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Article

Application of quantum dot light-emitting diode harvest by quantum dot solar cells

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ABSTRACT

Recent progress in photovoltaic (PV) cell usage has been hindered due to a shortage of suitable materials that emit adequate wavelengths of light energy and convert it to electricity. Quantum dot light-emitting diodes (QLEDs) and quantum dot solar cells (QDSCs) have been identified as promising artificial light sources and PV cell types to nicely fit into this solution, not only complying with that but also being controllable, flexible, portable, and lightweight. The purpose of this study is to provide a review of the application of how QLEDs can be collected for QDSCs. First, we introduce QLEDs as artificial light sources, briefly outline their mechanics and benefits, and compare them to other light sources for QDSC harvesting. Then, we summarize the mechanisms that occur when a QDSC absorbs a photon from a QLED, as well as how these energy flow pathways influence artificial light energy harvest. Finally, we explore the optoelectronic properties of lead sulphide (PbS) and lead selenide (PbSe) as appropriate quantum dots (QDs) materials for current applications in QDSC and QLED technologies. We anticipate that the literature will be comprehensive and relevant to the scientific community interested in creating artificial light energy harvesting and thus researching the most recent alternative method of getting healthy energy.

1. Introduction

With an irradiation level of 1.8×10^{14} kW at the Earth's surface [1], sunlight is an important energy source. This sun's electromagnetic radiation spans a wide variety of wavelengths, from radio waves to infrared, visible, and ultraviolet light, as well as X-rays and gamma rays. This energy is essential in our daily lives. The wavelength energy, in particular, is found mostly in the ultraviolet, visible, and infrared ranges. The percentages of this wavelength received on the Earth's surface are as follows: ultraviolet (UV) radiation (400 nm) accounts for less than 9% of the total; visible light (VIS) (400nm 700 nm) accounts for 39%; and infrared (IR) accounts for around 52% [2]. Solar cells or photovoltaic (PV) devices are materials or devices capable of converting light energy into electrical power and current. Because the irradiance spectrum of sunlight is broad and extends from the ultraviolet (300 nm) to the near-infrared (2500 nm), the PV materials used for typical solar cells have broad absorption spectra [3]. Solar cell research continues, with a growing emphasis on developing cells that respond well over the largest variety of wavelengths [4]. It should be noted that most solar cells in the market today do not convert all wavelengths into electricity. One of the fundamental limitations of contemporary solar cells, according to Lin et al. [5], is a lack of absorbing material in the ultraviolet (UV) area. Even when the correct wavelengths are used, Narendra et al. [6] discovered that photovoltaic cells do not convert all of the light into electric charge. According to Semonin et al. [7], typical solar cells only extract a fixed quantity of energy from each sun photon. In a photovoltaic cell, for example, silicon atoms absorb energy from light wavelengths that nearly match the visible spectrum [6]. In actuality, monocrystalline and polycrystalline solar cells can only capture wavelengths in the visible range (550 nm). In PV systems, the failure of PV cells to properly absorb electromagnetic wavelengths generated by solar radiation results in severe power loss or energy conversion deficit. The process of gathering energy from ambient light sources and storing it in a consumable electrical energy form is referred to as light energy harvesting. Energy harvesting technology makes it possible to build autonomous, stand-alone, or self-powered electronic devices that do not rely on batteries for power. Lighting devices emit photons at various wavelength ranges, depending on the luminescent substance employed and the light generation process [8]. Different lamp types employed use different emission methods to produce their illumination, and the spectrum composition of the produced light differs between the lamp kinds [9] in order to bring more efficient lighting as well as to avoid environmental hazard issues [10]. When it comes to artificial lighting, Quantum Dot Light

Emitting Diodes (QLEDs) are the best. LEDs are more stable, providing a stable current supply and adequate temperature management, more cost-effective, and more energy efficient because they have higher conversion efficiency from electricity to light [11]. Furthermore, the consistent and significant rise in brightness, efficiency, and lifetime of QLEDs over the last several years has stimulated further optimization for prospective applications of self-emissive QLEDs in lighting, projection displays, transparent displays, outdoor digital signage, and car headlamps [12]. This development of new QLEDs with mechanical flexibility, lightweight, large-area emission uniformity, long-term stability, low thickness, solution-process compatibility, and low mass production costs results in uniformly large area luminarie and under favorable optical energy band gap, which encourages us to find more applications for it. Currently, not all PV cells absorb a wide variety of wavelengths. The wavelength of incident light influences photovoltaic selection [13]. Regardless of the type of light source utilized to provide illumination, the solar cell used as the power supply for energy harvesting devices should capture enough energy to run robustly when installed [10]. According to Gangasani, [14], common black silicon panels are best at absorbing visible light at peak times of the day, whereas QD solar cells can absorb power from the ultraviolet, visible, the infrared lighting range to produce their power, day and night. In essence, the quantum dot layer is the layer that absorbs sunlight and converts the photon's energy to electrical energy via the photovoltaic effect [15].

