Journal of Polymer Science and Engineering 2024, 7(1), 4276.
https://doi.org/10.24294/jpse.v7i1.4276

Review

Advancements in nanohybrids: From coordination materials to flexible solar cells

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CITATION

Khan S, Ullah I, Khan S, et al. (2024). Advancements in nanohybrids: From coordination materials to flexible solar cells. Journal of Polymer Science and Engineering. 7(1): 4276. https://doi.org/10.24294/jpse.v7i1.4276

ARTICLE INFO

Received: 17 January 2024
Accepted: 22 February 2024
Available online: 28 March 2024

Abstract: This comprehensive review explores the forefront of nanohybrid materials, focusing on the integration of coordination materials in various applications, with a spotlight on their role in the development of flexible solar cells. Coordination material-based nanohybrids, characterized by their unique properties and multifunctionality, have garnered significant attention in fields ranging from catalysis and sensing to drug delivery and energy storage. The discussion investigates the synthesis methods, properties, and potential applications of these nanohybrids, underscoring their versatility in materials science. Additionally, the review investigates the integration of coordination nanohybrids in perovskite solar cells (PSCs), showcasing their ability to enhance the performance and stability of next-generation photovoltaic devices. The narrative further expands to encompass the synthesis of luminescent nanohybrids for bioimaging purposes and the development of layered, two-dimensional (2D) material-based nanostructured hybrids for energy storage and conversion. The exploration culminates in an examination of the synthesis of conductive polymer nanostructures, elucidating their potential in drug delivery systems. Last but not least, the article discusses the cutting-edge realm of flexible solar cells, emphasizing their adaptability and lightweight design. Through a systematic examination of these diverse nanohybrid materials, this review sheds light on the current state of the art, challenges, and prospects, providing valuable insights for researchers and practitioners in the fields of materials science, nanotechnology, and renewable energy.

Keywords: coordination materials; nanohybrids; advanced energy storage; solar cells

1. Introduction

Coordination materials-based nanohybrids represent a fascinating frontier in materials science, where the synergy between organic ligands and metal ions creates versatile structures with multifunctional properties. These nanohybrids, often designed at the molecular level, leverage the unique coordination chemistry of metal ions to impart specific functionalities to the resulting materials. One of the distinctive features of coordination materials is their ability to form well-defined structures through coordination bonds, leading to the assembly of organized and tailored architectures. In the realm of nanohybrids, coordination materials find application in a myriad of fields, ranging from catalysis and sensing to drug delivery and energy storage [1]. The controlled synthesis of these hybrids allows for the precise incorporation of organic ligands and metal ions, enabling the fine-tuning of their properties for targeted applications. For instance, the incorporation of luminescent metal complexes into coordination nanohybrids has paved the way for advanced imaging and sensing technologies, capitalizing on the inherent properties of the metal ions to emit light under specific conditions. Moreover, coordination materials-based nanohybrids exhibit remarkable catalytic activities owing to the inherent reactivity of metal centers. The well-defined coordination environments provide an ideal platform for catalytic reactions, and these hybrids have been employed as efficient catalysts in various chemical transformations. The modular nature of coordination materials allows for the incorporation of different metal ions and ligands, enabling the development of catalytic nanohybrids with tailored reactivity and selectivity. In the realm of drug delivery, coordination materials-based nanohybrids offer a unique combination of biocompatibility and controlled release properties. The metal-ligand coordination bonds can be designed to respond to specific stimuli, such as pH or temperature, triggering the release of encapsulated therapeutic agents at targeted sites. This precise control over drug release enhances therapeutic efficacy while minimizing side effects. Furthermore, the advent of coordination materials-based nanohybrids has made significant strides in the development of advanced energy storage and conversion systems. Metal-organic frameworks (MOFs), a subclass of coordination materials, have emerged as promising candidates for applications in batteries and supercapacitors due to their high surface areas and tunable porosities [2].

The unique properties of these nanohybrids position them as model support structures for developing nanomaterials with extraordinary performance features [3]. The design of luminescent nanohybrids for bioimaging purposes has been explored through various approaches in the literature. Silica luminescent nanohybrids containing Eu^{3+}-complexes were synthesized using three distinct methods to determine the most efficient approach for obtaining highly emissive final hybrids suitable for cell imaging applications, leveraging the luminescent probe properties of Eu^{3+}. The synthesis process involved the transformation of dense Stober silica nanoparticles (SiO_2) into luminescent hybrids through a series of well-defined steps. The surface of SiO_2 was first functionalized with APTES, and the amine group subsequently reacted with salicylaldehyde to form a Schiff base ligand (SB), resulting in the SiO_2-SB system. The coordination of Eu^{3+} ions to SB, followed by the displacement of coordinated water molecules with dibenzoylmethane (DBM), led to the creation of the hybrid SiO_2-[Eu1]. Tris-[Eu(DBM)$_3$] complexes coordinated to the imine groups grafted on the SiO_2-SB surface were employed to generate the SiO_2-[Eu] hybrid. A novel Eu^{3+}-Schiff base combination with a triethoxysilyl group was grafted onto the SiO_2 surface to produce the third hybrid, SiO_2-[Eu].

