not available on night. So, we need energy storage devices which we can be used on night when solar radiations are not available. Phase change materials (PCMs) are a very helpful way to enhance the heat energy storage capacity of various solar energy systems [22].

The creation of nanocrystals is closely tied to the glass industry; in fact, color is added to glass in antiquity by melting metal into the glass mixture. By reducing copper oxides in a reducing environment, metallic copper nanocrystals are formed, yielding red glass [23]. Red colored glass is formed in the presence of gold nanocrystals [24]. Due to their numerous optical and magnetic uses, which span from non-linear optical devices to ornamental materials, glasses incorporating metal nanoparticles are extensively researched systems [25].

Due to their low solubility, the majority of medicines (about 70%) in the research pipeline now fall into class II and have a rate of dissolution that limits absorption. Various methods have been employed to improve the solubility and/or bioavailability of medications that are poorly soluble, such as complexation, micro-/nanonization, inclusion of cyclodextrin, salt production, and solid dispersions [26]. Because nanotechnology has a targeted delivery impact with lower toxicity, it is important for medication delivery, diagnostics, and illness treatment. Because of their high drug loading capacity (up to 100%), nanocrystals have gained popularity as a means of treating a variety of illnesses. So, nanocrystals play important role in targeted drug delivery process [27].

Solar energy is widely available and may be used to generate electricity, thanks to photovoltaics (PV). Terrestrial photovoltaics (PV) have been used more widely since the early 2000s as a renewable energy source that offers a practical substitute for burning fossil fuels and a means of slowing down global warming [28].

Nanocrystal architectures have emerged in recent years as transformative materials for improving optoelectronic devices and paving the way for innovations in energy harvesting and storage technologies. Graphene, transition metal dichalcogenides, and novel carbon structures have dramatically improved the performance, efficiency, and sustainability of applications across high-speed communication, imaging, renewable energy, and environmental monitoring. These materials have superior optical, electrical, and structural properties that compensate for the inadequacies found in traditional systems, thereby creating breakthroughs in photodetectors, organic electronics, and solar energy technologies. In addition, nanocrystals are being used in water treatment and targeted drug delivery as an example of their multifunctional role in addressing global challenges.

2. Nanocrystal Synthesis and Engineering

There are different methods for the synthesis of nanocrystals as shown in Figure 1. The figure classifies several synthesis methods for nanocrystals into two main approaches: the Top-Down and Bottom-Up strategies. The Top-Down approach involves breaking down larger particles into nanocrystals through techniques such as milling methods (bead milling and piston gap) and high-pressure homogenization. Instead, the Bottom-Up approach relies on building nanocrystals from smaller molecules or atoms by precipitation methods such as hydrosols, freeze drying, nano morph, and spray drying. A combination approaches is also used in synthesis of nanocrystals. Other methods like Spray freezing into liquids and rapid expansion from liquified gasses are also used in the synthesis.

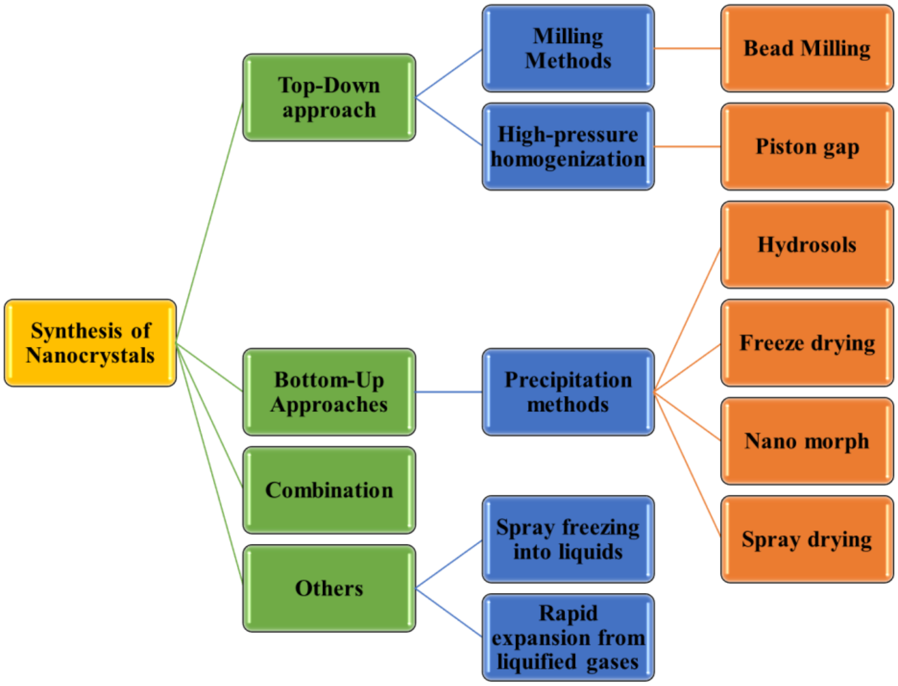

Figure 1. Different methods for the synthesis of nanocrystals.

2.1. Colloidal synthesis

Colloidal synthesis involves the wet-chemistry techniques to produce nanocrystals (NCs) of specified composition and morphology. These crystals are usually of size ranging from 10-100 nm. These colloidal nanocrystals help understand the electrochemical reactions which are involved in energy storage [29]. Here, we will discuss various colloidal techniques for NCs synthesis.

2.1.1. Chemical reduction

In typical colloidal synthesis, the metal precursor is reduced in the presence of organic or aqueous solvent using some surfactant as a catalyst as shown in Figure 2 [30, 31]. Aqueous environment is essential for the synthesis of noble metal NCs. Metal salts are reduced by using polyol such as ethylene to glycol or diethylene glycol as a solvent in the presence of capping agents like citrate, halogen ions or polyvinylpyrrolidone (PVP) [32]. Non-noble metal NCs can be synthesized in both organic and aqueous environment. These NCs have less specificity of size and composition as very strong reducing agent is required for their synthesis in aqueous environment [33] . Binary metal oxide NCs are synthesized by the breakdown of metal acetates and carboxylates precursor in the presence of organic ligands such as carboxylic acids, diols and amines [34].

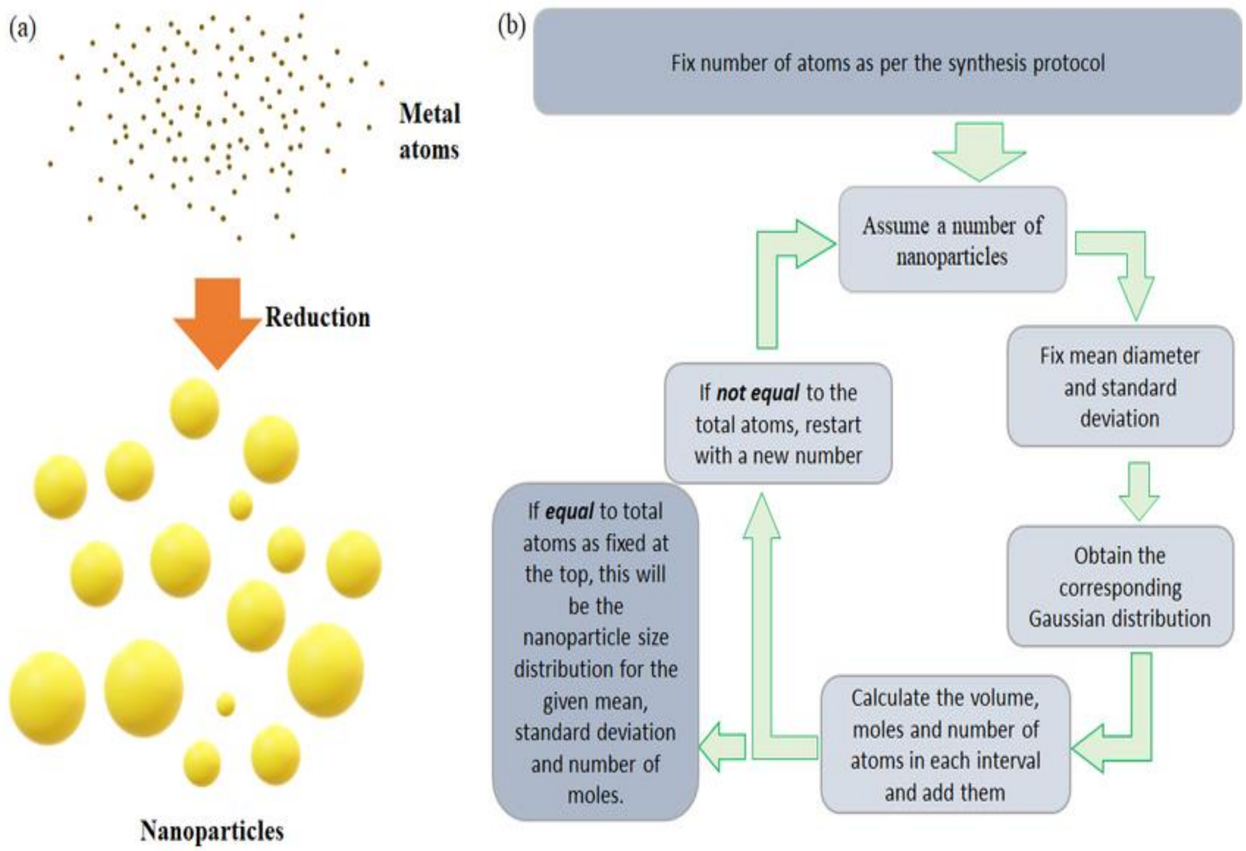

Figure 2. Schematic route of colloidal synthesis of nanocrystals [31].

2.1.2. Composition and size control of NCs

Surfactant plays important role in regulating the size of NCs. Different parameters during the reaction such as an atmosphere, concentration, temperature, injection rates, and reactor volume need to be carefully monitored during the synthesis to get NCs of desired shape and composition [30]. Most commonly used reducing agent is ethylene glycol. It can dissolve most of the metal salts, have high boiling point which allows variation in reaction temperature. Its reduction power depends on temperature, so it is important in shaping NCs [29].

2.2. Stöber synthesis

This two-step method involves an ammonia-catalyzed sol-gel reaction in which tetraethylorthosilicate (TEOS) is hydrolyzed in the presence of water and alcohols like ethanol, followed by condensation [35, 36] Figure 3). Hydrolysis is the replacement of the ethoxy group (Si-OR) in a pentacoordinate transition state by silanol groups (-Si-OH), whereas condensation involves the combination of two silanol groups with the elimination of water and leads to the formation of a siloxane bond between them. Condensation is very fast and is not rate determining step. Normally, hydrolysis occurs in an aqueous solution, but in this synthesis, ammonia has been used as a catalyst where it enhances the rate of both hydrolysis and condensation efficiently. The nucleophilicity power of OH^- is much higher in ammonia than in water [37].

The second step is condensation. Here, silanol groups (-Si-OH) of silica monomers or oligomers condense to form siloxane (Si-O-Si) bond. This also involves nucleophilic substitution reaction. The reaction rate for this step is higher than the hydrolysis reaction because silanole groups are deprotonated more readily than water. That's why silanole prefers large siloxanes to attach rather than small oligomers [38] [36].

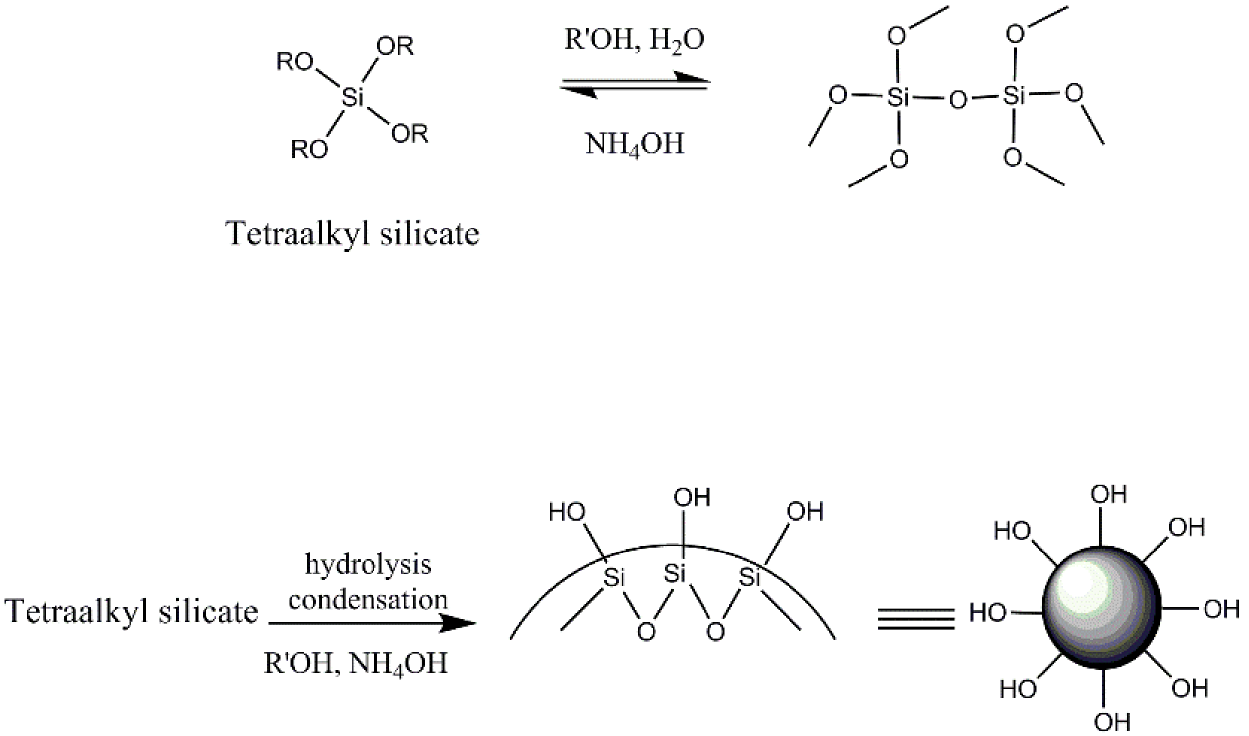

Figure 3. Schematic illustration of Stober synthesis [36].