The conversion of light energy that does not come from sunshine into electricity is known as artificial light energy harvesting. Various approaches for harvesting artificial light, sunlight, and ambient (both outdoor and indoor) light have been used to increase the performance of PV cells in this regard. At the same time, various studies on artificial light energy harvest for PV systems have already been conducted, including Adi et al. [16], which studied artificial light energy harvesters using low start voltage solar cells; Manimegalai and Meenakshi [9], which presents the performance of solar cells under different electric lighting sources in indoor environments; Lucarelli et al. [17] investigated flexible perovskite solar cells for artificial light harvesting by using a white light-emitting diode (LED) lamp as a light source at 200 and 400 lx, values commonly found in indoor environments; Chirap et al. [18] presented a preliminary study on the possibility of using indoor light radiation as an energy source for autonomous sensor nodes. However, none of these research looked into the use of QLED harvesting for QDSC. In this regard, recent advances reveal that QDSCs can absorb wavelengths in the infrared, visible, and ultraviolet regions of the electromagnetic spectrum. Simultaneously, QLED emits electromagnetic wavelengths in the infrared, visible, and ultraviolet ranges (similar to natural sunlight), which is promising for artificial light energy harvesting for QDSC. As a result, among the QDs active materials used in QDSC and QLED, Lead Sulphide (PbS) and Lead Selenide (PbSe) have been identified as suitable, as they can produce wavelengths that cover the emission and absorption range between 350 - 2000 nm and are sufficiently sufficient as potential candidates for artificial light energy harvest for PV cells. Also, if QDSC is designed to harvest light from QLEDs, new methodologies for the development of artificial light energy harvesting would perform better. This is why we decided to conduct research on the Application of Quantum Dot Light Emitting Diodes (QLEDs) harvest for Quantum Dot Solar Cells (QDSCs), with the goal of improving artificial light energy harvest. To achieve high conversion efficiency, QLED is intended to emit wavelengths of light that are near in proximity and are all absorbed by QDSC. This will undoubtedly introduce a new method of harvesting artificial light. The pioneering work and benefits of both QDSC and QLED are briefly described below, and their distinctive features for artificial energy harvesting over conventional energy sources are shown. Finally, we identify and discuss potential QDs materials, as well as detail how QDSC will capture light energy from QLED in the near future.

2. Pioneering studies of QLED and QDSC

Lighting technologies are sunlight substitutes in the 425-675 nm spectral band, where sunlight is most concentrated, and the human eye has evolved to be the most sensitive [19]. Lighting history [20] can be understood as the evolution of increasingly efficient technologies for producing visible light within a spectral range while avoiding wasted light outside of that zone [19]. Over the last 150 years, the development of lighting solutions has been driven by a number of variables, including lower cost, higher brightness, longer lifetime, and more efficient devices that employ more environmentally sustainable materials [21]. In 1907, a British scientist called Henry Joseph Round reported light emission from a crystal detector, introducing the concept of a light-emitting diode [22, 23]. Oleg Vladimirovich Losev, a Russian researcher, presented a paper describing the first light-emitting diode [23-24], also known as Solid-State Lighting (SSL), in 1927. The first practical visible-spectrum (red) GaAsP LED was produced in 1962 by researcher Nick Holonyak Jr., dubbed "the father of the light-emitting diode," at General Electric Company in New York [25]. Since then, LED has substantially surpassed other lighting technologies and continues to do so. However, Mark Reed created the phrase quantum dot in 1988. Alexey Ekimov discovered it in a glass matrix in 1981, while Louis E. Brus discovered it in colloidal solutions [26, 14]. Louis Brus created a quantum model of spherical quantum dots based on the effective mass model [26] of QDs materials in 1985. QLEDs were created as a result of many enhancements, modifications, and applications of QDs materials. And were created for the first time in 1994 utilizing an Indium Tin Oxide (ITO) anode/QD polymer emission layer/metal cathode [27]. Since the first report on QLEDs in 1994, QLED performance has been significantly enhanced by the use of various QD materials. To date, QLEDs have been one of the most prominent optoelectronic devices made from various materials. In essence, the first experimental evidence of the photovoltaic effect was presented by French physicist E. Becquerel in the early nineteenth century [28]. However, until the 1950s, when US researchers devised a method of generating energy, cell efficiency remained at 1%. Several developments followed until QDSC was unveiled.