All three luminescent hybrids exhibited red emission, extended lifetimes (0.34–0.61 ms), and remarkable photostability under continuous 340 nm UV light exposure. Characterized by a spheroidal form and a size of 100 nm, the hybrids were evaluated using the LUMPAC software program and the Horrocks equation to determine quantum efficiency (QE) and the quantity of coordinated water molecules (qH_2O) to the Eu^{3+}. While all three synthesis methods showed promise, SiO_2-[Eu] emerged as the optimal hybrid based on photophysical results, boasting higher QE and color purity values. Moreover, SiO_2-[Eu] demonstrated non-toxicity (**Figure 1**), as evidenced by its bio-viability in CHO-k1 cells at various dosages. The effectiveness of SiO_2-[Eu] as a luminous stain for cell imaging was further validated through exploratory cell imaging assays, where the internalization of nanoparticles within the cells was confirmed by Eu^{3+} ($^5D_0$ ^7F_J) narrow emission bands, showing distinct cell marking in proximity to the nucleus. In conclusion, SiO$_2$-[Eu] exhibited favorable characteristics in terms of form, size, optical properties, and biocompatibility, positioning it as a promising candidate for use as a luminous stain in cell imaging applications [4].

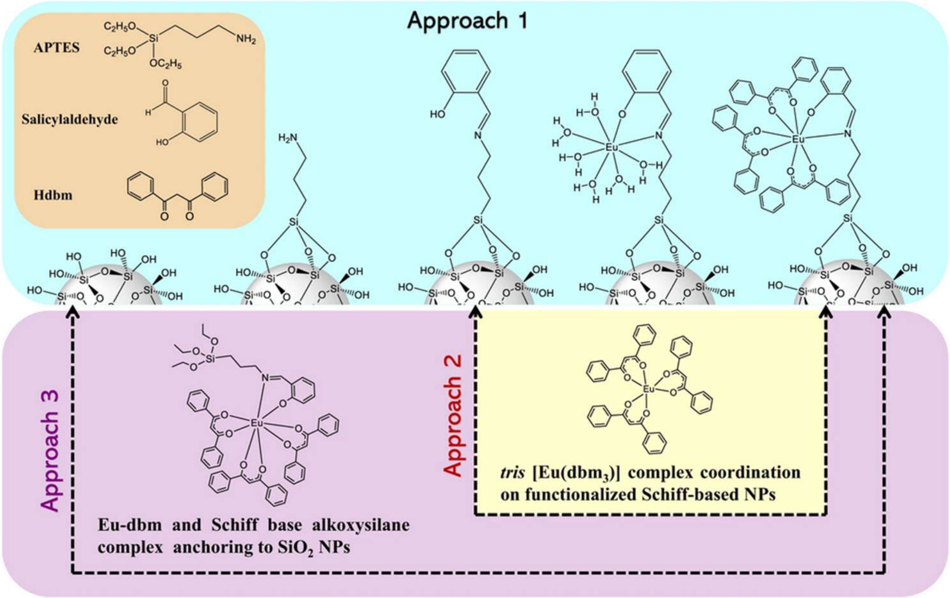

Figure 1. Three approaches for Silica luminescent nanohybrids containing Eu^{3+}-complexes SiO$_2$ [Eu] in CHO-k1 cells [4].

2. Synthesis of CPs nanostructures

The synthesis of conductive polymers (CPs) nanostructures involves crafting nanoscale architectures with enhanced electrical conductivity and distinctive properties, combining the electrical characteristics of metals with the mechanical features of polymers. The synthesis process encompasses several key steps. Firstly, an appropriate monomer, such as aniline, pyrrole, or thiophene, is selected based on the desired properties of the final nanostructure. Various polymerization methods, including chemical oxidation, electrochemical polymerization, and oxidative polymerization, offer tailored approaches to CPs nanostructure production. Chemical oxidation, utilizing agents like ammonium persulfate, is apt for bulk synthesis, while electrochemical methods, involving an electrode for precise control, offer advantages in size and morphology modulation. Oxidative polymerization, with agents like ferric chloride or bromine, allows for specific shape and size control. Template-assisted synthesis, utilizing porous materials or nanostructures, and surfactant-assisted synthesis, employing stabilizing surfactants, contribute to dimension and shape regulation. Doping, a crucial step employing acids, salts, or electron-accepting molecules, enhances electrical conductivity. Thorough characterization using techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) evaluates size, morphology, crystallinity, and chemical structure. Finally, exploring applications in sensors, flexible electronics, energy storage devices, and emerging technologies leverages the unique electrical and mechanical properties of CPs nanostructures. Through meticulous control of synthesis parameters, researchers can tailor CPs nanostructure properties for specific applications, contributing to advancements in materials science and electronic devices. The structure and morphology of the CPs sensing layers, which are the result of structural effects, are intimately connected to the sensing responses. To meet the needs of various types of sensor setups, a variety of procedures have been investigated to construct 0D, 1D, 2D, and 3D CPs nanostructures. Thus, the process used to create the CPs nanostructures is crucial for the integration of sensors [5]. Research interest has been growing in the "MXene" family of massive, recently discovered 2D materials. The substance has good optoelectronic, physicochemical, thermoelectrical, and mechanical capabilities [6] and is made up of transition metal carbides and nitrides. The formula $Mn + 1XnTx$, where $n = 1, 2$, or 3, may be used to show MXene. M stands for a transition metal (such as Mn, Sc, Cr, Nb, Ta, Mo, and Hf), X for a C or N element, and T for various surface functional groups or atoms (–OH, O, or F). The predecessors of MXene are MAX phases, which have the common formula $Mn + 1AXn$, where A is any element from groups IIIA and/or IVA of the periodic table. X indicates a C and/or N element, and $n = 1, 2, 3, 4$, and 5 [6].