2.3. Controllable synthesis of hydrous TiO_2 colloidal spheres (HTCS)

The general synthetic routes of HTCS can be described as follows: $Ti(OR)_4$ like titanium isopropoxide, TTIP was rapidly added to a mixed solution of alcohol, acetonitrile, and water that contained pre-dissolved SDA under vigorous stirring. White precipitates were formed in 1 or 2 minutes under appropriate conditions. After further agitation for 5 min, the suspension was sealed and left for 2-6 hours. The aging process stabilizes and completes the condensation of nanosized TiO_2 hydrates within their parent sphere. Fine HTCS are obtained after removing the liquid from it through centrifugation followed by washing with water [39].

2.3.1. Size control of HTCS

The final size of HTCS particles is a function that largely depends on the kinetics of the hydrolysis of $Ti(OR)_4$. The higher hydrolytic kinetics increases the particle size. In practice, it is possible to attain desired properties by adjusting several synthetic parameters, such as the concentrations of $Ti(OR)_4$ and SDA, reaction temperature (T), specific concentration (Rw), the choice of solvent, and any additives used [40]. Rw and T are the most crucial parameters that the average particle size of HTCS relies upon. With a value of Rw, it shows progressive decreases in particle size. A highly accepted theory is that the number of nucleation centers created had been responsible for explaining the influence of Rw or kinetics of hydrolysis for size-controlled synthesis. In particular, the larger Rw increases the nucleation center leading to the generation of smaller colloidal spheres [41].

Colloidal hot injection synthesis

The nanoparticles of the CFTS material were prepared from copper(II) sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), stannous sulfate ($SnSO_4$), iron(II) sulfate, and powder sulfur in a stoichiometric ratio. The mixture of copper, tin, and iron in the concentration of 0.15 M:0.075 M:0.075 M was prepared under inert atmosphere, followed by the addition of 10 mL of oleyl amine. This was then heated to 130 °C for 30 minutes as shown in Fig. 4. The temperature of this step was increased to 250 °C and held steady for another hour under an argon atmosphere. Meanwhile, in a separate flask, 4.0 M of sulfur powder was mixed with 5 mL of oleyl amine and heated to 80 °C for one hour. Molten sulfur was then dropped into the melt of copper, iron, and tin [42].

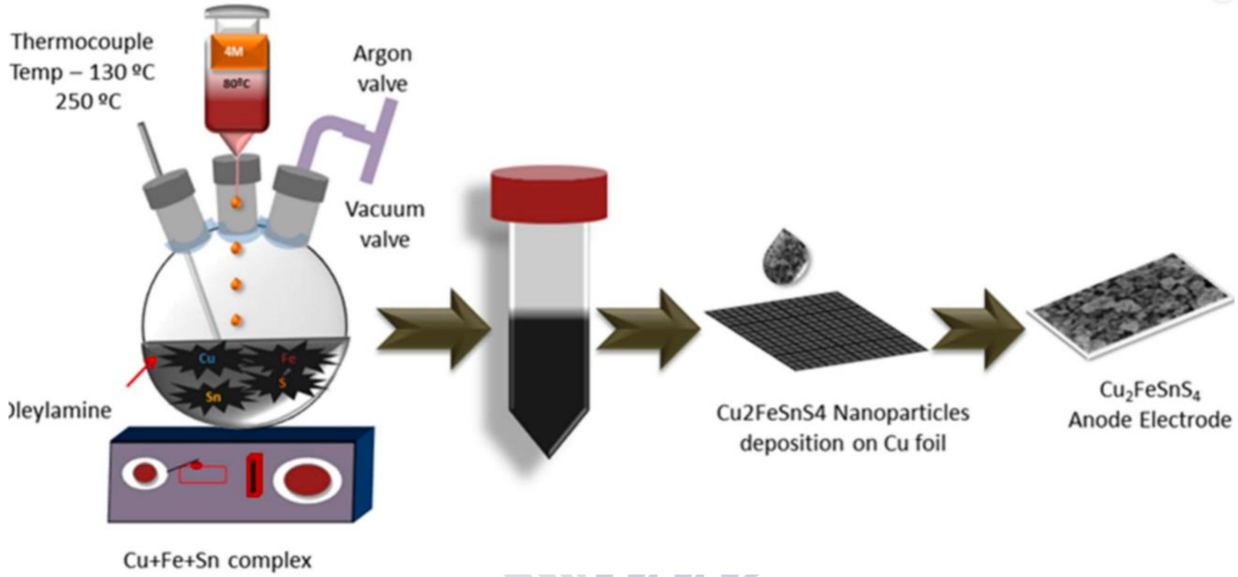

Figure 4: Synthesis procedure of CFTS NPs using colloidal hot injection method [42].

The reaction was allowed to proceed for 30 minutes at the same temperature, resulting in the formation of a homogeneous blackish solution. The entire process was alternated between vacuum and argon atmospheres. Once the reaction was complete, the three uncovered flasks were placed in a cold-water bath to cool down. The resulting CFTS residue was dispersible in organic solvents, specifically a mixture of 5 mL of toluene and 40 mL of isopropanol. Colloidal blackish CFTS nanoparticles were obtained by centrifuging the precipitate at 5000 rpm. IPA and toluene were utilized to remove both polar and non-polar impurities [43].

2.4. Template assisted synthesis techniques

The template assisted synthesis technique of nanocrystal synthesis uses a template to control the formation of nanostructures of specific morphology. Templates are defined as guiding elements that promote the formation of a specific product from reagents that can assemble in multiple configurations. Template plays its role in aligning atoms in specific arrangement. It also provides platform of structure formation and provides attractive interaction to units present around it [44]. Template assisted synthesis is further divided into three classes depending on the type of template. These types are soft template method, hard template method or colloidal template method. Once template is prepared then the desired material is fabricated on surface by coating or chemically by addition, elimination etc. when reaction is completed, template is removed either by calcination or dissolution [45]. Figure 5 illustrates a schematic overview of the material fabrication process utilizing these templates.

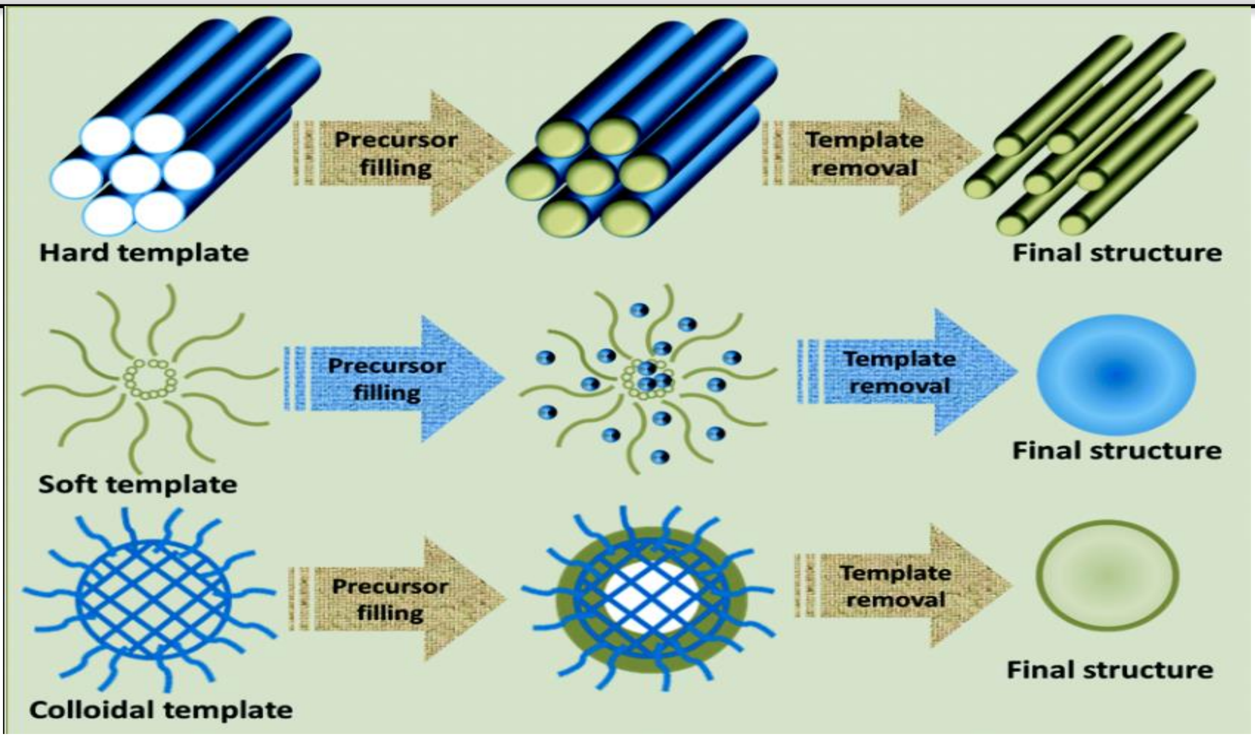

Figure 5. Schematic demonstration of synthesis of material using different templates [45].

2.5. Template-assisted electrochemical synthesis

Polypyrrole (PPy) nanorods embedded with CdSe nanoparticles were produced using an established technique of templated electropolymerization on anodic aluminum oxide (AAO) substrates. Ag layer was coated on the AAO membrane. Then, three electrodes setup was introduced as shown in Figure 6. These electrodes are acting as working containing AgCl, reference and counter electrodes [46]. First, sacrificial silver layer was coated electrochemically at -800 mV for 5 minutes to seal any pores at the bottom of membrane. Then, over these silver rods gold was coated at a potential of -750 mV followed by the growth of CdSe-embedded polypyrrole nanorods, achieved by maintaining a potential of 1200 mV for 2 hours, using 20 mL of a specially prepared tetrahydrofuran solution containing 0.1 M pyrrole, 1 mg of CdSe nanoparticles, and 0.1 M tetrabutylammonium tetrafluoroborate [47].

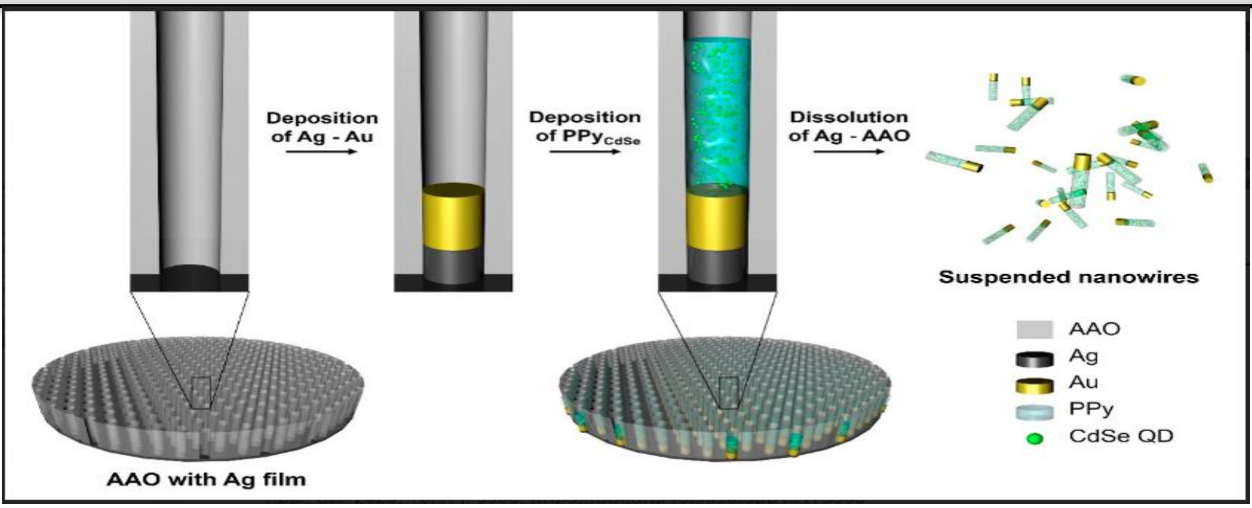

Figure 6. Schematic demonstration of synthetic procedure for the CdSe-embedded PPy nanorods [46].

2.6. Soft-template synthesis of mesoporous materials

Soft-template synthesis is comprised of two steps. During first step, mesostructured composites are formed via micelle formation and in second step Structure-Directing Agents (SADs) are eliminated and these composites are converted into mesoporous material as shown in figure 7 [48]. For the synthesis, suitable SDAs are chosen. Usually, SDAs with low molecular weight are preferred but this low molecular weight limits the control on pore size [49]. To synthesize desired pore size and wall thickness Block Copolymers (BCPs) are used. The commonly used BCPs and SDAs contain both hydrophobic and hydrophilic units. In second step, mesoporous material is separated from SDAs to increase their stability. SDAs are not thermally stable, thus BCP-based SDAs are preferred which are thermally more stable [50].