3. Features and benefits of QLEDs harvest for QDSC over conventional energy sources

Quantum dots are nanocrystals made of III-V semiconductor materials (for example, GaN, GaP, GaAs, InP, and InAs) and II-VI semiconductor materials (for example, ZnO, ZnS, CdS, CdSe, and CdTe) with all three dimensions in the 1-10 nm range [21]. They are also known as zero-dimensional nanocrystals because the electrons and holes therein are contained in all three dimensions, and their diameters typically range from 1 to 10 nm [29]. Basically, QDs materials have many features, of which a few are in Table 1. QLED is an LED that generates light by using QDs materials as emission materials. QLEDs are thought to be the next generation of light-emitting technology based on nanoparticles and have been shown to be particularly appropriate for a wide range of applications, including artificial lighting systems. Cost-effective QLEDs have the potential to be an excellent light source, meeting desirable form factors such as flexibility, lightweight, and uniform large-area illumination, yet with a restricted emission spectrum and high-power density wavelengths. The most essential aspects that led to the development of QLEDs were cost-effectiveness, substantially higher brightness, and efficiency, as well as more stable devices produced from environmentally sustainable materials. With that, here are some few features of QLEDs in Table 2.

Table 1. Characteristics of QD materials, explaining some of their importance over bulk materials

Characteristics of QDs	References
Are designed to absorb light in one wavelength range and re-emit in another	[30]
Absorption of UV photons in quantum dots produces more electrons than near-infrared photons	[31]
Their band gaps are tunable across a wide range of energy levels by changing the size of the dots	[32]
The properties of a quantum dot are determined by size, shape, composition, and structure	[33]
QD has the ability to tune the bandgap, making quantum dots desirable for solar cells	[14]
QD absorption edge is further driven to lower-wavelength regions	[34]
QD has the ability to confirm the chosen higher efficiency by assigning the appropriate values of quantum dot width size (QDW) and barrier thickness (BT)	[35]
A mixture of monocrystalline quantum dots optimized for different wavelengths	[14]
Are nearly perfect emitters with internal quantum efficiency (IQE) close to unity for all colors	[36]

QDSC is a PV cell that generates electricity by using QDs materials as the absorbing PV material. To successfully harvest incident solar energy photons and transform them into free charge carriers, photovoltaic material should have a greater absorption coefficient [51]. In essence, QDs have been used to form quantum dots solar cells (QDSCs) in photovoltaics for the following reasons: (1) tunable band gap depending on QD size, (2) large extinction coefficient, (3) stability toward water and oxygen, and (4) multiple exciton generation (MEG) with single-photon absorption [52-54]. According to Zhang et al. [55] and Tian and Cao [56], the principles for choosing materials to construct solar cells are as follows: 1) optical absorption is primarily determined by the band gap of active materials, and therefore, the materials with narrow and direct band gaps are preferred; and 2) the device structure should be designed by choosing materials with well-matched energy levels that may establish a suitable energy gradient, allowing the charges to transport highly efficiently within the solar cell. Moreover, other features of QDSCs are described in Table 3. To gain a better grasp of the applications, energy bandgap, and active material (QD) size in QDSC and QLED. In the following, we present a brief description of how to improve artificial light energy harvesting.

Table 2. Characteristics of QLEDs. These characteristics identify some advantages of QLEDs over conventional LEDs

Characteristics of QLEDs	References
Emit light by absorbing light due to the flow of electric current	[37]
Can easily achieve luminescence with different wavelengths	[38]
Controlled by the optical properties of the nanoparticles	[39]
It provide a constant photon output	[40-41]
It absorbs the emitted blue light and then transfers it to red and green to create the desired white color	[37]
Three primary colors (red, green, and blue) all possess high photoluminescence (PL) quantum yields (QYs) nearly or approaching 100%	[42]
Color-converted hybrid LED emitting at a longer wavelength can be developed	[43]
High luminance with low turn-on voltage and more suitable for industrialization	[44]
It is energy-saving and long-lasting compared to pre-existing light sources, such as incandescent light	[45]
Mechanically flexible, transparent, and lightweight properties	[46]
Capacity to be a light source spread over a larger area than a point light source	[47]
Low energy consumption, long lifetime, robustness, absence of a warm-up period, favorable controllability, and good color rendering	[48]
They produce high-intensity light emission and absorption due to the confinement induced by a high transition rate	[49]
Recombination of electrons and holes yields blue light, which corresponds to the energy bandgap of the semiconductor material	[50]

Table 3. Characteristics of QDSCs. These characteristics indicate some advantages of QDSC over conventional solar cells

Characteristics of QDSCs	References
Absorbing all wavelengths of visible sunlight plus the UV and Infrared	[32]
Mostly in the near-infrared region	[57]
Makes infrared energy as accessible as any other	[32, 58]
UV-visible absorbance spectra for the quantum dots have a long tail extending to the far end of the visible region	[57]
Emit up to three electrons per photon due to multiple exciton generation as opposed to only one for standard crystalline silicon solar cell	[31, 59]
Photon wavelengths ranging from ultraviolet to infrared, which make up the solar spectrum, can be absorbed with variations of dot sizes	[60-61]
It produces more than one bound electron-hole pair, or exaction, thereby doubling normal conversion efficiency numbers seen in single-junction silicon cells	[32]
Their absorption edge is further driven to lower-wavelength regions	[34]
Have high solar conversion efficiency	[62]