3. Properties of coordination material-based nanohybrids

The properties of coordination material-based nanohybrids underscore their significance in the realm of materials science. These nanohybrids exhibit a remarkable interplay between organic ligands and metal ions, giving rise to a diverse range of functionalities [7]. Their unique coordination chemistry enables the formation of well-defined structures, allowing for precise control over their size, shape, and composition. Coordination material-based nanohybrids often boast enhanced mechanical, thermal, and electrical properties, making them versatile candidates for various applications. The tunability of these properties is further augmented by the choice of metal ions and ligands during the synthesis process. Additionally, coordination nanohybrids frequently exhibit superior catalytic activities, making them valuable in catalysis and sensing applications. Their inherent biocompatibility and tailored release mechanisms also position them as promising candidates for drug delivery systems. As the exploration of these nanohybrids advances, their properties continue to be fine-tuned, paving the way for innovations in fields such as energy storage, biomedical applications, and catalysis [8].

4. Emerging solar cell technologies

4.1. Lead-based perovskite materials

Lead-based perovskite materials have emerged as a transformative force in the fields of photovoltaics and optoelectronics. These materials, typically adopting the ABX_3 crystal structure, where A is a cation, B is a metal cation, and X is an anion, exhibit exceptional optical and electronic properties. Particularly, lead halide perovskites, such as methylammonium lead iodide ($MAPbI_3$), have demonstrated outstanding power conversion efficiencies in solar cells, rivaling traditional silicon-based technologies. The facile and cost-effective fabrication processes, including solution-based deposition techniques, make lead-based perovskites attractive for large-scale production. However, their commercial viability is tempered by concerns regarding the toxicity of lead, urging researchers to explore alternative compositions, such as tin-based perovskites. Ongoing research endeavors focus on enhancing the stability, scalability, and environmental impact of lead-based perovskite materials, aiming to unlock their full potential for clean energy applications. Despite challenges, the rapid progress and immense promise of lead-based perovskite materials continue to drive innovation and reshape the landscape of renewable energy technologies. Kojima et al. employed $MAPbI_3$ and $MAPbBr_3$ as the first perovskite materials to be used in DSSCs as sensitizers, and Pb-halide-based perovskites have since drastically changed the field of PVs [9]. The photovoltage and photocurrent of the device are significantly altered by the employment of I and Br ions as halide anion in the PSCs. Pb-based perovskites have a number of exceptional qualities that make them suited for optoelectronic uses. They are semiconductors with an almost perfect direct band gap (1.6 eV), and for single-junction solar cells, the Schockley-Queisser gap is 1.43 eV. They have an extremely high absorption coefficient ($a = 5 \times 10^4$ cm^{-1}), which is nearly 25 times more than Si's and even better than GaAs [10]. Because e- and h+ have balanced, very tiny effective masses for enhanced conveyance using charge carriers [11], with a 1 m diffusion length, photo-generated charge carriers have a long lifespan. Planar and lateral structures are the two forms of architecture that may be employed in the creation of perovskite single-crystal devices. A planar or conventional sandwiched structure is an example of the solar cell architecture that is most often used. Malinkiewicz et al. [12] created a planarly structured single crystal device; in this work, the team combined fullerene derivatives with MAPbI3 as a donor material. Their planar devices were made using a thermally deposited 285 nm MAPbI3 thin film at ambient temperature. Sandwiched between materials that act as an electron acceptor (PCBM) and an electron blocker (polyTPD) is a film. The manufactured device established a benchmark PCE of 12% for an organic solar cell based on fullerene [13], and since then, additional small-molecule-based hybrid solar cells have reached PCEs of 18% [12,14]. In contrast to the typical arrangement of a planar-structured device, lateral-structured single-crystal devices exhibit improved thermal and mechanical characteristics, providing the device with more stability.