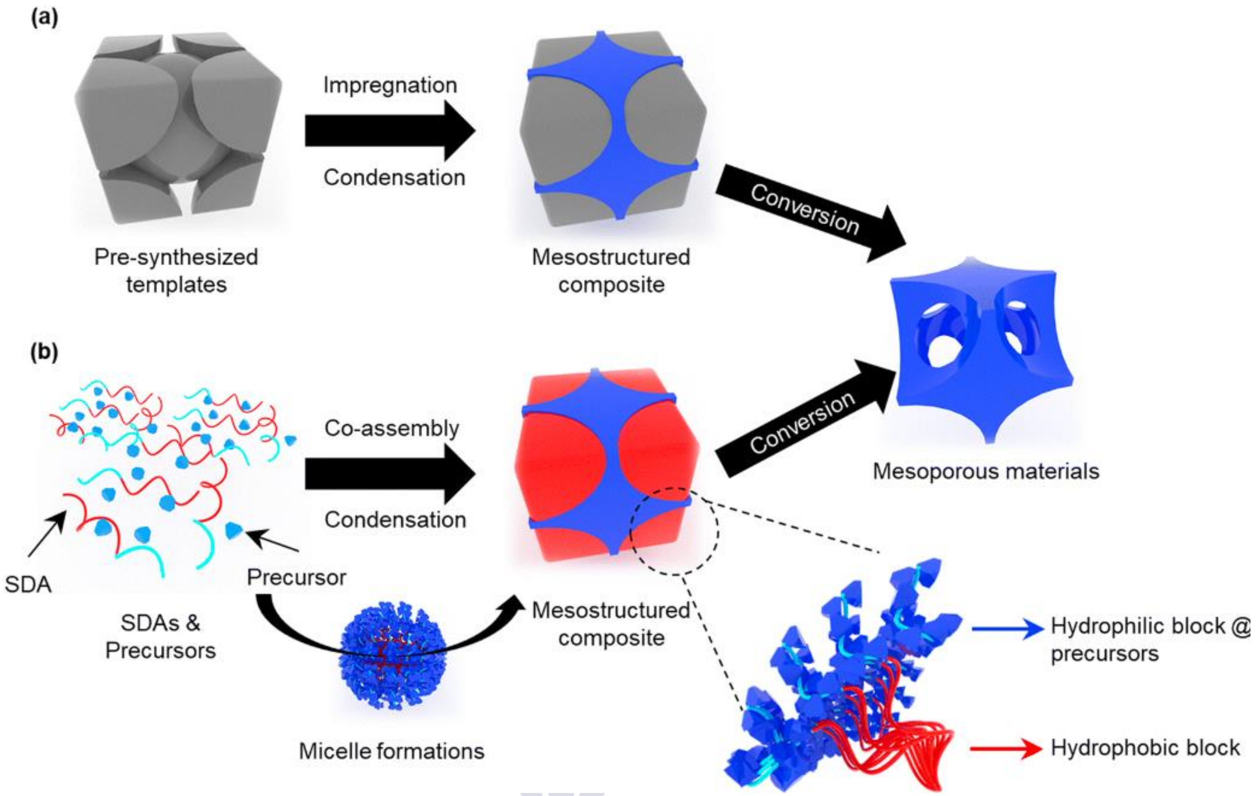

Figure 7. Schematic representation of (a) hard- and (b) soft-templating methods for fabricating mesoporous materials [48].

3. Recent progress in template-assisted synthesis of porous carbons for supercapacitors

3.1. Synthesis of porous carbons with hard templates

There are different strategies for synthesis of porous carbon shown in figure 8. Porous carbons of desired chemical and physical properties can be synthesized effectively using the hard template method [51]. Hard templates usually used to produce porous carbon are $CaCO_3$, NaCl, polystyrene, AAO, MgO, ZnO and SiO_2 [52]. ZnO template plays dual function. It acts as a template as well as plays role in physical activation. ZnO template can be removed by washing with acid or pyrolysis [53]. There are four steps of synthesis of porous carbons. First hard template of desired nature is prepared. Then, carbon source is introduced to the template. In the third step, calcination is done at very high temperature and finally hard template is removed by using base or acid [54]. New templates for PCs synthesis are much better than conventional template method due to low cost and their easy removal [55].

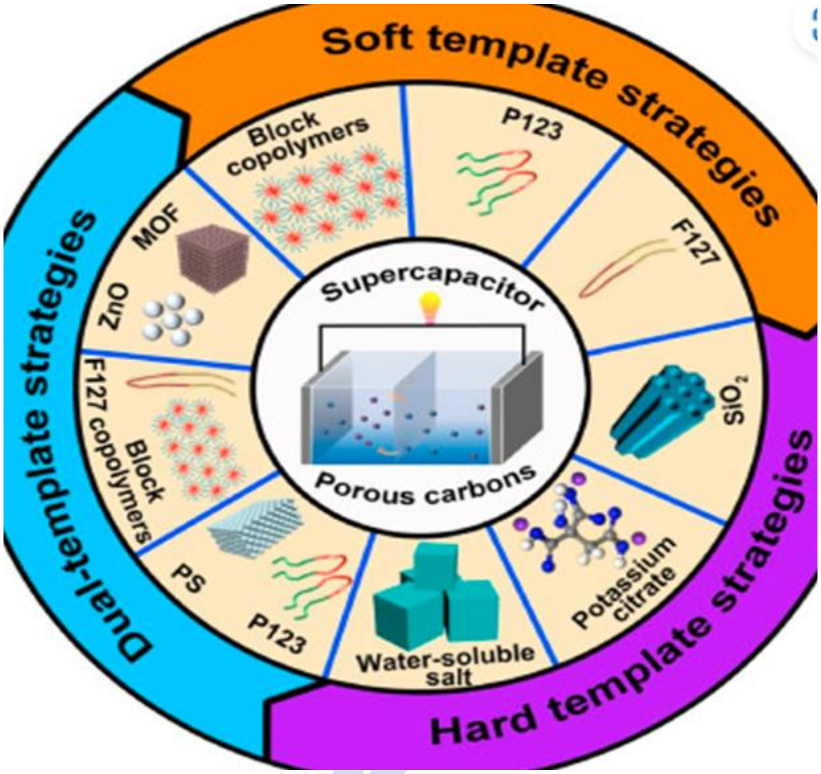

Figure 8. Representation of different template strategies for preparation of PCs [54].

4. Importance of size, shape, and composition control in tailoring optoelectronic properties

Nanomaterials are defined as materials with sizes ranging from 1 to 100 nanometers. Due to their small dimensions, they exhibit different behaviors compared to bulk materials, along with unique mechanical, electrical, physical, and chemical properties. Reducing materials to the nanoscale results in significant changes and enhancements in their physical properties [56]. On larger scale there is not significant change in properties with change in size and shape. But on nanoscale properties show a significant change with change in size or shape [57]. With the change in shape and size mechanical and electrical properties also change. As the size of nanomaterials decreases, their cohesive energy diminishes because the number of dangling bonds increases [58]. This change in energy causes increase in energy band gap and lowers the melting point. Dielectric constant also changes with change in shape and size of nanostructures [59].

In nanotechnology, the ability to accurately control the size and shape of nanoparticles is essential, as these factors significantly impact their performance and characteristics [60]. This includes effects on biological function, catalytic efficiency, light absorption, electrical properties, and magnetic qualities [61]. The synthesis method employed can result in nanoparticles with distinct physicochemical and structural features, allowing for diverse applications in fields such as electronics, optoelectronics, optics, electrochemistry, environmental science, and biomedicine[62]. The method of synthesis being used depends on desired size, shape and morphology of NCs. Nanomaterials (NMs) are divided into different classes depending upon their size, composition, origin and shape [63]. These divisions are given in Figure 9.

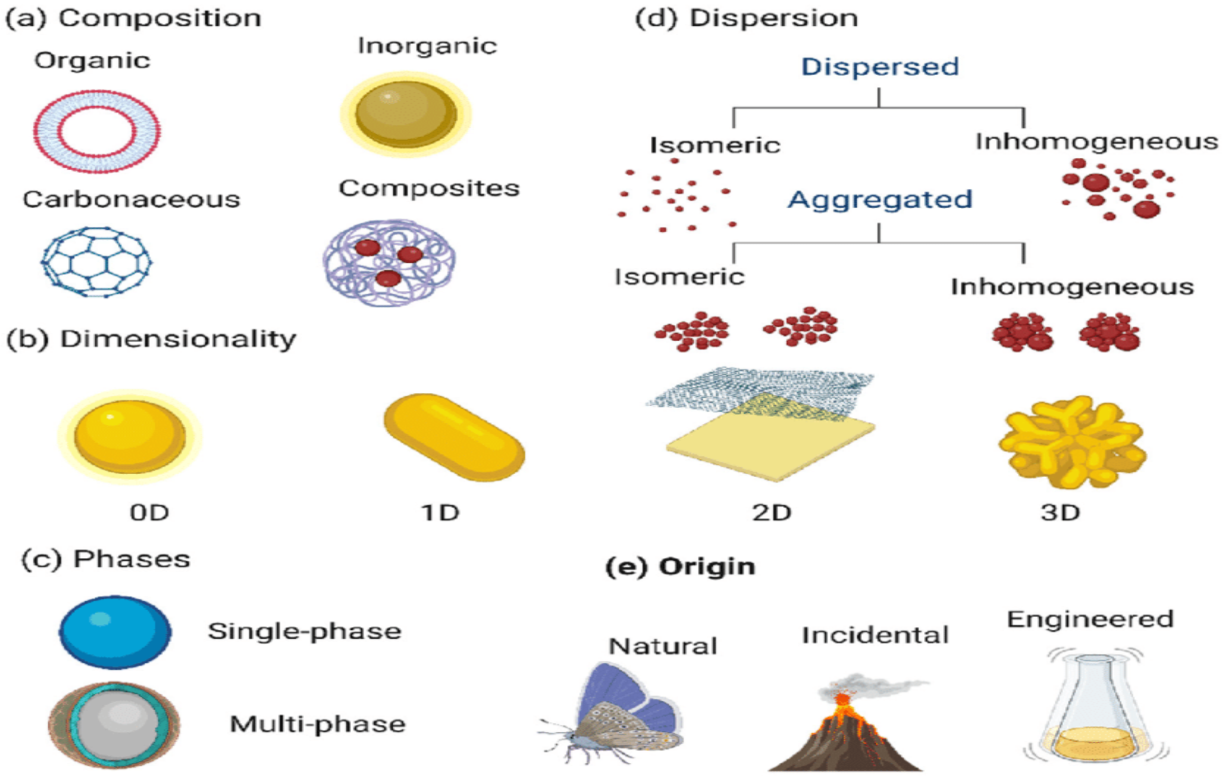

Figure 9. Representation of how nanomaterials can be classified in function of their composition, dimensionality, phases, dispersion, and origin [63].

The optical characteristics, such as the optical band gap and refractive index, play a crucial role in determining the suitability of a material for optoelectronic applications. These properties can be enhanced by adjusting the size of nanoparticles [64]. To address this limitation and effectively restore optical activity, various researchers have undertaken a range of initiatives. A simple way to improve SnO_2 optical and electronic properties is to create it in tiny structures or nanostructures. When these tiny structures are made, they change the regular pattern of atoms that exists in larger pieces of the material [65]. This change means that the behavior of the material's energy levels (band edge quantum states) becomes very different from what we see in the larger form of SnO_2.

Using this approach, SnO_2 has been created in various forms, including: zero-dimensional (0D) nanoparticles, one-dimensional (1D) nanorods, two-dimensional (2D) nanosheets, and self-assembled three-dimensional (3D) hierarchical nanostructures [66]. Co-doped ZnO nanoparticles were synthesized using the hydrothermal method to explore the impact of cobalt and boron on the structural, microstructural, and optoelectronic properties of ZnO nanoparticles [67]. The hexagonal Wurtzite structure of the ZnCoBO nanoparticles was confirmed through c/a ratio measurements. Fourier transform infrared (FTIR) studies were conducted and analyzed. Additionally, the energy band gaps of the samples were calculated. The findings revealed a nonlinear relationship between the refractive index and cobalt concentration. Furthermore, cobalt doping was found to enhance the Urbach energy value in B-doped ZnO nanoparticles [68].

The properties of materials can also be altered by modifying composition of nanoparticles. In recent years, semiconductor nanoparticles have garnered significant attention because of their remarkable properties, including distinct optical features, a greater surface-to-volume ratio, and unique electronic characteristics compared to bulk materials [69]. Zinc oxide (ZnO) is an essential inorganic material known for its hexagonal structure and a direct bandgap of about 3.36 eV, with a larger bandgap of 60 meV at room temperature. Its remarkable properties make ZnO suitable for a wide range of electronic devices, such as sensors, diodes, LEDs, nano lasers, photodetectors, and as an electrode material in supercapacitors and solar cells [70]. The material's advantages, including pyroelectric and piezoelectric characteristics, high electrochemical activity, low cost, ease of synthesis, and nontoxicity, further enhance its appeal for advanced applications [71]. Nanostructured ZnO nanoparticles that are doped with transition metals hold great potential as diluted magnetic semiconductors for spintronic applications. The combination of silver (Ag) with ZnO alters its properties, leading to the emergence of distinctive optical features in Ag-ZnO. The doping of ZnO with silver (Ag) also improves its photocatalytic activity [65].

5. Recent advancements in the synthesis of nanocomponent and heterostructure nanocrystals

Recently, synthesis of nanocomponents and heterostructure nanocrystals have led to complex nanomaterials with improved properties. Through colloidal synthetic methods, colloidal synthetic techniques now enable the fabrication of multicomponent nanocrystals with intricate heterostructures by combining distinct materials with architectures ranging from core/shell to heteromeric arrangements. Lead halide perovskite-based heteronanocrystals (PHNCs) showed stability and tunability in the optical and electrical properties [72].

In addition, band alignment engineering in heterostructure nanocrystals has been exploited for making properties suited to different applications, such as lighting devices and lasers, photocatalysis, etc. [73]. The synthesis of nanorod heterostructures, one of the simplest anisotropic nanocrystals heterostructures, is influenced by the control of important thermodynamic factors and their kinetics, such as crystal structure, surface energies, and reaction conditions, among others [74].Recent discoveries in nanocomponents and heterostructure nanocrystals resulted in multiscale nanomaterials synthesis with properties significantly improved.

The colloidal synthetic routes used today provide for the ability to prepare complex multicomponent nanocrystals with complicated heterostructures such as core/shell or heteromer configurations [75]. Lead halide perovskite-based heteronanocrystals (PHNCs) showed higher stability, alongside tunable optical and electrical properties, which made it useful for several applications [72]. The most important controlling factors of design and synthesis of nanorod heterostructures, which are the simplest anisotropic nanocrystal heterostructures, are crystal structure, surface energies, and conditions for the reaction. Such breakthroughs can be expected to open up ways toward more complex and functional nanomaterials [76].