3.1 Applications of QDs materials in QDSC and QLED

QD, as the name suggests, is based on quantum theory, with each quantum dot acting like an atom with a well-defined energy level that can be individually controlled. QDs are materials with practical uses in semiconductor devices, quantum computers, medical devices, lighting, bio-imaging, solar cells, LEDs, displays, biosensors, optoelectronic devices, biomedical, instrumentation, display, biological and chemical, and others. Quantum dots (QDs) have many distinct optical properties, including high photoluminescence (PL), quantum yield (QY), high color purity, size-tunable emission wavelength, and solution-processed synthesis, making them promising materials for next-generation light-emitting diodes (LEDs) in display and lighting applications [41, 63-68]. QLEDs, on the other hand, may provide narrow emission spectrum and emission wavelength tunability simultaneously solely by QD synthesis, removing the need for extra techniques during device design [12]. In essence, the absorptivity of QD materials over a controllable large range of wavelengths makes them suited for QDSCs. In fact, QDs have been confirmed as the next-generation solar cell and lighting technologies.

3.2 Energy bandgap of QD materials in QDSC and QLED

The band gap is the area surrounding the active layers of QDs materials such as QDSC and QLED. It is a critical parameter in the conversion of photon energy to electric energy or electric energy to photons. The most noticeable effect of quantum QDs materials applications is the size dependency of the band gap. The intriguing electrical features of quantum dots result from their particular size [33]. The width of the quantum dot band gap varies with size and chemical composition, allowing for facile tuning of absorption and emission spectra, which is impossible with atoms but desirable for optical features [69]. This dimension dependence allows the bandgap energy to be modulated by altering the size of the QD [70-71]. The bandgap tunability with the QDs size variation is achieved via the quantum confinement effect [72]. In essence, quantum size effects, also known as quantum confinement effects, influence the electrical and optical properties of semiconductor QD nanoparticles. The quantum confinement effect is responsible for the ability to tune absorption and emission wavelengths across the whole visible spectrum as a function of quantum dot size [73]. Because electrons and holes in a bulk semiconductor are free to migrate and there is no confinement, they have continuous energy values, where energy levels are so close to each other and packed that energy bands develop [74]. With that, it is possible to tailor the absorption and luminescence bands from the IR to the visible area by reducing the crystal size to 1-20 nm [75 - 82]. By embedding low energy-gap wells or dots within a high energy-gap matrix, nanostructured solar cell architectures, in particular, strive to harness a broad range of photons at higher voltages [83]. This indicated that the shorter the band gap, the more photons are absorbed, and the more electrons are promoted into the conduction band and, therefore, available for current production [84]. As a result, the splitting of energy levels in both the valence and conduction bands corresponds to a substantial quantum confinement effect observed in tiny QDs [85]. However, excessively small QDs would result in too low optical absorption for the photo-electrodes, which will have a negative impact on the solar cells [56]. In an ideal world, quantum dot cells would be coupled with classic thin-film semiconductor cell designs or used in conjunction with a mixture of nanocrystalline quantum dots tuned for different wavelengths [13]. This feature makes quantum dots appealing for multi-junction solar cells [32, 86-87], which use a range of materials to boost efficiency by harvesting multiple sections of the sunlight spectrum. Therefore, one of the most important concerns in QDSC and QLED research is the size dependency of the band gap.

3.3 The Sizes of QD materials for QDSC and QLED

QD material is defined as material with a size of 0 - 9 nm. It is made of materials that vary in size. It has also become a key parameter in the development of QDSC and QLED. Large radii provide strong confinement to achieve extensive wavelength tunability. However, a narrower size distribution has the potential to improve QD solar cell efficiency in a variety of ways. Electron transport may be improved in smaller QDs because bigger QDs act as a band tail or shallow trap, making the transfer more difficult. Second, the open-circuit voltage (VOC) of QD solar cells near the contacts may be limited by the narrowest band gap (biggest size) QD [88]. As a result, larger QDs have more energy levels and are more closely spaced, allowing the QDs to absorb photons with less energy, whereas small QDs absorb photons with high energy. With that, we can say size-dependent band gaps of QDs materials can be used as tunable structures to absorb and emit light from ultraviolet to infrared wavelengths.