4.2. Dye-sensitized solar cells (DSSCS)

The dye-sensitized solar cell (DSSC) provides a practical and effective technology for the delivery of energy in the future. It offers comparable power conversion efficiency (PCE) to traditional silicon solar cells at cheap manufacturing and material costs. Titanium oxide (TiO_2) is a common, affordable, and environmentally safe DSSC material. In order to print DSSCs on the mass production line, a roll-to-roll method might be used since DSSC materials are less prone to contamination and processable at room temperature. DSSCs are a great option for interior applications since they work better in lower light intensities. The development of molecular engineering has led to the introduction of colorful and transparent thin films to increase their aesthetic qualities. Such advantages have so far sparked a lot of research interest and commercialization activity. This study considers device modeling, cutting-edge methodologies, and unique device topologies to explore advanced approaches and research trends for this promising technology [15]. As a result, the dye-sensitive solar cells (DSSC) (**Figure 2a**) [16], a novel form of solar cell consisting of a counter electrode, an electrolyte containing iodide-triiodide ions, and a nanocrystalline porous semiconductor electrode that absorbs dye [17], have been thoroughly researched. Based on photosensitization caused by the dyes on the wide-band-gap mesoporous metal oxide semiconductors [18], it is a device for converting visible light into electricity. Due to the dye's absorption of a portion of the visible light spectrum, this sensitization has occurred. Sensitized dye functions by receiving solar energy and transforming it into electrical energy. **Figure 3b** illustrates the DSSC's basic operating concept. It falls under the following categories of flows: 1) an electron went through an excitation cycle; 2) TiO_2 was injected into, and iodine was reduced at the counter electrode; 3) an electron performed external work [19]; 4) the electrolyte was diffused; and 5) the oxidized dye was restored. Due to its potential uses in environmental protection and energy production, titanium dioxide (TiO_2) has recently attracted the attention of researchers from all over the world. It has been used primarily in DSSC due to its nanocrystalline mesoporous nature, which translates to a high surface area for dye adsorption [20]. The solar energy may then be used to excite the absorbed dye molecules to create electron-hole pairs that are then divided and transported into the TiO_2 lattice. The dye's absorption spectrum and its anchoring to the surface of TiO_2 are crucial factors in determining the cell's effectiveness [21]. The comparison of semiconductor solar cells and DSSCs is given in **Table 1**. Much attention has been paid to the dye since it is crucial for absorbing visible light and converting photon energy into electricity, paid to survey the effective sensitizer dyes [22]. Porphyrins [23], platinum complexes [24], and other organic dyes have been created and utilized as sensitizers together with other metal complexes [25]. Ru-based complex sensitizers are often employed because of their superior effectiveness and long lifespan. These benefits, however, are outweighed by their high price and propensity to degrade in the presence of water [26]. Additionally, it is considered to be extremely poisonous and carcinogenic.

Table 1. Comparison between semiconductor-based solar cells and dye-sensitive solar cells (DSSC) [16].

	Semiconductor solar cells	**Dye-sensitized solar cells**
Transparency	Opaque	Transparent
Pro-environment (material & process)	Normal	Great
Power generation cost	High	Low
Power generation efficiency	High	Normal
Color	Limited	Various

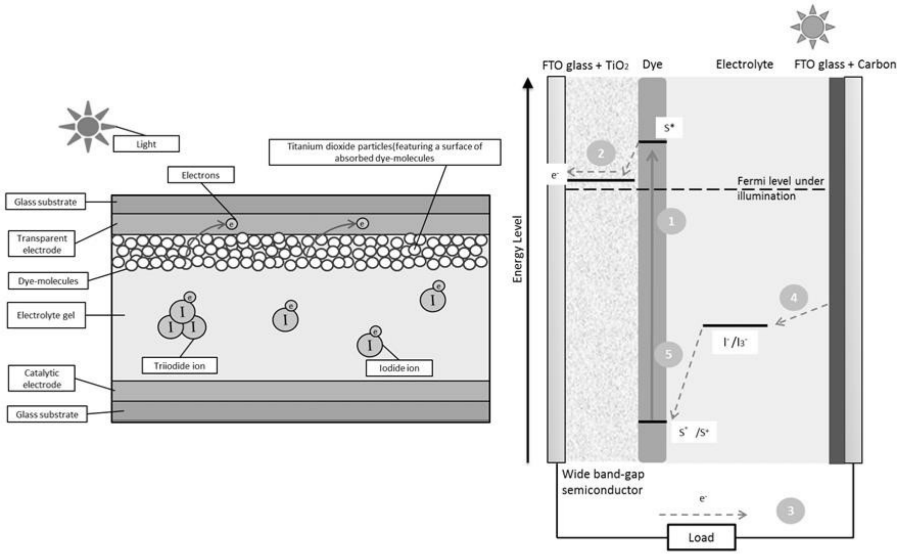

Figure 2. (a) the structure of DSSC; **(b)** the mechanism of DSSC [16].

The dye-sensitized solar cell (DSSC), one of the several solar technologies, holds out the most hope for a low-cost, highly-manufacturable answer to an energy economy free of fossil fuels and their negative effects. The overall conversion efficiency of DSSCs documented in the literature, however, has only grown by 4% in the last 25 years. This chapter gives a general overview of the DSSC architecture, discusses the state of the technology today, and considers the causes that have prevented cell efficiency from improving despite enormous amounts of effort. in advancing technologies. It emphasizes the extremely difficult and complicated nature of DSSC optimization as well as the necessity of multiscale first principles mathematical modeling of DSSCs to fully comprehend the physics, dynamics, and interactions [27] of internal DSSC components. These models enable in silico design and DSSC optimization and can characterize cellular activities at various temporal and geographical dimensions [28].