6. Optoelectronic Properties of nanocrystals

In recent decades, nanocrystals, particularly semiconductor nanocrystals, have been thoroughly investigated and have been found to exhibit many outstanding optoelectronic properties. Nanocrystals are usually between 1 and 100 nanometers, showing unique physical and chemical properties that are totally different from their bulk state [77, 78]. The quantum confinement effect is primarily considered the cause for these differences since it occurs when materials are reduced to sizes smaller than the exciton Bohr radius. These constrained dimensions change optical, electrical, and chemical properties, putting nanocrystals at a strategic frontline in modern optoelectronics that range from LEDs and photodetectors to solar cells and many more advanced technologies [79, 80].

6.1. Quantum Confinement Effect in Nanocrystals

It was remarked in 1980 that the absorbance spectra of PbS nanocrystals exhibit a "blue shift" with respect to bulk films of the same material but the shift was correctly interpreted as an effect due to size quantization of electronic states within the nanometer-sized particles, exactly like the quantum confinement of electrons in a semiconducting quantum well or quantum wire [81]. This model for the electronic density of states (DOS) has gained great popularity and is still used—as well as being vastly over-interpreted—in the interpretation of the unique optoelectronic properties of the wider family of nanocrystal materials [82, 83]. The quantum confinement model has very little, and certainly not zero, value primarily for two reasons: The DOS of quantum confinement is only an approximation that is valid just for cubic crystals with infinite mass and perfect interfaces. Quantum confinement models (Figure 10) are basically compatible with experiment only for relatively narrow-gap semiconductors that actually constitute all materials. Thus, other chalcogenide nanocrystals cannot easily explain the quantum confinement effects with individual optical properties [84-86].

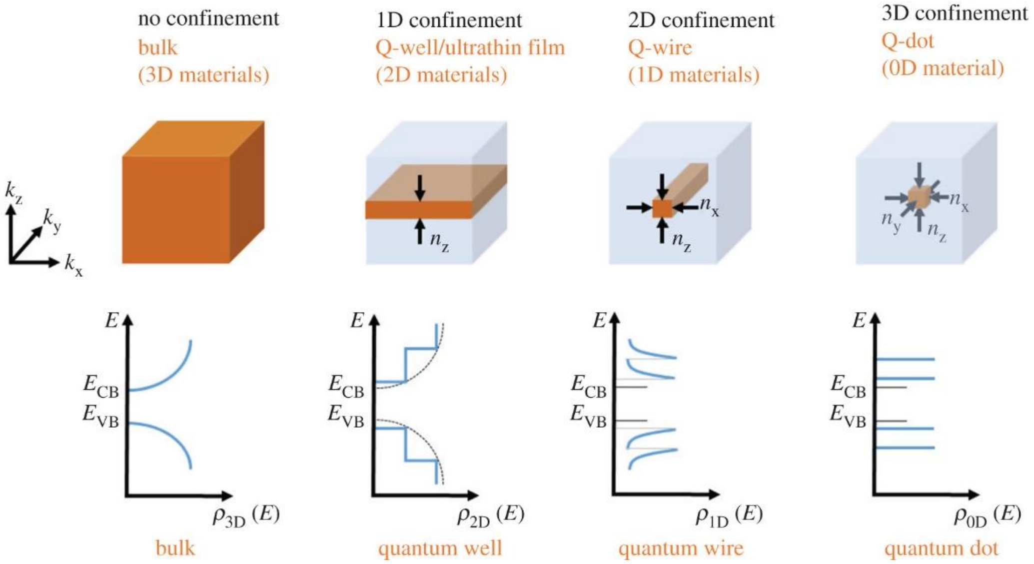

Figure 10: Schematic representation of symmetry breaking and the functional form of the density of states in materials confined to 1D, 2D, and 3D structures [87]

The quantum confinement effect is one of the fundamental principles governing the behavior of nanocrystals. It arises when the size of a nanocrystal approaches the de Broglie wavelength for both electrons and holes, typically within the nanometer scale [88, 89]. At these dimensions, energy levels in the material become quantized, leading to discrete electronic states. This contrasts with bulk semiconductors, where the energy levels remain continuous due to the larger particle size [90]. The quantum confinement effect significantly alters the bandgap energies and optical absorption spectra of nanocrystals, making them highly sensitive to size variations [91, 92].

The bandgap-the energy difference between the valence and conduction bands-in bulk materials is constant. For the nanocrystals, however, this bandgap increases as the size of the crystal decreases. The effect is particularly very well observed in materials like CdSe, PbS, and ZnO, where small exciton Bohr radii make the effect more pronounced [93-95]. The Brus equation gives a quantitative relationship between the size of the nanocrystal and bandgap where bigger gaps correspond to smaller particles. One of the big features of such properties is toward application in tuneable optical properties [96].

Nanocrystals show vast potential applications in the quantum dots of photovoltaic cells, LEDs, and biologics imaging applications due to their tuneable band-gap dependent on size [97]. The tuneable band-gap in the nanocrystals through tuning the particle size has opened an opportunity for the design of materials with tailored optical properties and electronic important for the advancement of nanotechnology-based applications in Multi scientific and industrial fields [57, 98].

6.1.1. Influence on Optical Properties

Quantum confinement effect plays the very important role in defining the optical absorption and emission characteristics of nanocrystals what in turn defines the wide-ranging applications of this technology [99]. The widening of the bandgap provides characteristic onset of absorption blue-shift with decreasing size of nanocrystals: meaning that this material starts to absorb light at higher energy levels [100, 101]. This size-dependent behaviour is particularly useful for optoelectronic devices, such as LEDs and quantum dot solar cells, in which it is important for performance and functionality to control the emission wavelengths precisely [102, 103].

In addition, nanocrystals have very intense size-dependent photoluminescence properties. General rule of thumb is that smaller nanocrystals emit light at larger wavelengths as they correspond to higher energy emissions while the larger crystals emit at lower energy and at longer wavelengths [104] . This tunability in emission wavelengths has been extensively harnessed in quantum dot-based displays and other optoelectronic devices that demand colour-tuneable emissions [105, 106]. Such nanocrystal advances resulted in the creation of next-generation technologies that exploit unique optical characteristics in these nanoscale materials to further enhance performance and versatility in applications from display technologies to solar energy conversion [107, 108].

6.2. Tunable Bandgap and High Absorption Coefficients in Nanocrystals

One of the most promising properties of nanocrystals is their tunable bandgap, which can be made virtually independent of the spectral range by precise adjustments of size, composition, and surface chemistry. With this tunability, electronic and optical properties of nanocrystals can be tailored to the needs of different applications, especially in photovoltaic ones [109]. For instance, the bandgap of photovoltaic materials can be optimized based on the size and composition of the nanocrystals used in the systems. Optimizing the bandgap is essential for improving the energy conversion efficiency of solar-energy-conversion systems, as a well-engineered bandgap allows for more percentage points of solar light to be absorbed, thus effectively raising the overall energy conversion efficiencies [110, 111].

Another property that nanocrystals exploit is that they absorb a thousand times more photons than their bulk counterpart. That is due to the higher possibilities of electronic transitions between distinct states originating from the quantum confinement effect [112, 113]. Further reduction in screening in these nanostructures with increase optical responses (Figure 11). With bigger values of absorption coefficients, larger photovoltaic applications would be useful, which shall allow a thinner absorber without reducing light absorption efficiency. Such thinning decreases the cost and uses less material, which are critical factors in the sustainable development of solar technologies [114, 115].

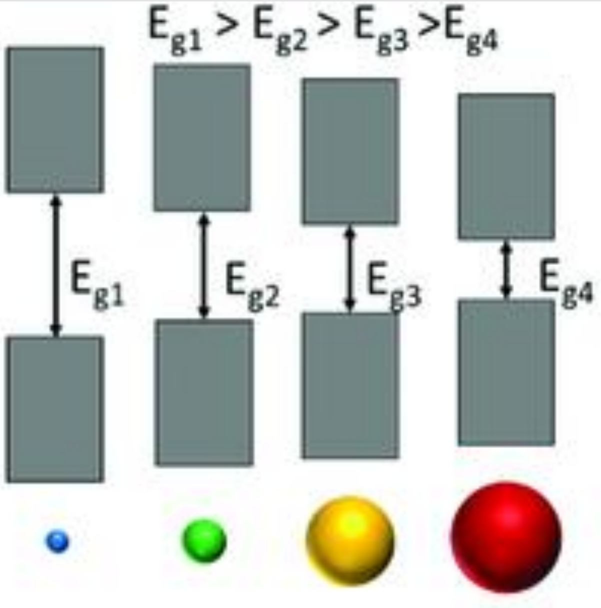

Figure 11: Scheme showcasing the band gap tunability in nanocrystals as a function of their size [116]

Significant progress in thin-film solar cells with nanocrystals, such as perovskites and colloidal quantum dots, has enabled the assumption of incredible power-conversion efficiencies under exploitation of these unique properties [117]. For example, the efficiencies of perovskite solar cells can be as high as 25% or more because of an optimized bandgap and high absorption of the perovskites [118, 119]. Similarly, colloidal quantum dots have also been investigated as tandem solar cells; here, their ability to absorb different parts of the solar spectrum improves the overall efficiency of the solar cell itself [120]. The advancement marked a new dimension in terms of solar technology and augured a bright future where nanocrystals might, in the future, change the face of renewable energy sources.

6.2.1. Enhanced Charge Transport and Carrier Dynamics

For an opto-electronic device such as solar cell, light emitting diode, or transistor, high efficiency in charge transport is very crucial to its performance. Nanocrystals with their special physical and chemical properties hold promise in enhancing charge transport mechanisms in these applications. Nanocrystals with their small dimensions and large surface area reveal excellent charge carrier dynamics, which has been recognized as significantly contributing towards their effectiveness in opto-electronic systems [115, 121].

Spatial confinement in nanocrystals is of great importance, which diminishes the recombination probability of carriers. Spatial confinement leads to localization of electrons and holes and thus reduces the chances of their recombination, hence increasing carrier lifetimes and mobility [122]. It is critical for the devices that charges must effectively travel over distances.

The surface chemistry of nanocrystals primarily plays a leading role in determining the charge transport property of the latter [5]. Depending on the ligands attached to the surface of nanocrystals well-designed, charge transport could be either augmented or depressed. For instance, short organic ligands help to enhance the packing density of nanocrystals, which eventually assists further charge transfer between the particles of them. Thus, superior charge transfer efficiency is attained with high performance nanocrystal-based transistors and solar cells acquired partially and significantly because of the characteristic efficiency attained in nanocrystal devices [123].

6.3. Comparison with Traditional Materials in Optoelectronic Applications

When comparing nanocrystals with traditional materials, it is clear that nanocrystals offer several advantages, particularly in optoelectronic applications such as LEDs, solar cells, and photodetectors.

6.3.1. Light-Emitting Diodes (LEDs)

LEDs based on the usual materials, such as gallium nitride (GaN) and indium gallium phosphide (InGaP), suffer from a fixed emission wavelength, meaning it cannot be tuned by these LEDs to really use this technology fully on display technologies [124]. On the other hand, nanocrystals can quite easily have their light emission tuned across the whole visible spectrum through only one change in their size level [125]. This promises production of QLEDs with superior color purity, high brightness and low power consumption in comparison with traditional LEDs [126].

6.3.2. Photodetectors

Nanocrystals can provide better sensitivity and faster response time than classical material for photodetector applications due to large absorption coefficients, as well as good charge transport properties [127]. PbS-based infrared photodetectors are preferable for photodetection schemes compared with silicon-based photodetectors thanks to the application of nanocrystals in these devices [128]. Moreover, the values of the bandgap of the nanocrystals are tunable, which allows designing photodetectors within a quite broad range of wavelengths: from ultraviolet to infrared values [129].

6.3.3. Solar Cells

Nanocrystals have great potential for the next-generation solar cells [130]. For decades, most markets have seen silicon-based solar cells as the king, but it has high manufacturing costs and limits the efficiency since it has a fixed bandgap [131]. Its advantage in this category is that the nanocrystal solar cells, perovskite solar cells, and the colloidal quantum dot solar cells have several advantages of lower production cost, flexibility, and tunable bandgap that allow for absorbing the solar range over a much wider spectrum[132]. Such features tend to boost the fast development of the nanocrystal solar cells toward a high power-conversion efficiency over 20% [133].

7. Nanocrystal based devices for energy harvesting

7.1. Photovoltaic devices

The majority of 80–90% of the present solar cell technology is still based on silicon material and silicon is the backbone of the photovoltaic module [134]. It is due to its numerous uses in the first-generation bulk, second-generation thin-film and third-generation nanostructured solar cells. While being used in the field, silicon technology has been proven to be robust and reliable. Nevertheless, for non-concentrated silicon solar cells, the highest reported efficiency is around 25%. This efficiency limitation drives research into novel materials and designs to further drive solar energy conversion [135]. Also the concerns have been raised over the high cost of silicon wafers derived from raw ingredients [136]. To lower costs and increase efficiency in solar cells, new materials with plentiful availability, reduced toxicity, stability, and easy deposition procedures should be used [137].

Nanocrystals (NCs) have proved to show promising potential in enhancing the efficiency of thin-film solar cells. They can be used in solar cells in varied ways, such as luminescent species for converting photons in passive layers that alter the solar spectrum [138]. Aqueous NCs have shown environmental friendliness and economic efficiency while CdTe NCs reached unprecedented power conversion efficiency of 5.73% for the aqueous material-based thin-film solar cells [139]. Halide perovskite (HP) NCs have also gained attention due to its peculiar characteristics that align well with perovskite solar cells (PSCs). This area of embedding research on HP NCs into PSCs is still in its infancy and hence requires more attention and focused efforts from scientists to fill in the gap of HP NC and PSC research [140]. The composition of heterostructure NC can be tuned so as to control carrier dynamics, allowing for a long carrier lifetime and effective carrier transport [139]. More future research would be required to close in the synthesis gap of NCs to their application in thin-film solar cells.