4. Suitable QDs materials for QLEDs harvested by QDSC

CdS, CdSe, PbS, PbSe, PbSSe, $CuInS_2$ $CuInSe_2$, and CdSSe nanocrystals QDs materials are all used as active materials for both QDSC and QLED. In this work, PbS and PbSe QD materials outperform the others due to their high emissivity or absorptivity throughout a wide range of wavelengths (ultraviolet, visible, and ultraviolet). Although the band structures of all lead chalcogenides (PbX), that is, lead selenide (PbSe), lead telluride (PbTe), and lead sulphide (PbS), are remarkably similar [89]. Lead-based chalcogenides (particularly PbS and PbSe) are among the most investigated for application in solar cells [90]. Another intriguing behavior reported for PbS and PbSe QDs is multiexciton formation, which is the generation of several excitons after the absorption of a single photon with energy hv 3 Eg [91-92]. However, the exciton peaks in quantum dots' absorption and emission spectra that give rise to their intriguing features for optoelectronic applications are not unique to PbS and PbSe QDs [93]. PbS nanoparticles, on the other hand, exhibit larger open-circuit voltages than PbSe but lower photocurrents in comparable cells [94]. To obtain improved performance with PbS and PbSe QDs, a better understanding of particle size management and energy bandgap is required. The bandgap widths could be reduced or expanded to a desired wavelength that could be absorbed by the QDSC spectrum in the ultraviolet, visible, and infrared regions, whereas conventional semiconductors could not. These two compounds have small bandgaps as bulk materials at room temperature (0.37 and 0.27 eV for PbS and PbSe, respectively) [90, 95]. As shown in Table 4, PbS and PbSe QDs materials have broad absorption and emission spectra that can provide the possibility for the excitation of different energies. However, due to the large Bohr exciton radius (20 nm for PbS and 34 nm for PbSe) [96], quantum size effects are already visible at larger crystal sizes (usually 1 - 20 nm) [97], allowing for bandgap engineering over a wide spectrum range [90]. Strong confinement can also add energy spacing even larger than the original bandgap of PbS or PbSe of around 0.2-0.4 eV, resulting in a wide resonance tunability by size ranging from

600 to 2000 nm, meeting the growing demand for near-infrared emitters and high conversion efficiency solar cells [93].

Table 4. The exciton parameters for various materials. The table identified PbSe and PbS as QDs materials having large exciton Bohr radius and narrowed energy bandgap when compared to the rest. These parameters make them suitable to be adopted for both QDSC and QLED active materials [72, 97]

Semiconductor Materials	Exciton Bohr radius (nm)	Bandgap at 300K (eV)
PbSe	46	0.28
Ge	24.3	0.67
PbS	20	0.42
GaAs	12.5	1.43
CdTe	7.5	1.6
CdSe	4.9	1.84
Si	4.3	1.14
ZnSe	3.8	2.8
CdS	2.8	2.58
GaN	2.1	3.5
CuBr	1.2	2.9

In this study, PbS and PbSe QD materials prioritize UV (100 - 400 nm), visible light (400 - 750 nm), and infrared (750 - 2500 nm) radiation emission and absorption by QLEDs and QDSCs, respectively. As demonstrated in Table 4, PbS and PbSe QDs have modest bandgaps of 0.42 and 0.28 eV, which are fewer than those of conventional semiconductors, which have bandgaps that are always greater than 1.0 eV. As a result, PbS and PbSe have exciton Bohr radius of 20 and 46 nm, respectively, confirming size-quantized transitions in the restricted region of the electromagnetic spectrum and exhibiting strong band-edge photoluminescence tunable from 100 to 2000 nm. Therefore, these properties of PbS and PbSe QDs in QLED and QDSC devices, would allow us control some of their important electric and optical properties, as discussed in the following.

4.1 Lead sulphide (PbS) QD material

Lead sulfide (PbS) has been the most studied and successfully used in photovoltaic applications [98], and has been studied in various research and industrial fields because it absorbs and emits infrared (IR) radiation in the near and shortwave IR wavelength ranges [99-101]. PbS QDs have these features, which make them excellent for light absorbers or IR emitters in solar cells, photodetectors, and infrared LEDs [102]. Because of its broad absorption spectrum (from near-infrared to IR), high peak-to-valley ratio (> 4), narrow band emission (FWHM 100 nm), and strong PLQY [102], earth-abundant lead sulfide (PbS) QDs are widely regarded as potential materials for QDSCs [103-110]. In addition, PbS has a high absorption coefficient of 1-5105 cm1 and a Bohr excitation radius of 18 nm [111-112]. Luther et al. [113] shown that PbS QD solar cells can withstand continuous light for more than 1000 hours. More notably, freshly constructed PbS solar cells demonstrate an amazing open circuit voltage (0.8 V) that exceeds that reported previously [103]. Surface passivation of QDs is also observed to have improved the open circuit voltage in a PbS QD-based cell with a 2.8% efficiency [114]. With an Eg in the near IR region of 0.41 eV [115-116], PbS is one of the most intensely investigated low-energy bandgap (Eg) semiconductors. Furthermore, due to their large Bohr radius (20 nm) and wide band gap (gap) tuning range (0.4 eV to 1.5 eV), prevalent investigations in QD solar cell (QDSC) materials. The emission wavelength of lead sulphide QDs can be controlled between 900 and 1600 nm depending on size, which lies in the infrared (IR) regime of the electromagnetic spectrum [92]. This allowed PbS QDs' band gap to be adjusted from infrared to visible spectrum [117]. PbS QDs may absorb light in the near infrared wavelengths, according to Zang et al. [118], with a band gap ranging from 1.77 to 0.69 eV. This corresponds to a range of absorption energies ranging from 0.71 to 1.28 eV [119 - 120]. As a result, single junction implementations based on lead sulfide (PbS) colloidal quantum dots (CQDs) feature bandgaps that can be adjusted into the far infrared, which is generally difficult to achieve [32]. This means that some of the energy available in the infrared and ultraviolet spectrums is not absorbed by ordinary solar cells.