4.3. Coordination material-based nanohybrids in DSSCS

A sensitizer molecule (often several dye molecules) is used in dye-sensitized solar cells (DSSCs), a solar photovoltaic device that transforms solar energy into electrical energy. The cost of manufacturing DSSCs is much cheaper than that of traditional silicon-based solar cells since they do not include pricey silicon. Their commercial usage has been hindered despite the cost benefit by their generally poor chemical stability and low photo conversion efficiency (PCE). The two most costly components of PV technology, the platinum counter electrode (CE) and ruthenium-based dyes, may be replaced with less expensive ones; however, some recent advances showing PCE in the region of 15% imply that DSSCs can be a low-cost alternative to PV technology. In the DSSC, the material choice for the CE is critical. performance because its primary function is to draw electrons from the outside circuit and catalyze a redox process to decrease the electrolyte ions. Due to their intriguing catalytic activity and intriguing physicochemical features, transition metal chalcogenides (sulfides/selenides), among others, have lately gained significant study attention as CE materials as an alternative to platinum. This chapter begins with an explanation of the fundamental operation of the DSSC, with a focus on the function of the CE. This is followed by a summary of the typical procedures for the synthesis of sulfides and selenides-based CE for DSSC application. We next compare output metrics, including PCE, stability, and fill factor, to the literature on the state of the art for DSSCs made with sulfides/selenides-based CEs. Finally, we summarize the overall conclusion and discuss the scope for future research [29].

4.4. Organic solar cells (OSCS)

A promising new low-cost thin-film photovoltaics technology is the organic solar cell (OSC). With the advancement of low-bandgap organic material synthesis and device processing technologies, the power conversion efficiency (PCE) of OSCs has surpassed 16% for single junction and 17% for organic-organic tandem solar cells. The OSCs' lackluster device stability is the biggest impediment to their commercial applications. The elements affecting OSC stability are enumerated here. Oxygen, water, radiation, heating, metastable morphology, diffusion of electrode and buffer layer materials, and mechanical stress are the stability-limiting elements. The most recent developments in methods to strengthen the stability of OSCs are reviewed, including material design, active layer device engineering, employing stable electrodes and encapsulating materials, inverting the shape, and improving the buffer layers. Also included are the guidelines from the International Summit on Organic Photovoltaic Stability. The different research approaches that may be used to attain the necessary device efficiency and stability are outlined, opening up prospective routes for the successful commercialization of OSCs [30].

The most promising organic solar cells (OSCs) for use in wearable energy resources and photovoltaics incorporated into buildings are those that are flexible and semitransparent. As a result, the development of novel flexible bottom or top transparent electrodes, the design and synthesis of high-performance photoactive layer and low-temperature processed electrode buffer layer materials, and the engineering of device architecture have all contributed to the rapid development of flexible and semitransparent OSCs in recent years. Flexible OSCs have the best power conversion efficiency at over 10%, while semitransparent OSCs have the highest at 7.7% with an average visual transmittance of 37%.

4.4.1. Factors limiting the stability of OSCS

The stability of OSCs in the real world might be limited by a variety of circumstances, which is different from the research setting in labs. In this section, we go over the elements—metastable morphology, electrode and buffer layer diffusion, oxygen and water, radiation, heating, and mechanical stress—that affect OSC stability over the course of their whole lifetimes (**Figure 3**). The essential element of OSCs is an active layer, which typically consists of two or three phases (donor phase, acceptor phase, and mixed donor/acceptor phase) [31]. Because organic components [32,33] move around so much, phase separation is always metastable. Micro-focused grazing incidence small-angle X-ray scattering (mGISAXS) was utilized by Muller-Buschbaum. To examine the metastable morphology of a polymer/fullerene mix. A morphological deterioration model was put out by them (**Figure 3a–d),** in which the donor domains drift apart from one another (smaller domains disappear while bigger ones increase) [34].

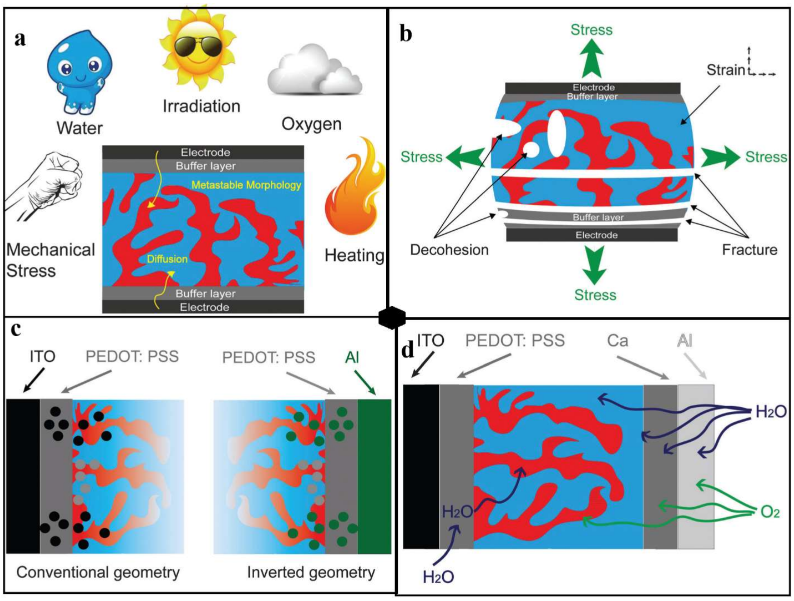

Figure 3. Organic solar cells (OSCS); **(a)** schematic diagram of the factors limiting the stability of OSCs; **(b)** schematic diagram of the device under mechanical stress; **(c)** schematic diagram of the diffusion of electrodes and buffer layers; **(d)** schematic diagram of the diffusion of oxygen and water [35].