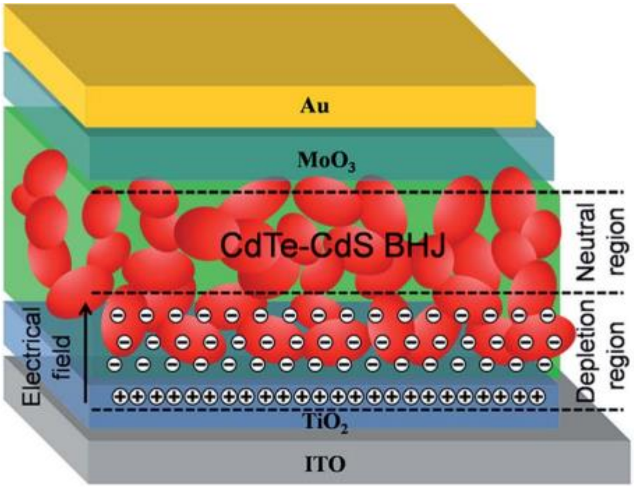

Figure 12: The planned action mechanism of the invented CdTe NCs solar cells [139]

Nanocrystals considerably improve the efficiency of thin-film solar cells (TFSCs) using a variety of novel ways. For example, the two-step sintering technique of colloidal nanocrystals, especially cesium lead bromide ($CsPbBr_3$), has been demonstrated to generate high-quality polycrystalline films with bigger grain sizes and lower trap densities, resulting in increased solar performance and efficiency [141]. Furthermore, integrating plasmonic nanoparticles, such as silver, into silicon TFSCs has resulted in significant efficiency increases, with combinations yielding as high as 18.3% due to improved light absorption. Furthermore, utilizing nano grating patterns in cadmium telluride (CdTe) TFSCs resulted in a 21.66% improvement in efficiency through optimized light trapping [142]. Overall, these developments emphasize the potential of nanocrystals and nanostructures in greatly improving the performance of thin-film solar cells [143].

Thin-film solar cells have emerged as a promising alternative to traditional silicon-based solar cells due to their potential for lower manufacturing costs and the ability to be fabricated on flexible substrates. The incorporation of nanocrystals into thin-film solar cells has been explored as a way to enhance their efficiency and performance.

Nanocrystals can be used in various components of thin-film solar cells, such as:

- Light-absorbing layers
- Charge transport layers
- Passivation layers

The use of nanocrystals can provide several benefits, including: enhanced light absorption and trapping, improved charge carrier separation and transport and increased open-circuit voltage and fill factor. Nanocrystal-based thin-film solar cells have demonstrated promising efficiency improvements compared to their bulk counterparts: Perovskite solar cells with nanocrystal light-absorbing layers have achieved power conversion efficiencies (PCEs) up to 25.2% [144]. Quantum dot solar cells with nanocrystal active layers have reached PCEs of 16.6% [145]. Copper indium gallium selenide (CIGS) solar cells with nanocrystal buffer layers have shown PCEs up to 22.9% [146]. Recent research has focused on several solar cell materials, such as thin films of CdTe, CZTS, SnSbS, and CIGS, dye-sensitized TiO_2 and ZnO, composite materials like CuO/ZnO and CIS/TiO_2, homojunction materials like Cu_2O, and perovskite-based solar cells [147].

7.1.1. Nanocrystal Selection

Nanocrystals provide a versatile material platform for fabricating PVs from various semiconductors using standard manufacturing and processing techniques. Nanocrystal inks are simply created with the necessary chemical composition and then included into a regular PV production flow.

7.1.2. CdTe thin films

Research on CdTe thin film solar cells began in the 1950s, and current efforts aim to improve its efficiency. With an ideal band gap of 1.49 eV for single-junction devices, commercial CdTe solar cells may achieve efficiencies of above 20% [148]. In August 2014, First Solar announced a device with 21.0% conversion efficiency[149]. The efficiency of CdTe/CdS thin film solar cells was found to be 22%[147]. However, the presence of flaws in grain boundaries and intra-grain dislocations may be a concern for CdTe-based solar cells in terms of efficiency stability. It is assumed that the carriers recombine, lowering the average life span of minority carriers [150]. CdTe solar cells' photovoltaic performance is influenced by several aspects, including open circuit voltage (Voc), fill factor (FF), substrate selection, close circuit current, and deposition area. The configuration of the solar cell determines its performance; for example, the superstrate solar cell has been used to increase the solar cell's absorption capabilities [151]. Optimization of values of Voc and FF for optimum deposition fabrication technologies of the CdTe solar cells are around 1000 mV and 85% respectively. Such optimized values of Area, Voc, current density (Jsc)), Fill factor (%) and efficiency (%) could reach 1.0623cm2, 0.8759V 30.25 mA/cm^2 79.4% and 21.0 CdTe solar cell at laboratory scale [111]. The build in voltage and the net acceptor density of the absorber region in the materials of CdTe thin film can be improved to enhance Voc. An increased doping level with dopant material Cu, is known to improve the higher value of Voc, however, the value of FF decreased with increase in Voc and therefore the overall performance of the solar cell is impacted [147]. Increased acceptor density will decrease the width of the space charge region. The effects of compensating acceptors were also observed due to the probability of Cu involvement into the window layer [152]. These effects cause the reduction in space charge width that increases the chance of light absorbance in the undepleted region [153].

The great concern for cadmium telluride (CdTe) thin film solar cells is the management in photovoltaic technology due to excellent efficiency and low costs. However, there are many environmental problems associated with their manufacturing and the time usage to be spent in their use. Main environmental issues arising from the production and for extended times of usage of CdTe thin film solar cells based on recent research findings. However, $CdCl_2$ is somewhat expensive as well as toxic because cadmium ions leak. $MgCl_2$ and $SrCl_2$ could be presented as alternatives as these are non-toxic as well as economical with comparable efficiencies [154, 155]. CdTe solar cells are susceptible to deterioration in relation to environmental factors such as corrosion, delamination, and micro-cracks. Such degradations will lead to extreme power loss and highlight the requirement of increasing the robustness of the CdTe module with regards to environmental strength [156].

7.1.3. CdTe based quantum dots solar cells

Nanotechnology and quantum dots (nano-sized semiconductor particles) have been incorporated into solar cells to take their efficiency to unprecedented levels beyond what is theoretically possible as dictated by Shock–Queisser thermodynamics. Quantum dots possess size-dependent properties with extraordinary tunable band gaps, high extinction coefficient, and importantly multiple exciton generation. Quantum dots were reported to alter the value of the band gap of CdTe to a desirable value by changing the size of the quantum dot.

It has been promisingly known in photovoltaic applications that quantum dot sensitized solar cells (QDSSCs) can enhance the photoelectric conversion efficiency considerably. The CdTe/CdS and CdTe/CdSexS1-x, for example, are core/shell structures of type-II that have enhanced light harvesting, while suppressive charge recombination to provide power conversion efficiencies over 7% [157]. It has been found that with the introduction of a buffer layer of ZnS, the efficiency of QDSSC greatly increases, and this happens by enhancing the dispersion of electrons from the back-scattering surface [158]. Various deposition techniques are used, which include direct adsorption [159] and blade coating [160]. This has brought about an aqueous CdTe quantum dot solar device with efficiencies up to 8.06% in combining magnesium zinc oxide (ZMO) as a window layer with interlayer CdS and using CdCl2 for high-temperature annealing [160]. Such improvements suggest room for having CdTe-based QDSSCs as alternatives in the adoption of solar cell technology.

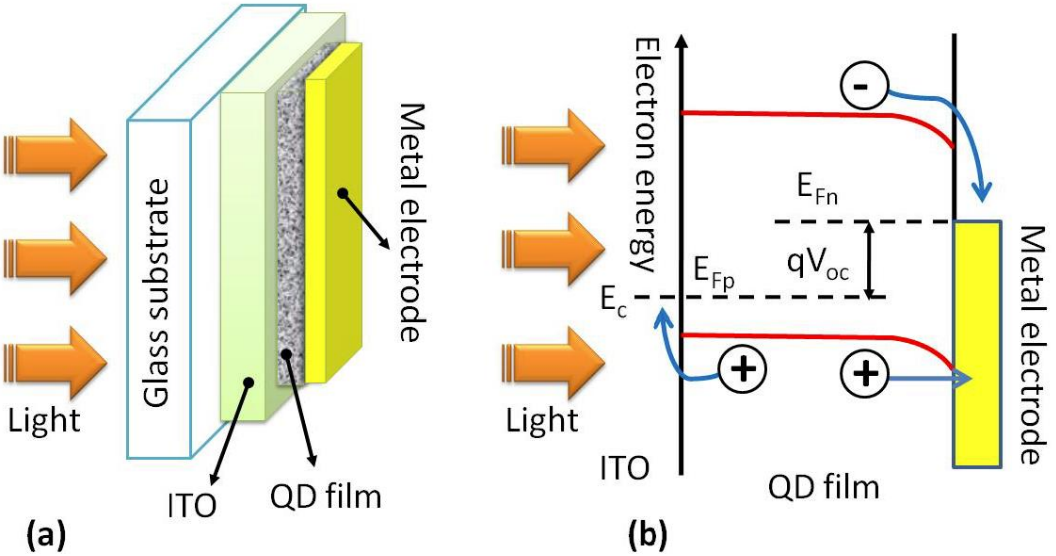

Figure 13: CdTe based quantum dots solar cells [161]

The performance of CdTe QDs can be significantly enhanced through doping, such as with indium (In) or silver (Ag), which influences their size, shape, and electronic properties, leading to improved power conversion efficiencies (PCE) of up to 28.6% with In doping and from 0.85% to 1.66% with Ag doping [162, 163]. Furthermore, CdTe QDs exhibit excellent visible light absorption and charge separation capabilities, making them suitable for solar-to-fuel conversion applications [164]. Overall, CdTe QDs represent a versatile and efficient option for next-generation solar energy technologies.

7.1.4. CZTS thin films

In favor of its appealing properties, copper-zinc-tin-sulfur (CZTS) thin films are a very promising material for photovoltaic applications. Results from studies have reflected that Cu_2ZnSnS_4 (CZTS) thin films have potentially attractive optical and electrical properties for solar cell applications. The primary advantage of CZTS is its earth-abundant elemental composition that does not contain any toxic material. It is, therefore, considered as a better alternative to traditional semiconductor materials such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), containing rare and toxic elements. CZTS is known to have a tunable band gap of 1.4-1.5 eV and has a high absorption coefficient of above 10^4 cm^{-1} in the visible region [165].

Several deposition methods were considered, among which are the spray pyrolysis [166], SILAR method [167], cosputtering followed by sulfurization [168], and spin coating [169] and sputtering followed by heat treatment processes which improve their crystallinity and morphology, respectively, the films can be obtained [170, 171]. Significant effects on the quality of films arise from the sulfurization temperature and annealing conditions. Optimal temperatures of around 580 °C yield dense, flat films with higher grain sizes and better power conversion efficiencies reaching up to 3.59% [172]. More importantly, Cu-Zn disorder present in the films can enhance electrical conductivity and thermoelectric performance, making it suitable for tunable electronic application purposes [173]. X-ray diffraction and Raman spectroscopy always confirm the kesterite CZTS structure in these studies and are important for studying the structural and optical properties of CZTS films [174].

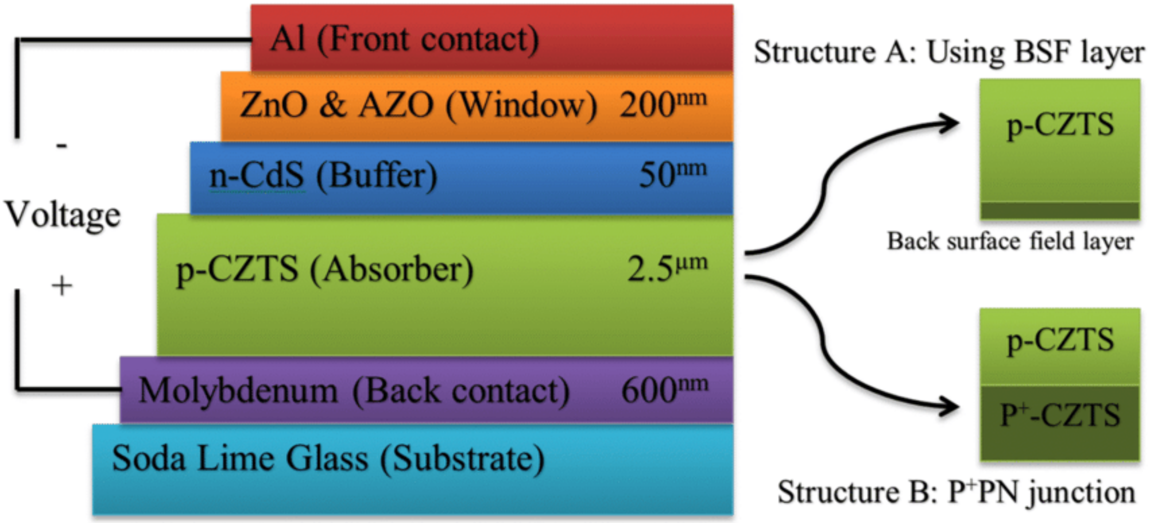

Figure 14: Basic structure of CZTS-based thin film solar cell and two proposed structures; structure (A) with inserting p^+-CZTS intermediate layer and structure (B) dual layer with p^+pn junction [175]

The optical band gap for CZTS films varies between 1.5 to 1.98 eV, and they are found to be feasible for PV application [176]. Electrical characterization reveals p-type conductivity with a resistivity of about 10^{-2} Ω-cm [176]. While these deposition methods seem promising, a lot remains to be done in optimizing the properties of the films and removing secondary phases for enhanced photovoltaic performance. Thin films of CZTS can thus be regarded as a robust, flexible, and efficient choice for solutions in sustainable energy.