4.2 Lead selenide (PbSe) QD material

Semiconductor PbSe quantum dots exhibit high infrared (IR) and near-IR absorption characteristics [121], are optically active, and are frequently employed as a suitable sensitizer in solar cells. [122 - 123]. PbSe QDs, with a bandgap of 0.26 eV and an absorption wavelength of 4770 nm [73], are probably the better choice for generating many excitions from a single absorbed photon and quick hot electron transport from active layer to counter electrode [125]. PbSe QDs materials are a viable candidate for QLED harvesting by QDSCs due to their size-tunable optical bandgaps, facile solution process abilities, low production cost, low operating temperature, excellent air stability, and appropriateness for the flexible substrate [73]. PbSe quantum dots absorb infrared light and can be used in both renewable energy systems and optical devices [121]. PbSe nanoparticles have found use in IR detectors due to their long wavelength [73]. However, by shrinking the crystal size to a few nanometers, the band gap can be brought within the visible region. A PbSe QD with a diameter of 5.7 nm has a band gap of 0.72 eV, leading to an absorption wavelength of 1720nm, as opposed to a bulk band gap of 0.26 eV [73]. PbSe QDs have a high quantum confinement energy of over 0.5 eV [122]. This substantial quantum confinement in PbSe QDs opens up new possibilities for electro-optical applications [67]. Simultaneously, a large degree of quantum confinement effect should improve charge carrier transit [123, 126]. Multiple carrier generation in PbSe nanocrystals has demonstrated that two or more excitons can be produced by a single photon with an energy larger than the bandgap [127-128]. In Schottky cells, it was also shown that employing smaller PbSe QDs with bigger bandgaps (Eg) results in a greater open-circuit voltage (V_{OC}) [129]. This translates to a band gap energy greater than 0.8eV [122], with exciton Bohr radii of 46 nm, which is far larger than in any other semiconductor. As a result of recent improvements in the study of PbSe and PbS QDs, we anticipate big breakthroughs in the development of QDSCs and QLEDs in the near future of light energy harvesting.

5. Description of QDSC harvesting QLED

QDs allow for the emission and absorption of light at particular wavelengths. Simultaneously, QDSC and QLED can absorb and emit wavelengths spanning from ultraviolet to infrared. To collect acceptable wavelengths using QDSC, suitable emitted wavelengths from QLED are required. This enables us to create a controllable system for harvesting artificial light energy with a high conversion efficiency.

A common QLED structure is made up of a sandwich-like panel of indium tin oxide (ITO) and a metal electrode with a hole transport layer (HTL)/QD/electron transport layer (ETL) [130]. Under forward bias circumstances, ITO anode holes and metal cathode electrons are pumped into the HTL and ETL, respectively [130]. The HTL and ETL holes and electrons are subsequently transported to the QD emission layer to create excitons. Finally, photons emit light via the radiative recombination of excitons [130-131]. Figure 1 depicts the structure QLED and QDSC, which is made up of individual layers from top to bottom. The layers of QLED include an anode, which collects and conducts external (electric) energy to a hole injection layer (HIL); HIL, which injects holes to a hole transport layer (HTL); and HTL, which transports holes to QD material. In this layer, QD collides with holes to generate excitons, a process known as electron-hole recombination. When holes excite a QD material, a transition from the ground to an excited state occurs. Electrons have a lot of energy when they are energized. The exciton is subsequently relaxed to its ground state. Light energy is emitted here when excess energy is produced as a result of recombination and relaxation. The energy from the emitted light (photon) is subsequently transmitted through the electron transport layer (ETL) through the transparent cathode and lastly, through the glass layer. The light emitted by QLED is directed directly to the QDSC. Photons absorbed by QDSC must travel through the glass layer, anode, and HTL to reach the active QD material. Photons collide with QD material in this layer to generate energy. This causes the formation of an electron-hole pair in the form of an exciton between the conduction and valence bands. When electrons quickly move into the conduction band to form electric fields, they are captured by ETL and transported to the metal cathode and finally to the external circuit. The electric charge (electron) generated by QDSC is subsequently removed as energy gain, with a portion of it feeding QLED via its external input.