The efficiency of bulk heterojunction (BHJ)-based organic solar cells (OSCs) has significantly increased during the past several years. However, more advancements are required for precision device fabrication and large-scale roll-to-roll (R2R) manufacture of this technology. The essentials of a BHJ OSC, including its operating principle and performance traits, are highlighted in this article. Different degradation variables impacting the operational life of OSCs are explored, and the significance of stability for device longevity is supported. Last but not least, methods to increase OSC stability include encapsulating the device, controlling morphology in the BHJ layer, and interfacial engineering using buffered layers. The emphasis is placed on the utilization of inverted geometry and different electrode materials. In addition, a straightforward mathematical model of OSC deterioration trends is suggested. This study covers practically all of the major factors that are thought to be crucial for understanding the current condition of BHJ OSCs regarding stability and deterioration [36,37].

4.5. Coordination material-based nanohybrids in PSCS

Coordination material-based nanohybrids have emerged as promising components in the development of perovskite solar cells (PSCs), offering innovative solutions to enhance their performance and stability. PSCs, with their remarkable light-absorption properties and cost-effective fabrication methods, have gained attention as next-generation photovoltaic devices. Integration of coordination nanohybrids into PSCs involves incorporating tailored nanoscale architectures, often derived from metal-organic frameworks (MOFs) or other coordination materials, to address challenges associated with PSCs. The unique properties of coordination nanohybrids contribute significantly to PSCs. These materials can serve as electron or hole transport layers, enhancing charge carrier mobility within the solar cell. Their tunable structures and functionalities allow for precise control over interfaces, leading to improved charge separation and reduced recombination losses. Additionally, coordination nanohybrids can function as stabilizing agents, mitigating the notorious issue of perovskite material degradation due to moisture or temperature fluctuations. In the quest for efficient and stable PSCs, the incorporation of coordination material-based nanohybrids has shown promising results. Researchers are exploring various strategies, such as incorporating nanohybrids as interlayers or modifying the perovskite layer itself, to optimize device performance. By leveraging the unique properties of coordination nanohybrids, PSCs can potentially achieve higher efficiencies, enhanced long-term stability, and reduced manufacturing costs, paving the way for the widespread adoption of this renewable energy technology. As advancements in materials science and nanotechnology continue, coordination material-based nanohybrids stand at the forefront of innovations in PSCs, bringing us closer to a sustainable and efficient future for solar energy.

High-performance perovskite solar cells (PSCs) require a substantial amount of hole-transporting material (HTM). HTMs based on inorganic, organic, and hybrid (organic-inorganic) materials have been effectively produced and studied throughout the years. With the use of 2,2',7,7'-tetrakis (N,N-di-p-methoxyphenylamine) and 9,9-spirobifluorene (spiro-OMeTAD) as HTM, perovskite solar cells today achieved an efficiency of 22.1%. Alternative materials are needed since the synthesis and price of organic HTMs provide a significant challenge. Inorganic HTMs have significantly improved in stability and power conversion efficiency (PCE) during the last few years. CuOx just attained the PCE of 19.0% with more consistency. These discoveries demonstrate that for next-generation PSCs, inorganic HTMs are superior to organic HTMs. In this paper, we primarily concentrated on the most recent developments in inorganic and hybrid HTMs for PSCs and emphasized how the stability and efficiency of PSCs were increased by switching from metal oxides to HTMs. Therefore, we anticipate that the energy levels of these inorganic HTMs will fit the valence band of perovskites extremely well, and increased efficiency will aid in the practical deployment of low-cost PSCs in the future [38].

4.6. Silicon solar cells

Historical advancements that led to the creation of high-efficiency crystalline silicon solar cells are recognized and explained. Despite the development of laboratory cells that perform close to their theoretical maximum, commercial cell designs still need to undergo substantial development in order to reach their full potential. To achieve commercial devices of 20% efficiency from solar-grade substrates, in particular, the development of cell structures and processes that enable fully activated device volumes in conjunction with well-passivated metal contacts and front and rear surfaces is crucial (yet not particularly difficult). Manufacturers will be forced to adapt their designs in this way by the inevitable trend toward smaller substrates if they don’t want to suffer significant performance losses. Thin-film crystalline silicon cells, which are a kind of thin-film technology, are anticipated to take over at some point. a credible candidate. It is especially important to achieve devices with fully activated volumes (diffusion lengths much greater than device thicknesses), well-passivated metal contacts and surfaces, and the crucial inclusion of light trapping because current commercial techniques and processes are generally unsuitable for thin-film fabrication. A key characteristic of this laboratory cell is its extremely good light trapping, which disproves the long-standing criticism of crystalline silicon regarding its poor absorption properties and, correspondingly, perceived inability to achieve high-performance thin-film devices. The recent achievement of 21.5% efficiency on a thin crystalline silicon cell (less than 50 urn thick) adds credibility to the pursuit of crystalline silicon in thin films. The parallel-multijunction cell is a low-cost, low-quality polycrystalline silicon material. Over the next 10 years, structure may offer a method for attaining fully active cell volumes with the ability to reach acceptable efficiencies at a low cost.