7.1.5. Copper Indium Gallium Selenide (CIGS)

Copper Indium Gallium Selenide (CIGS) technology is promising thin-film photovoltaic technology characterized by the high absorption coefficient, so that it can use much thinner films than the traditional silicon solar cells. This technology deposition involves copper, indium, gallium, and selenium on a glass or flexible substrate at a thin layer [177]. CIGS has demonstrated the greatest promise because of its high efficiency and the prospect of low-cost manufacturing; it attains the record efficiency of 22.8% and closely approaches that of crystalline silicon cells but uses much fewer materials because of their high absorption coefficient [178]. CIGS solar cells are fabricated through the deposition of semiconductor layers on substrates-glass or plastic-with efficiencies very close to 23.61% for best cases [179]. The electrodeposition method is preferred because of its simplicity and lesser expense, while performance is determined by the choice of counter electrode [180]. Additionally, improvements in manufacturing processes, such as ultrasonic bonding and lamination, have been reported to enhance electrical performance greatly, which has enhanced efficiency from 11.45% to 13.86% [181]. Therefore, although the market share of CIGS is low in comparison to crystalline silicon, the positive prospects of cost reduction along with its greater environmental compatibility do position it as a disruptive technology within the solar energy marketplace [182]. The recyclability of CIGS panels also ensures economic viability and sustainability, important aspects of end-of-life management [183].

To date, further research continues to be directed towards improvement of material characteristics, cell configuration, and fabrication techniques to assure improved performance and lower costs [184]. As the advancement of CIGS technology moves forward, it can lead to becoming one big disruptor in the photovoltaic market by offering a greener option than cadmium telluride solar cells [185].

7.1.6. Perovskite solar cell

Known as high-power conversion efficiencies, better than 20%, with low-cost manufacturing, the third-generation solar cells, in particular, perovskite solar cells (PSCs), are characterized by a light-absorbing material, organometallic halides, such as methylammonium lead iodide, herein abbreviated as $MAPbI_3$, sandwiched between ETL (electron transport layer) and HTL (hole transport layer), with charge collection boosted and recombination losses reduced to the minimum level [186, 187]. In addition, different architectures, including inverted configurations and planar heterojunction, have been addressed to optimize the performance. Others include hybrid electrode structures, where there are great versatilities of device configuration that improve the efficiency of charge collection [188]. The current-voltage characteristic stability and hysteresis still show rapid gains in efficiency but remain under intense research topics [189]. Overall, PSCs would provide a promising gateway towards sustainable energy solutions. They are efficient and economically viable [190].

7.2. Photodetectors

Photodetectors exhibit tremendous relevance in optoelectronic devices with the capacity to transform light impulses into electrical signal. They have a wide range of uses, including sensing, environmental monitoring, biological imaging and optical communication [191]. Dimensions of nanocrystals smaller than the excitonic Bohr radius allow for size-tunable optoelectronic properties, allowing properties to be tailored on-demand for particular applications. In particular, the development of wet chemistry synthesis of colloidal nanocrystals makes them promising building blocks for the next generation of low-cost, solution-processable optoelectronics, such as those that emit light, sense, and harvest [192].

7.2.1. Conventional photodetectors

Conventional photodetectors including mainly photomultiplier tubes, photodiodes and avalanche photodiodes are expensive and complex in that they are made using several vacuum based deposition techniques and are short in length to width ratios [193].

7.2.2. Nanocrystal based photodetectors

Nanocrystal thin films are attractive for various applications due to their excellent photoresponsivity, lower power consumption, and extended operational wavelengths. They also feature a quick response time, good photo detectivity, elasticity, and low cost for solution processing [194]. These qualities make them suitable for high-resolution, lightweight shortwave infrared image sensor arrays, broadband UV photodetectors, and high-performance single pixel imaging sensors, among other uses in security and defense industries [195].

7.2.3. High sensitivity and responsivity of nanocrystal-based photodetectors

As compared to thin-film semiconductor materials, the non-epitaxial nanocrystals (NCSs) possess some exciting features such as light absorption, high photoluminescence (PL) quantum yield, unique energy levels based on their size and shape, and ability to hybridize with different types of sensitizing metal nanostructures [196]. Researchers have even recently reported extremely high sensitivities of NCs based photodetectors. The photocurrent/pump power figures of merit known as Responsivity is simply the ratio of the photocurrent to the power of the incident light which has been found to be almost constant with respect to the number of Incident photons and its reverse time. High photo pressure has been explained by the excessive photo-induction of carriers in the NCs, the extremely rapid separation of charge carriers from the surface of the NCs, and the then hot carriers collapse into the electrodes to instantaneously excite a photonic response. However, the hot carriers, which are formed by the light energy absorbed by the NCs, are free to move within the crystal unless there is either a large volume or a large density of states in the NCs to allow intra-NC energy transfer [197].

7.2.4. Common nanocrystal used in photodetection

The silicon (Si) NCs are without a doubt the most well-controlled among the most developed NCs investigated at the nanoscale. To reduce the dispersion of their physical characteristics, Si NCs need to be very dense and have strong size homogeneity. In fact, due to high density of silicon NCs with no structural flaws and a regulated size, they increase the sensitivity of optoelectronic devices [198]. For the detection of infrared region highly sensitive photodetector is required. IR photodetectors have historically used indium gallium arsenide (InGaAs) and mercury cadmium tellurium (HgCdTe). Although they have very high sensitivity but they contain some heavy metals which are very dangerous for human health. The creation of high sensitivity photodetectors has focused a lot of interest on nanoparticle (NP)-based photodetectors, which are made using inexpensive chemical synthesis techniques. In addition to outperforming traditional photodetectors, they also exhibit excellent compatibility with silicon and flexible substrates [200]. Numerous materials, such as graphene, organic semiconductors, and quantum dots (QDs), have been researched for use in high gain photodetectors [201].

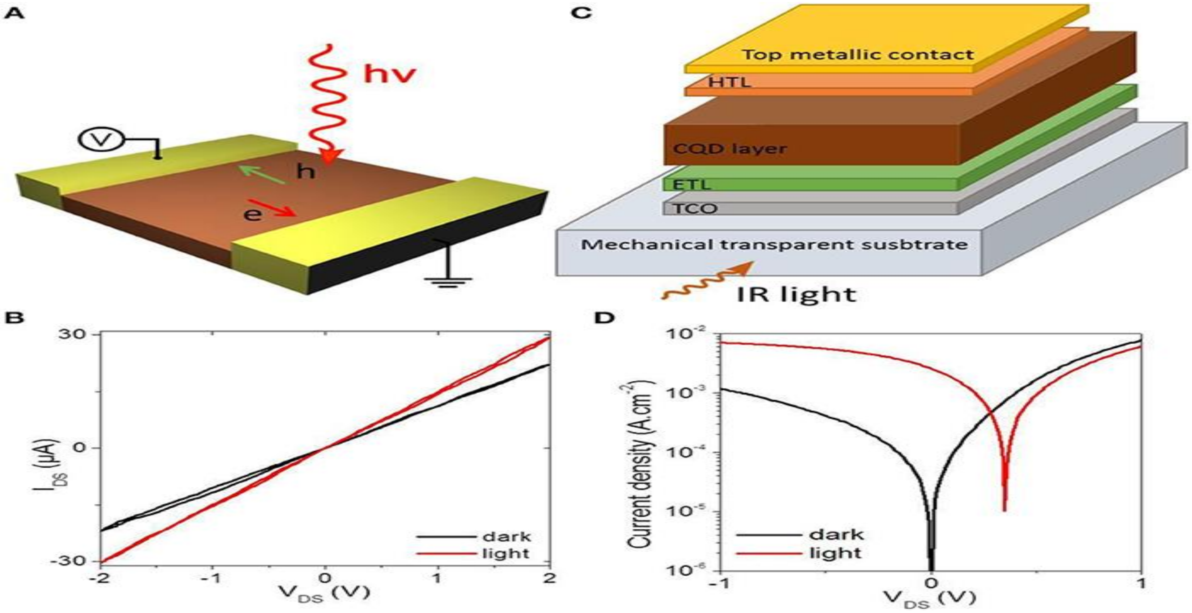

Figure 9. (A) Scheme of a photoconductive device in planar geometry. (B) I-V curve of a photoconductive device under dark condition and under illumination. (C) Scheme of a photodiode in vertical geometry. TCO, ETL and HTL stands respectively, for transparent conductive oxide, electron transport layer and hole transport layer. (D) I-V curve of a photodiode under dark condition and under illumination [199].

7.3. Photocatalytic devices

As the world's population goes up, so do the drops in natural sources. However, there is a huge desire in this world for innovative techniques to convert solar energy into fuels. Photochemistry has been used in the research activities of several scientists since the invention of the first solar-driven water-splitting system

They are also known as solar-driven energy conversion devices. The core components of this device include a light-absorbing semiconductor, cocatalyst, and electrolyte. One of the most promising configurations is the two-cell photoelectrochemical PEC solar-driven water-splitting system, referred to as tandem solar cells [202].

In principle, these systems require photocatalysts with 1.23 eV band gap energy. This means that the Fermi level of the photocatalyst should match the energy required for the most minimum amount needed to elevate electrons from the valence band to the conduction band. However, the theoretical band gap energy is not sufficient for practical photocatalysis, especially in a Nano powder form, since it may be eased by several effects that reduce the binding strength of the photogenerated charge carriers. This prevents exciton formation and eventually decreases the true efficiency of the solar device [203].

This means that the semiconductor has to be nanopowder, a form in which it enhances photoanode detection through solar-driven water oxidation. The light absorption increase can be achieved through a uniform distribution of very small nanoparticles on the TiO_2 surface. This is shown as the increased RGB intensity means that for the photocatalysts that constitute TiO_2, the band gap is becoming narrower. Nanocrystalline photocatalysts made from TiO_2 can effectively produce non-Faradaic water oxidation currents under visible light [204].

7.3.1. Applications of nanocrystals in solar driven fuel cells and water splitting

Nanocrystals have emerged as key materials in advancing solar-driven fuel cells and water splitting technologies due to their unique properties and capabilities.

7.3.1.1. Enhanced Photocatalytic Efficiency

Recent studies have shown nanocrystal-based photocatalysts can efficiently improve the rate at which water can be split in the presence of solar light. The nanocrystals can absorb a much broader part of sunlight that enhances the rate of splitting water through photocatalytic reactions into hydrogen and oxygen. The increase in surface area allows nanocrystals to have an enhanced interaction with the reactants, with further improvement in kinetics [205].

7.3.1.2. Optimized Catalytic Activity

The primary function of the nanocrystal catalysts is to convert sunlight into fuel efficiently. Optimizing electronic properties by varying the size and shape of the nanocrystal according to the requirement would directly influence the catalytic activity. Optimization would be necessary in the process of producing hydrogen from the water; a fuel cell requires this [29].

8. Innovative Structures for Performance Improvement

Improved performance of photocatalysts by water splitting can be realized through new nanocrystal structures. For photocatalytic processes, nanocrystal structures are designed so as to maximize light absorption with minimum electron-hole recombination. The improvement in photocatalytic efficiency observed in their experiment affirms the applicability in practice [206].

9. Nanocrystal-based Devices for Energy Storage

Advanced technologies using solar energy have been booming for the development of a carbon-neutral and renewable society. Nowadays, photovoltaic cells show the highest potential for widespread sustainable electricity production, and photo(electro)catalytic cells could supply various chemicals. However, both of them suffer from complicated structures and external energy loss with needing the connection of energy storage devices or matter to compensate for intermittent sunlight. Newly developed photoelectrochemical energy storage devices can now successfully convert and store solar energy into a single two-electrode battery, which simplifies the configuration and decreases external energy loss [207].

Supercapacitor and battery, holding promising potential together in nanocrystal-based devices for applications in energy storage, shall incorporate the two supreme technologies of supercapacitor and battery into hybrids that are referred to as supercapatteries with high specific power and high energy density. The advanced energy and power capabilities in nanomaterials in the form of metal oxides, phosphates, sulfides, and carbon-based structures all along pursue the integration of high performance in supercapacitors and batteries [208].

Several nanostructures, including carbon nanotubes, nanofibers, and metal nanoparticles, have been explored and identified for supercapacitor, lithium-ion battery, and even hydrogen storage applications [209]. vanadium-based nanostructured oxides synthesized via templates and hydrothermal synthesis are the most promising electrode materials in supercapacitors where the specific capacitances exceed 100 F. Nanofabrication and nanohybridization techniques have opened the doors towards the development of the next generation energy storage devices with better performance [210].

9.1. Supercapacitors

. Supercapacitors are very advanced energy storage devices, merging the benefits of capacitors and rechargeable batteries [211]. These have great power density, fast recharge rates, long cycle life, and wide temperature operation. Supercapacitors can be classified into three categories: electric double-layer capacitors, pseudo capacitors, and hybrid supercapacitors, each with its respective mechanisms of charge storage. Although supercapacitors display excellent power density, they achieve much lower energy density than that of batteries [212]. Their unique properties allow them to adapt well to numerous applications, including automotive industries, energy harvesting, and stabilization of the grid. Supercapacitors can be integrated with batteries in hybrid energy storage systems (HESS) for electric vehicles, combining benefits from each technology [213].

9.1.1. Nanocrystal based supercapacitors

Recent results make nanocrystal-based supercapacitors promising in the area of high-performance energy storage. High charge storage capacity and energy density characterize metal halide perovskite nanocrystals, with particular affinity for tin [214]. In the case of nano crystallized nickel-cobalt borides, significant specific capacity, good rate capability, as well as in situ conversion to nano crystallized Ni-Co (oxy)-hydroxides during cycling, were observed [215].