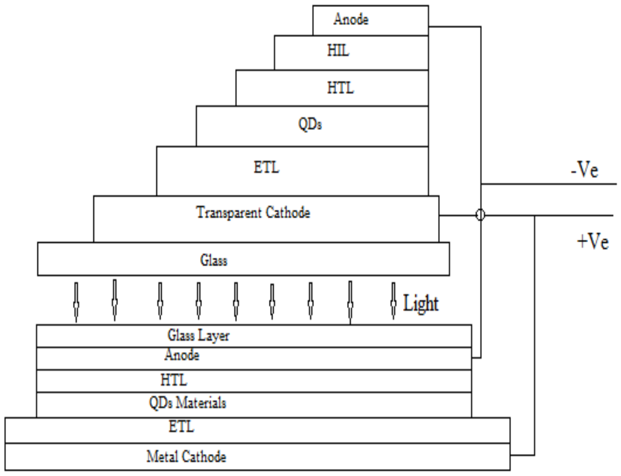

Figure 1. Schematic diagram of the QDSC harvesting QLED. From top to bottom, a typical QLED device gets excited by external energy passing through an anode, a hole injection layer (HIL), a hole transport layer (HTL), QD material, an electron transport layer (ETL), transparent cathode and a glass to irradiate QDSC. QDSC then gets excited by light from QLED that passes through a glass layer, anode, HTL, QD material, ETL, and metal cathode to produce electricity. The electric energy produced is then use to feed QLED by harvesting part of it as energy gain from the system

A QDSC's principal function in this system is to harvest QLED light energy and convert it to electrical energy. The quantity of energy absorbed by QDSC is determined by artificial light-harvesting techniques such as light power density, spectrum response, spectral power distribution, energy bandgap, absorptivity and emissivity, intensity, and size of active materials (QD) in both QDSC and QLED. Following that, various methodologies are employed to acquire a better knowledge of how PV cells work. The most crucial is current-voltage (I-V) characterization, also known as current density versus voltage (I-V). The I-V model is based on four (4) factors, which are commonly referred to as short circuit current density (JSC), open circuit voltage (VOC), fill factor (FF), and efficiency (η).

6. Limitations and recommendations of the study

Glass, anode, cathode, ETL, and HTL are all layers in both QLED and QDSC. In both QLED and QDSC, these layers are crucial for charge stability, injection, separation and recombination, and the transit of holes and electrons. Furthermore, freeform, collimator, luminescent solar concentrator, wavelength shifter, color filters, and luminescent down-shifting (LDS) are proposed to sandwich between QLED and QDSC to achieve high conversion efficiencies, limit energy losses, and harvest a desired energy outcome. Unfortunately, this study did not present full understanding of these parameters but gave hints of the importance of sandwiching the materials in between QDSC and QLED as follows.

6.1 QLED freeform lenses

The freeform lens is recommended for sandwiching on QLED to re-direct the light beam onto the QDSC. It is intended to provide uniform illumination with more than 90% of the light energy in the chosen beam pattern [132]. The use of free-form optics in the design of secondary optical components for LEDs is a recent trend [133]. The benefits of free-form optics are their distinct design, small size, and accurate irradiation control [133-134]. The use of wavelength conversion materials such as yttrium aluminum garnet (YAG) phosphor on top of a blue or UV LED is regarded as the best way to obtain the necessary light [135].

6.2 QLED collimator

The collimator is an optical element that redirects and deflects photons from the QLED source to parallel rays on QDSC. In this study, the collimator's role is to improve incident optical power per unit area with respect to geometrical parameters for a specific design; improve system stability to a precise design parameter and fabrication errors; reduce irradiance scattering between the medium of QLED and the QDSC; maximize the field size of irradiance into the desired size of QDSC; and eliminate irradiance outside the QDSC region.

6.3 Clustering of multiple QLED

Clustering Multiple QLEDs is the process of grouping QLEDs in order to illuminate a specific size of QDSC. It is crucial in determining the wavelength dimensions. Because of the tiny size and limited light output of individual QLED components, several QLED configurations may be required to illuminate large light arrays. The spectrum properties of various light sources can be adjusted to meet varied purposes by varying their light output [135].

6.4 Luminescent solar concentrator (LSC)

A luminous solar concentrator (LSC) is a device that traps solar radiation across a vast area before channeling the energy (through luminescent emission) to cells positioned on the material layer's thin edges [32]. LSCs combined with QDSCs boost the performance of light energy harvesting even further.

6.5 Wavelength shifters

Materials that shift the wavelength of light are known as wavelength shifters. It generates more, fewer, or equal wavelengths ideal for QDSC harvesting. Sandwiching a wavelength shifter between QDSC and QLED would aid in controlling the system and producing an efficient method of harvesting artificial light energy.

6.6 Position of QLED towards QDSC

The intensity of QLED varies with distance from QDSC. However, the effect may be minimal. However, as light travels further, it is absorbed, scattered, and even reflected by particles in the air or by the air itself. As a result, light is more effective at close range. To accomplish optimal light energy conversion, the distance between QDSC and QLED must be considered.