First silicon cells, 1940–1950

Russell Oh1 of Bell Laboratories discovered a clearly defined barrier while researching recrystallized melts of commercially high-purity silicon. Fortunately, impurity segregation during the recrystallization process led to the formation of these natural connections. He referred to one side of the junction as “positive” or “*p*-type” and the other as “*n*-type” (the functions of acceptors and donors were not understood at the time). The computation of cell voltage polarity has been made easier for future generations thanks to this lucky naming decision! Because of the absence of control over the junction position and the caliber of the crystalline silicon material, Russell Ohl was unable to create functional cells from these natural connections, as illustrated in **Figure 2**, with efficiencies significantly below 17 [39].

By better utilizing the solar spectrum, it is possible to increase the cell efficiency of silicon solar cells in three different ways: photoluminescence (shifting photons into wavelength ranges better accepted by the solar cell), down-conversion (cutting one high-energy photon into two low-energy photons), and up-conversion (combining low-energy photons into one high-energy photon). This study discusses the appropriateness of current materials for use with silicon solar cells and presents the state-of-the-art of these three approaches [14].

The crystalline silicon (c-Si) solar cell has been recognized as the only affordable, long-term, sustainable, and environmentally acceptable renewable energy source to displace fossil fuels since its invention. Si-based photovoltaic (PV) technology has advanced at a pace that is sufficient for the job. It has increased to 55 GW, controls 90% of the market, and has an admirable track record of price reductions (**Figure 4**). By 2020, it is predicted that the market will expand by 20 to 30 percent and produce 100 gigawatts (WP) annually [1]. Cost reduction to compete with fossil fuels has been the main driver of Si PV’s industrial growth. Solar cell production costs have decreased from $76/WP in 1977 to $0.3/WP in 2015. This cost is still 3–4 times higher than carbon-based fuels [40].

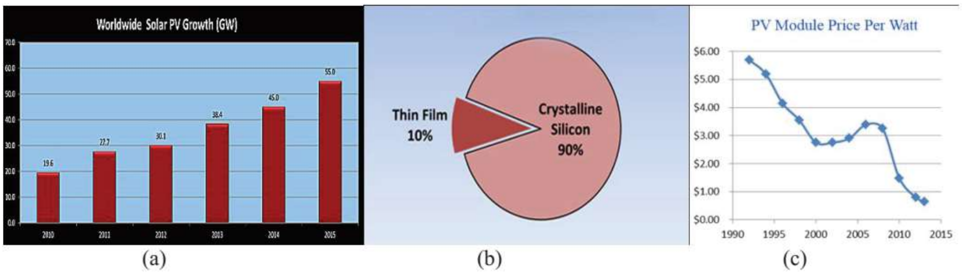

Figure 4. (a) PV growth from 2010–2015; **(b)** crystalline Si PV market share; **(c)** reduction in PV module price [40].

4.7. Tandem solar cells

Tandem solar cells represent a cutting-edge advancement in solar photovoltaic technology, aiming to maximize energy conversion efficiency by stacking multiple layers of solar cell materials with complementary absorption spectra. Unlike traditional single-junction solar cells that are limited by the Shockley-Queisser efficiency limit, tandem solar cells leverage the concept of spectral utilization to capture a broader range of solar radiation. In a tandem configuration, each layer is designed to absorb a specific portion of the solar spectrum, ensuring that a larger fraction of sunlight is converted into electricity. This tandem architecture typically combines materials with varying bandgaps, allowing them to absorb light at different wavelengths. Common tandem cell designs include the integration of silicon-based cells with thin-film technologies like perovskite or organic photovoltaics. One of the primary advantages of tandem solar cells is their potential to achieve efficiencies beyond what is possible with standalone solar cells. By efficiently utilizing a broader range of the solar spectrum, tandem cells have demonstrated the ability to surpass the limitations imposed by individual materials. Moreover, tandem configurations can be tailored for specific applications, such as space exploration or terrestrial power generation, by optimizing the choice of materials and bandgap combinations. While tandem solar cells hold great promise for significantly improving energy conversion efficiencies, challenges remain, including the development of stable and scalable manufacturing processes, managing the complexities of integrating different materials, and addressing cost considerations. Nevertheless, ongoing research and development efforts continue to propel tandem solar cells toward commercial viability, offering a path toward more efficient and sustainable solar energy utilization in the future [41].

4.8. Quantum dot solar cells

Quantum dot (QD) solar cells have the capacity to use hot photogenerated carriers to produce larger photovoltages or higher photocurrents, which has the potential to raise the maximum thermodynamic conversion efficiency of solar photon conversion up to roughly 66%. In order to gather hot carriers in QD array photoelectrodes before they relax to the band margins by phonon emission, the first effect relies on miniband transport. The latter effect relies on using hot carriers in QD solar cells to improve impact ionization processes and produce and collect more electron-hole pairs. The three QD solar cell configurations—photoelectrodes with QD arrays, QD-sensitized nanocrystalline TiO_2, and QDs distributed in a mixture of hole- and electron-conducting polymers—are all explained. These high-efficiency setups call for and we report preliminary findings on slower hot electron cooling in InP QDs [42] for slow hot carrier cooling durations. Quantum dot (QD) solar cells have the capacity to use hot photogenerated carriers to produce larger photovoltages or higher photocurrents, which has the potential to raise the maximum thermodynamic conversion efficiency of solar photon conversion up to roughly 66%. In order to gather hot carriers in QD array photoelectrodes before they relax to the band margins by phonon emission, the first effect relies on miniband transport. The latter effect relies on using hot carriers in QD solar cells to improve impact ionization processes and produce and collect more electron-hole pairs. The following three QD solar cell arrangements are described: (1) photoelectrodes with QD arrays; (2) nanocrystalline TiO_2 that has been QD-sensitized; and (3) QDs that are disseminated in a mixture of hole- and electron-conducting polymers [43]. We report preliminary findings on slower hot electron cooling in InP QDs, which are necessary for these high-efficiency designs [44,45].