Recent interest in cellulose nanocrystals (CNCs) stems from their unique physicochemical properties, biodegradability, and sustainability as building blocks for supercapacitors [216]. Furthermore, when metallic cerium-based metal-organic framework nanocrystals are combined with carbon nanotubes, the result has been superior electrochemical performance arising from the exploitation of redox activity inherent in Cerium Metal-Organic Framework (Ce-MOF) in conjunction with the conductivity of carbon Nanotubes (CNTs) [217]. Such progress in nanocrystal-based supercapacitors points out the way toward more promising systems for energy storage using these systems: improved specific capacitance, energy density, and cycling stability.

9.1.2. Design of cellulose nanocrystals-based supercapacitors

Toward sustainability, flexibility, and excellent performance, recent literature has been more concerned with the development of supercapacitors based on cellulose nanocrystal (CNC). CNCs present large surface area, surface chemistry that can easily be tailored, and mechanical stability over flexible electrodes [218]. Reduced graphene oxide nanocomposite membranes were shown to deliver exceptional volumetric capacitance and energy density in all-solid-state supercapacitors [219]. Further, different synthesis processes including acid hydrolysis and mechanical exfoliation for the production of CNCs and their derivatives have attracted attention for use in supercapacitor applications. Latest developments include building the chiral nematic activated carbon aerogels loaded with metal oxide nanoparticles that portray high porosity, magnetization and good capacitance retention [216, 220].

9.1.3. Performance of nanocrystal-based supercapacitors

Nanocrystal-based supercapacitors are gaining much attention due to impressive performances combined with specific features. Nano crystallized nickel-cobalt borides, NCBs, display extreme capacitive capabilities, which have shown specific capacity of 966 C g^{-1} and energy density of 74.3 Wh kg^{-1} when operated in asymmetric supercapacitors [215]. In recent times, CNCs: Cellulose nanocrystals are now emerging as one of the prominent biocompatible, biodegradable eco-friendly options for supercapacitor applications [219]. Cobalt-based nanomaterials have been increasingly applied to supercapacitors based on cobalt's abundance, good electrical conductivity, and also a good specific capacitance. Investigated strategies to improve electrochemical properties include designing mesoporous structures to accommodate such volume changes and enhance the pseudo capacitance [221]. Of key interest, therefore, is the gradual transformation of core NCBs to nano crystallized Ni-Co (oxy)-hydroxides during cycling that retains a high specific capacity [215]. All these have underscored the potential of nanocrystal-based materials for further development toward high-performance supercapacitors.

9.2. Nanocrystal based batteries

Nanocrystal-based batteries have recently been focused on the materials and structures with potential for energy storage. Composites based on nanocellulose have shown a lot of promise as flexible energy storage devices, given their eco-friendly and multi-functional properties [222]. Additional possible future generations of metal-ion batteries are derived from different vanadium-based nanomaterials: Sodium, Potassium, Magnesium, Calcium, Zinc and Aluminum among others, whose different structures and compositions make them distinct [223].

9.2.1. Innovation in lithium-ion batteries

Researches in nanostructured electrodes of lithium-ion batteries have gained some encouraging results. Metal oxide nanocrystals, such as those depicted by copper nanoparticles and fluorine-doped materials, exhibit outstanding performances in the nanoarchitecture of batteries with higher capacity and efficiency [224]. Emerging as alternatives to graphite, silicon-based nanoelectrodes show improved performances notwithstanding certain challenges. Researchers are looking forward to different nanostructured materials towards the resolution of pulverization problems [225]. Such nanostructured anodes and cathodes have shown improvements in kinetic, stability, and rate capability [226]. Moreover, nanoparticles added to electrolytes and separators enhance the conductivity and strength of mechanical properties, and nanofluids and nanocomposite phase change materials assist the regulation of heat. All these promising aspects indicate that very detailed work needs to be carried out on cost, performance, and stability trade-offs for the commercialization of nano-LIBs [227].

9.3. Nanocrystal based hybrid systems

Hybrid systems of substantial interest due to their multi-functional properties and wide potential application range involve nanocrystals. Hybrid systems combining semiconductor nanocrystals with organic polymers result in a match that grows the efficiency and stability of solar cells [228]. Quantum confinement and strong spin-orbit coupling are characteristic features of nanocrystals as well as typical for energy and charge transfer mechanisms, being strongly connected with these hybrid structures [229]. Cellulose nanocrystals (CNCs) are versatile components in nanohybrids, which provide improved mechanical and optical properties and therefore allow stimuli-responsive modifications on surfaces. CNC-based hybrid systems are thus applied in domains such as energy storage, wastewater treatment, or biomedical technologies. In addition to those application fields, CNCs have been used for self-healing composites and shape memory polymers and, therefore, added wide applications in smart materials. These developments point to the growing importance of nanocrystal-based hybrid systems in general, for materials science and engineering [230] [231].

9.3.1. Integration of nanocrystals in multi-functional energy storage devices

Nanocrystals are embedded into multifunctional energy storage devices, providing innovative solutions in energy conversion and storage. Materials assembled from nanocrystals can provide microwave absorption, electromagnetic interference shielding, and lithium-ion storage capabilities [232]. Photodoping of metal oxide nanocrystals enables multi-charge accumulation and light-driven energy storage, which may be integrated into solar energy conversion and storage [233]. Electrochromic energy storage devices include smart windows with energy storage, where the state of energy is monitored in real-time via color changes [234]. Various nanostructures including carbon nanotubes, nanofibers, metal nanoparticles and nanocrystalline hybrids are embedded into supercapacitor, solar cells, lithium-ion batteries, and hydrogen storage applications [235]. These nanocrystal integration advancements form a basis for the development of a new generation of multifunctional energy storage devices that are capable of providing more flexibility and higher performance.

10. 4D Printing in Nanocrystal Manufacturing

4D printing is a new technology that adopt or advance the 3D printing technology using intelligent materials that are adaptive to change in shape or function over time in response to various external stimuli [236]. A very much notable aspect concerning the development of additive manufacturing technology: from 3D to 4D printing, complex parts and device development, customized medical products, novel energy harvesting and storage devices, and many more [237]. This technique uses smart materials like shape memory alloys, polymers, and gels. These materials respond to factors such as temperature, humidity, light, and pH. The main components in 4D printing are the smart materials, printing methods used, and the stimulus conditions that trigger the transformations [238]. Although this is the latest field of design in architecture, aerospace, and biomedical engineering, with immense potential, much technology still remains to be overcome [236]. The possibility to create adaptive structures with increased flexibility during use is presented by this technology [238]. Therefore, 4D printing technology is expected to transform many industries and everyday life as this field further develops [239].

10.1. Principle of 4D printing

4D printing is an advanced manufacturing technology that expands on 3D printing by introducing time as the fourth dimension, enabling printed objects to change shape or function in response to external stimuli [240]. This technology leverages smart materials and intelligent designs to create structures that can transform from 2D to 3D configurations or shift between different dimensional forms [241]. The transformation is activated by various stimuli, including temperature, pressure, moisture, pH, light, or wind [239]. 4D printing relies on principles of solid mechanics to pre-embed mismatched deformations that can be activated later, making it a mechanics-based manufacturing approach. While 4D printing offers great potential for developing complex, adaptive structures, there are still challenges to overcome in mechanical design, printing techniques, and material synthesis [238] [241].

10.2. Potential benefits of 4D printing for nanocrystal architectures

10.2.1. Nanocrystal architectures

The ability of nanostructures based on nanoscale building blocks with a variety of assembly methods allows nanoparticle size, surface interaction, formation of crystallographic facets, and even atomic-level structural control. These features qualify nanocrystals to exhibit unique and rich properties in particular due to the collective behavior of assembled nanoparticles or DNA strands within three-dimensional space [242].

These attributes give rise to numerous applications in areas as diverse as photovoltaics, semiconductors, photonics, energy storage, catalysis, sensors, and nonlinear optics. Provided that the engineering of nanocrystal chemistry and interfacial layers is adequately performed, it should be possible to optimize carrier transport between nanoparticles, especially for low-dimensional carriers, when crystalline order is also present [243].

Thus, nanocrystal superlattices form an attractive field of research focusing on the collective properties of the components and characteristics of transport of a charge across the microstructures. It therefore implies that duly tailored architectures of nanocrystal superlattices may result in novel applications [244].

10.2.2. Potential benefits of 4D printing

The ability to use 4D printing in the design and development of nanocrystal structures can present revolutionary advantages, especially in terms of material responsiveness to environmental changes. This new development allows for dynamic structures that have abilities for self-assembly, self-repair, and development of properties over time, thereby greatly increasing functionality in all applications.

4D printing is revolutionizing industries in every sector: improved manufacturing efficiency and quality, reduced costs [245]. Nanomaterials have further enriched the 4D printing process to enhance physiochemical properties of printed objects to have innovative features [246]. For example, some near-infrared light responsive nanocomposites can provide reconfiguration capabilities and remote control over the shape of 4D printed items [247]. This interdisciplinary technology that brings together smart materials, structural design, and novel functions has led to exciting advancements in soft robotics, biomimetics, and biomedical devices Artificial intravascular implants, 4D-printed hearts destined for transplantation, and intelligent drug delivery systems are a few examples out of a long list, testifying to the huge potential of 4D printing in numerous sectors [248] [245].

This allows 4D printing to generate structures capable of responding to stimuli through shape morphing, such as changes in temperature or humidity, by enhancing adaptability [249]. Using nanomaterials, however, brings new mechanical properties with added functionalities such as electrical conductivity and antibacterial properties into these structures [250]. Biomedical devices could potentially be revolutionized in the field of 4D-printed nanocrystal architectures that can reduce such invasive procedures. In addition, they could be used in robots as well as energy systems with dynamic and evolving surroundings [251] [252].

10.3. Customization of shapes and functionalities

The new idea of 4D printing is really a revolutionary approach toward designing the nanocrystals' architectures in a way that structures can exhibit dynamic transformation with respect to changing shapes and functions in response to environmental triggers. This offers new possibilities for programmable transformations, in other words with the inclusion of smart materials and sophisticated design techniques, and will find applications areas in soft robotics and biomedical devices.

Recent advances in 4D printing allow for the creation of intelligent structures with shape-memory capabilities and function- oriented programmable changes. The technology draws upon stimuli-responsive materials, advanced 3D printing techniques, and geometrical designs for creating structures that change in response over time [248]. Improvements include nanocomposites responsive to near-infrared light for controlled remoting of shape changes and projection micro stereolithography, which is used in crafting high-resolution multimaterial shape-memory polymer structures [247].

The method has also been used to produce active, shape-changing designs through the use of UV cross-linked poly(lactic acid)-based inks, where iron oxide serves as a means of remote actuation and magnetic control. These advancements have expanded the realm of 4D printing and paved the way toward dynamic multifunctional structures with unique properties and behaviors for applications such as soft robotics, biomimetics, and biomedical devices [253] [248]. 4D printing is a technique that enables the production of complex designs, rendering an idea in 2D as 3D, and allows for enhancing the functionality of mechanical metamaterials. Advanced bioengineering may result in somewhat less invasive procedures with capabilities for customizable structure manufacturing by this technology [254].

10.4. Responsive materials for adaptive energy systems

Through the breadth of responsive materials that 4D printing technology leverages on, the adaptive energy system is able to respond to all these environmental changes with dynamics. This encompasses shape-memory polymers, hydrogels, and moisture-sensitive composites whose properties change in response to stimulus such as temperature or humidity. The examples, in this case, would be when a shape-memory polymer would once heat would adopt its preset shape, while hydrogels increase or shrink upon the presence of water [249] [255].

The alkoxyamine-based composites, with their common chemical reactions that could induce dynamic changes, are now opening doors to new possibilities in terms of adaptability [256]. Moreover, thermochromic composites exhibit the ability to change color and shape because of a fluctuating temperature, which can be used as an example to illustrate the multifunctionality of 4D printing materials) [257]. These developments make sense as pathways toward the construction of intelligent systems with self-adaptive capacities and effective response to their surroundings [258]. Hydrogels, liquid crystalline materials, and composites are some of the key materials used in 4D printing. Research is underway to further improve these materials in microscale performance [259]. New directions in recent research have involved control-based 4D printing, which incorporates sensors and control units to develop adaptive systems that sense environmental changes and uncertainties [260]. Such a smart structure would lead to the realization of smart textiles and soft robotics among other several multidisciplinary applications. Although challenges remain to be addressed before the technology can be scaled up for better accessibility and offered on a broader palette of materials, 4D printing holds promise in these respects [261] [262].

10.5. Case study of 4D printing technology

In this aspect, nanomaterial adds properties and functionality to printed structures enabling fields in the aerospace, medical, and intelligent device applications [246]. A dynamically controlled remotely operated and advanced platform of 4D printing constitutes a near-infrared responsive nanocomposite that promises the application of dynamic changes in biological structure and in the regulation of neural stem cell behavior.

The field has advanced significantly with innovations in smart materials, advanced printers, deformation techniques, and mathematical modeling. Case studies show its application in self-assembling structures, medical devices, and soft robotics. Nonetheless, the problem remains with the systems that can only fulfill specific strict requirements of shape change while providing smart, dynamic control over time and space [247] [263].

10.6. Applications of 4D printing in nanocrystal-based devices

Recent advancements in 4D printing have opened the door to vast applications in nanocrystal-based devices. CNCs are rapidly being implemented in 3D and 4D printing in tissue engineering, wound healing, and wearable electronics because they are biodegradable and their mechanical properties can be manipulated [264]. More than just improving the physicochemical characteristics of the printed structures, 4D printing along with nanomaterials introduces new functionalities and stimuli responsiveness [246].

TPP is a process that enables highly detailed, responsive micro- and nanostructures to be fabricated. In conjunction with this, near-infrared light-responsive nanocomposites may allow for the production of 4D printed objects capable of dynamic, remotely controlled shape changes for applications in constructing biological structures and influencing neural stem cell behaviors [265]. These advancements show the direction wherein 4D printing has the propensity to develop more advanced and responsive nanocrystal-based devices in all fields.