4.9. Flexible solar cells

Flexible solar cells represent a revolutionary development in solar photovoltaic technology, offering a versatile and adaptable approach to harnessing solar energy. Unlike traditional rigid solar panels, flexible solar cells are fabricated on flexible substrates, such as plastics or thin metal foils, allowing them to conform to curved or irregular surfaces. This flexibility opens up a wide range of applications, including integration into wearable devices, roll-able solar blankets, and other unconventional surfaces. The most common materials used in flexible solar cells include thin-film technologies like amorphous silicon, organic photovoltaics (OPV), and emerging materials such as perovskites. These materials provide the flexibility needed for the solar cells to bend and conform without compromising their energy conversion efficiency. One of the key advantages of flexible solar cells lies in their lightweight and portable nature, making them ideal for applications where traditional, rigid solar panels would be impractical. The flexibility also enables seamless integration into various surfaces, expanding the possibilities for solar energy harvesting in unconventional environments. Furthermore, flexible solar cells are particularly well-suited for portable and off-grid power solutions. They can be easily rolled up or folded, making them compact and easy to transport. This makes them valuable for applications such as camping, outdoor activities, and emergency power supplies. Despite the promising advantages, challenges remain in terms of achieving high efficiency and maintaining durability over extended periods, especially in outdoor conditions. Researchers are actively working on improving the stability and efficiency of flexible solar cells through advancements in materials and manufacturing processes. It has been stated that the electron is the supreme form of money in contemporary culture. Electricity is the most often utilized source of energy since it is silent, clean, portable, and quickly transformed into labor. However, except for a 16% contribution from nuclear fission, we mostly generate power by burning hydrocarbons and, ironically, far less expensive coal. For instance, coal accounted for over half (49%) of the 4.1 trillion kWh of power produced in the US in 2006. China alone will need to add around

25 GW of new capacity annually over the next ten years to keep up with demand, which is the equivalent of building one sizable coal power plant every week. Unfortunately, coal releases a lot of CO_2 that alters the climate, and it also includes mercury. Ocean and food chain contamination is being brought on by combustion. The largest challenge of our time is to generate power only from solar energy in order to reduce emissions and avert climate change [46]. Flexible thin-film solar cells are compact and strong mechanically. Flexible solar panels are anticipated to provide specialty items that call for lightweight, mechanical flexibility, and moldability into complicated designs, such as roof panels for electric cars, foldable umbrellas, camping tents, etc., with fast-expanding battery technology. In this article, we offer a thorough analysis of pertinent materials that may be used to create flexible solar cells. Metals, ceramics, glasses, and polymers have all been examined as substrate materials. In terms of active materials, we mainly concentrate on recently developed novel semiconductors such as organometal halide perovskites, conjugated donor/acceptor polymers, and tiny organic donor/acceptor molecules. the electrode Materials such as thin metal films/nanowires, conducting polymers, nanocarbons, carbon nanotubes [47,48], and transparent conducting oxides are discussed in the literature, along with the advantages, disadvantages, and potential of these materials for creating flexible photovoltaics of the future [49].

5. Conclusion

This review provides a comprehensive exploration of the diverse and dynamic landscape of nanohybrid materials, encompassing coordination material-based nanohybrids, luminescent nanohybrids, conductive polymer nanostructures [43], and the revolutionary realm of flexible solar cells. The synthesis methods, properties, and applications of these nanohybrids have been elucidated, highlighting their significant contributions to catalysis, sensing, drug delivery, and energy storage. The integration of coordination nanohybrids in perovskite solar cells (PSCs) emerged as a promising avenue, showcasing their potential to enhance device performance and stability. Furthermore, the synthesis of luminescent nanohybrids for bioimaging purposes and the development of layered 2D material-based nanostructured hybrids for advanced energy storage and conversion underscore the breadth of applications for these innovative materials. The exploration of conductive polymer nanostructures in drug delivery systems revealed their potential for controlled release and targeted therapeutics. The final segment of the review explores the transformative field of flexible solar cells, emphasizing their adaptability and lightweight design. The potential applications of flexible solar cells in portable and off-grid power solutions open new frontiers in solar energy harvesting. While these nanohybrid materials exhibit remarkable properties and hold promise across various domains, challenges such as stability, scalability, and environmental impact remain areas of ongoing research. Nevertheless, the collective advancements showcased in this review underscore the potential of nanohybrid materials to revolutionize materials science, nanotechnology, and renewable energy. As researchers continue to innovate and address existing challenges, these nanohybrids stand poised to contribute significantly to the advancement of technology and the realization of sustainable and efficient solutions for numerous applications.

Conflict of interest: The authors declare no conflict of interest.

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