This technology holds very much promise in the synthesis of nanocrystal-based devices, especially by addition of nanomaterials like cellulose nanocrystals (CNCs) and metal nanoparticles. Composite devices of magnetite and silver nanoparticles with polymer matrices yield materials that can be used for electrical applications and, concurrently, the incorporation of nanomaterials introduces antibacterial properties, which would make it the right choice for soft electronics and biomedical applications. More importantly, through 4D printing, shape-memory polymers can significantly change their shape in complexity, making these materials even more versatile in making advanced robotics and biomedical devices [250] [266].

11. Challenges and Future Prospects

11.1. Challenges in achieving high efficiency devices using nanocrystals

The high-efficiency nanocrystal-based device mainly presents challenges at the method of fabrication and stability of material, along with consistent performance. Therefore, it should be resolved to get reliable and scalable production for widespread use. The nanocrystal-based solar cells and LEDs have a lot of potentials, but there remain several barriers to reach high efficiencies. Perovskite nanocrystals, (PNCs), show brilliant optoelectronic properties with excellent stability, but PCEs for them are still much away from that of polycrystalline material. The two major challenges in PNCs are low short-circuit current density and scalability [267] [268].

Encapsulation of PNCs typically degrades their performance, especially when made into films or devices. The major challenges are color reproducibility, mass production scale, low stability, and toxicity issues. Although the most recent advancements have been made, the performance of perovskite nanocrystal solar cells is still trailing its respective bulk counterpart, which should not be less than 20%, and this remains a limitation that does not allow their wider applications and use [269].

In the quantum dots LEDs, the photoluminescence quantum yield is near perfect that is impressive, but outcoupling factors are yet very low and remain limiting for the device's performance. These issues need several novel strategies such as anisotropic nanocrystals in LED to improve light extraction efficiencies. Though intricate, nano-structure-based devices require critical modeling, since nano-structures offer distinct kinds of optoelectronic behavior from quantum-confined systems. Overcoming such barriers is important to fully realize the promise of high-efficiency nanocrystal-based optoelectronic devices [270] [271].

Colloidal perovskite nanocrystals demand extreme care in controlling the reaction environment in order to conserve their performance; otherwise, the reaction environment would lead to a drop in luminescence, which in turn affects performance as a whole. Synthesis methods for nanocrystals should not only be reliable but also scaled up to meet requirements especially if wet-chemical approaches are to be followed. Such approaches have shown promising hints but optimization towards consistency and quality is still required for better nanocrystals to be produced [272] [273].

11.2. Potential solutions

Although the high-efficiency applications, the optoelectronic applications based on nanocrystal devices hold promise with a plethora of challenges. Enhanced stability of c-PeNCs in solar cells and more easily scalable solutions form part of the hope associated with colloidal perovskite nanocrystals. Still, the power conversion efficiencies are lacking in comparison with polycrystalline material [267].

For QD-LEDs, one of the major challenges in achieving a high luminescent quantum yield under operation is linked with quantum dot chemistry and device architecture. Beyond spherical dots, anisotropic nanocrystals such as nanorods and nanoplatelets may provide particularly promising avenues for the improvement of light-extraction efficiency, overcoming some major limitations that exist for spherical quantum dots. Devices based on silicon nanocrystals have also been proven highly efficient with long-term stability through techniques such as energy band gap engineering and bipolar tunneling [274] [275].

11.2.1. Interface engineering

Interface engineering has been established as a crucial approach to improve the overall efficiency of numerous solar cell technologies. Optimization of interfaces between different layers in an organic solar cell enhances effectively device efficiency and stability [276]. Similarly, the optimization of semiconductor nanostructure interfaces in nanostructured photoelectrochemical devices enhances light absorption, charge-transfer, and catalytic reactions at its surface [277].

In perovskite solar cells, interface engineering played the key role in maximizing both efficiency and long-term stability, which helped address some of the major challenges in the commercialization process. The approach is specifically important to nanostructure solar cells, where their large specific interface areas and high density of interface states are concerned. Some common methods of interface engineering for all these technologies are modulation of anode and cathode interfaces, optimization of interconnecting layers in tandem devices, and variation of atomic composition and electronic structure of semiconductor nanostructures [278] [279].

Interface engineering can be the key in reducing lattice mismatch between core and shell in core/shell quantum dots, which leads to efficient carrier separation and minimal loss of recombination. Optimal electronic structures can thus be realized in electrocatalysts using methods such as crystalline–amorphous interfaces [280]. Interfacial passivation schemes have also been very successful in stabilizing and enhancing efficiency in photovoltaic devices halide-optimized nanocrystals, among others. Besides further enhancing the potential of perovskite solar cells in renewable energy applications, nickel oxide nanocrystals incorporation also exhibits improved stability on perovskite solar cells [281] [282].

11.2.2. Packing control

Packing control is one of the innovative ways through which efficiency in the use of nanocrystals in devices could be improved. Significant realization of efficiency in electronic, photonic, and phononic properties would be obtained by arranging and controlling the symmetry of nanocrystals with ease. Many applications therefore benefit from improved performance.

Such controlled molecular packing is crucial in organic semiconductors to further enhance charge transport [283]. Critical for the realization of high mobility in organic field-effect transistors, control over the device performance can be achieved, especially in large-area applications, by controlling the packing density and symmetry. Precise positioning of nanocrystals through techniques such as surface-templated electrophoretic deposition provides real scalability and reproducibility. Moreover, it is even possible to engineer the self-assembly of nanocrystals into superlattices through their controlled size and shape, whereby the designed proper packing arrangements fulfill the requirements set out by specific applications [284] [285].

11.2.3. Encapsulation chemistry

Recent times have witnessed the emergence of encapsulation chemistry as a potentially viable means to surmount the stability problems that have nagged most nanocrystal-based optoelectronic devices. In particular, perovskite nanocrystals (PeNCs) for their intrinsic property variability, cost-effective fabrication processes, and promising application in solar cells and LEDs, among others [267]. However, it's stability outside a controlled environment limits commercial feasibility. Encapsulation techniques have been proven effective in protecting PeNCs against moisture, oxygen, heat, and light. Improving core-shell structures and macroscale nanocomposites are solutions to enhance the robustness of PeNCs. More important, though, is the critical understanding of surface chemistry and ligand binding dynamics as a basis for further improvement in the stability of PeNCs [286] [287]. Although many significant challenges yet remain in nanocrystal-based high-efficient device developments despite the successful achievement, low short-circuit current density is viewed as one of the most critical challenges posed to nanocrystal solar cells [288]. By surface chemistry modification, like the techniques of ligand exchange, optical properties can be "tuned," and stability increases in a different environment. Hybrid inorganic/organic capping strategies provide amplified solubility that may also result in enhanced ordered-structure formation and will improve device performance in general. Such modifications are key to optimizing functionality and durability for nanocrystal-based systems [289].

11.2.4. Device architecture engineering

Device architecture engineering has proven to be a strong approach to overcoming difficulties in optoelectronic devices based on nanocrystals. New developments in perovskite solar cells include some outstanding novel bulk and graded heterojunction structures aimed at effective light management, defect passivation, and carrier extraction [290]. Other colloidal metal oxide nanocrystals have also been exploited as charge-transporting layers for solution processed devices, where superior processability along with tunable properties emerge. Still, more needs to be done on synthetic chemistry and ligand engineering along with post deposition treatments in order to achieve the best performance in optoelectronic devices [288].

Changing the incorporation of nanocrystals of varying shapes - nanorods or nanoplates also changes the light absorption profile as well as charge transport in optoelectronic devices [291]. Core-shell structures in hybrid solar cells, such as the incorporation of ZnO quantum dots on the ZnO nanorod, enhance both open-circuit voltage and short-circuit current density [292]. Interfacial engineering in perovskite LEDs has improved charge injection as well as reduced exciton quenching, achieving efficiencies greater than 20%. The work demonstrates the important role of shape engineering and interface optimization to enhance device performance [293].

11.3. Future of nanocrystal-based optoelectronic devices

Substantial breakthroughs in materials and integration techniques offer excellent potential for nanocrystal-based optoelectronic devices. The newly emerging materials such as $CuFeS_2$ nanocrystals are competitive to optical properties but strengthen the concerns related to raw material scarcity. At the same time, CdSe nanocrystals continue to further advance in photonic integrated circuits with functions of light generation and modulation [294] [295].

In addition to that, perovskite nanocrystals of metal halide also experience a surge since they show exceptional optical and transport properties for charge and thus best suited for the applications within solar cells and LEDs [296]. Studies also looked at structured photonic environments, thus allowing more improved control over light behavior, thereby performance improvement within devices. Innovation with respect to the light modulator using nanocrystals opens up multifunctional devices easily integratable in current electronics [297].

11.3.1. Impact on energy harvesting and storage

Nanocrystal-based optoelectronic devices are quite promising for energy harvesting and storage purposes. Colloidal semiconductor nanocrystals, which include metal oxides, phosphides, and chalcogenides, possess individual optoelectronic properties that are a result of quantum confinement effects [298]. These nanocrystals have been applied in a wide range of energy technologies, including photocatalytic hydrogen production, solar electricity production, and also energy storage through both lithium-ion batteries and supercapacitors [299].For example, CdSe/ZnS nanocrystals have been used for the improvement of optical detection and imaging in the ultraviolet range and for optical modulation in the visible spectrum of light [300]. Halide perovskite nanocrystals also have great potential in applications related to energy generation and harvesting. Nonetheless, for high-efficiency devices, improvement is still needed at the interfaces; one proposed solution would be in interface engineering, packing control, and further optimization of device architecture [298].

Nanocrystal-based optoelectronic devices have advantages in energy harvesting and storage through charge transport and light absorption enhancement. For example, Förster resonance energy transfer (FRET) has been exploited in metal halide perovskite nanocrystals (PNCs) to enhance current in hybrid structures, and has been utilized toward high-performance photovoltaics [301]. Similarly, silicon nanocrystals (SiNCs) show a lot of promise in energy harvesting under indoor light, yielding a record PCE of 9.7% [302]. Along with this, excitonic energy transfer in ultrathin silicon solar cells has been improved to a short circuit current up to 35%, further supporting the important role of nanocrystal sensitization to enhance device performance. These developments point toward the versatility of nanocrystals for generalizing optoelectronic systems toward application in energy-related fields [303].

12. Conclusion

Nanocrystals are the material that has come to change optoelectronic devices entirely by revolutionizing energy harvesting and storage technologies. As shown in this review, traditional optoelectronic materials suffer from severe disadvantages in terms of efficiency and tuning level and cost of production. Nanocrystals break paradigms, as they overcome these problems with very tunable properties, careful synthesis, and the best-known performance in key optoelectronic applications. Properties of nanocrystals can be controlled by maintaining their size is due mainly to the quantum confinement effect. Electronic and optical properties can be controlled by simple adjustment of the size, shape, and sometimes composition.

That's a great advantage that nanocrystals have over bulk: bandgaps are completely customizable, and there is very good charge transport with high absorption coefficients. This makes it possible to use nanocrystals in optoelectric devices which range from photovoltaic cells and photodetectors up to supercapacitors and batteries. All these properties together bring out a considerable improvement in the overall efficiency of the functionality of energy devices, beginning a new chapter in the development of advanced materials for sustainable energy systems.

Recent works on energy harvesting applications of nanocrystals, particularly in photovoltaics, reveal highly promising potential. Thin-film solar cells based on nanocrystals have a high promise towards delivering better efficiency, mainly due to enhanced light absorption and favorable properties for charge separation characteristics, thus ranking them at the very top as replacement candidates for conventional materials in solar energy systems. Nanocrystal-based photodetectors also show the possibility of offering better sensitivity and higher response, opening pathways toward other optoelectronics applications in the telecommunication and environmental monitoring sectors.

Nanocrystals have also found application in the construction of energy storage devices, notably in the creation of novel supercapacitors and advanced batteries. Due to high surface area and excellent charge mobility, nanocrystals are suitable both for increasing energy density and raising the power output of supercapacitors. Innovations related to the electrodes formed through the use of nanocrystals in lithium-ion batteries have supported much higher capacity as well as a higher rate of charge-discharge cycles. Hybrids that incorporate nanocrystals into energy storage devices are promising a new wide-ranging environment for multifunctional systems, combining the properties of both batteries and capacitors, opening doors to highly adaptable and efficient energy solutions.

One of the most exciting frontiers in nanocrystal research is the incorporation of 4D printing technology. It is a completely new technique enabling the customization of previously impossible or unattainable nanocrystal architectures using regular manufacturing techniques. The possibility of creating adaptive materials, responsive to an external stimulus, through 4D printing has opened up novel avenues for energy devices that can be self-assembled or change shape in the presence of an external stimulus. These advancements may lead to smart energy systems that can automatically adjust to environmental conditions for the purpose of creating even more power efficient and sustainable ways of energy production.

However, some challenges remain to be addressed before nanocrystals find widespread applications in commercial optoelectronic devices. Problems persisted are developing long-term stability, optimizing interface engineering, and improving the best control of packing. The most significant issues or challenges involved are advanced encapsulation chemistries and device architecture engineering. With further research, innovative solutions can be expected that make nanocrystal-based devices more efficient and reliable.

Optoelectronics based on nanocrystals has a bright future ahead of it. With continuous developments in manufacturing procedures, device engineering, and synthesis methods, nanocrystals are positioned to be crucial in forming the next wave of energy innovations. Their capacity to improve energy storage and harvesting systems is a wonderful fit with the world's expanding need for sustainable energy. Nanocrystals may hold the key to unlocking new levels of performance, flexibility, and efficiency in the energy sector as we continue to investigate and enhance these materials, bringing us closer to a more sustainable and energy-efficient future.

CRediT authorship contribution statement

Sumera Zaib: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Project administration, Resources, Visualization. **Balal Ahmad:** Investigation, Writing – original draft, **Imtiaz Khan:** Conceptualization, Formal analysis, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data has been included in the manuscript.

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