6.7 Color filters

A color filter is a media that permits color light to flow through. It filters certain hues by absorbing undesirable colors while allowing necessary ones to pass through. All hues of light can be produced with QLED. At the same time, QDSC can be configured to absorb all QLED hues. As a result, different color filters result in distinct spectral energy distributions. Light conversion to electricity can be improved by embedding a color filter at a specific distance between parallel QDSC and QLED. Hussein and Miqdam [136] investigated the impact of applying solar-colored filters to cover the PV panel in its outcomes, using seven different colored filters, and discovered that the wavelength/color produces the best PV panel outcome and the best power conversion.

6.8 Luminescent downshifting (LDS)

Luminescent downshifting (LDS) is an optical technique for increasing the spectral sensitivity of a solar cell by employing luminescent materials to convert high-energy photons to lower energy before they interact with the solar cells [137-144]. UV photons can be counted as effective as other longer wavelength photons if the down-converted photons are properly gathered by the host material beneath [87].

7. Conclusions

QLEDs have been identified as a light source capable of emitting desired wavelengths ranging from ultraviolet to infrared. Simultaneously, the QDSC may be adjusted to absorb wavelengths spanning from ultraviolet to infrared. This paper reviews the use of QLED and QDSC in the realm of artificial light energy harvesting for QDs PV cells. Both QDSC and QLED have satisfactory properties that are suitable in the field of light energy harvesting. The study also discovered that PbSe and PbS are among the most suitable QD materials examined to date. Although the application of QLED and QDSC in artificial light energy harvest can be extended to ambient light energy harvest and solar simulator, when new devices are developed, further applications will span a wide range of stand-alone energy systems.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] N. L. Panwar, S. C. Kaushik, S. Kothari, "Role of renewable energy sources in environmental protection: A review," Renew. Sustain. Energy Rev., 153, 1513–1524, 2011.

[2] Global Climate & Energy Project, (GCEP), "An Assessment of Solar Energy Conversion Technologies and Research Opportunities GCEP Energy Assessment," Analysis Summer 2006 Global Climate & Energy Project, Stanford University, Technical Assessment Report, 2006.

[3] S. Biswas, and H. Kim, "Solar Cells for Indoor Applications: Progress and Development", Polymers, 12, 1338, 2020. doi:10.3390/polym12061338

[4] P. Rawat, Performance Analysis of 300W Solar Photovoltaic Module under Varying Wavelength of Solar Radiation, International Journal for Research in Applied Science & Engineering Technology (IJRASET), 5(XI), 2478-2482, 2017. www.ijraset.com

[5] C-C. Lin, H-C. Chen, Y. L. Tsai, H-V. Han, H-S. Shih, Y-A. Chang, H-C Kuo, and P. Yu, "Highly efficient CdS-quantum-dot-sensitized GaAs solar cells," OPTICS EXPRESS A325, 20(S2), 2012.

[6] M. K. Narendra, H. S. Saini, K. S. R. Anjneyulu, and S. Kuldip, "Solar Power Analysis Based On Light Intensity", International Conference on Innovations in Electrical & Electronics Engineering (ICIEEE-2014), The International Journal of Engineering and Science (IJES), 2319 – 1805, 2014.

[7] E. O. Semonin, M. J. Luther, and M. C. Beard, "Quantum dots for nextgeneration photovoltaics", Review, 15(11), 508-515, 2012.

[8] T. H. Kim, W. Wang, and Q. Li, "Advancement in materials for energy-saving lighting devices, Frontiers of Chemical Science and Engineering, 6(1), 13-26, 2012. https://doi.org/10.1007/s11705-011-1168-y

[9] D. Manimegalai, and S. Meenakshi, "Energy Harvesting from Solar Cells Under Electric Lighting Sources in Indoors", ARPN Journal of Engineering and Applied Sciences, 11(19), 11395-11402, 2016. www.arpnjournals.com.

[10] N. Khan, and N. Abas, "Comparative study of energy saving light sources", Renewable & Sustainable Energy Reviews, 15(1), 296–309, 2011.

[11] F. Plyta, F. "Optical design of a fully LED-based solar simulator", Doctoral Thesis, Submitted in the partial fulfilment of the requirements for the reward of Doctor of Philosophy of Loughborough University, 2015.

[12] M. A. Triana, A. A. Restrepo, R. J. Lanzafame, P. Palomaki, and Y. Dong, "Quantum dot light-emitting diodes as light sources in photomedicine: photodynamic therapy and photobiomodulation", Journal of Physics: Materials, 3, 032002, 2020. https://doi.org/10.1088/2515-7639/ab95e8

[13] H. Jabbar, and T. Jeong, Ambient Light Energy Harvesting and Numerical Modeling of Non-Linear Phenomena. Appl. Sci., 12, 2068, 2022. https://doi.org/10.3390/app12042068

[14] S. Gangasani, "A Study on Quantum Dot and its Applications", International Journal of Innovative Research in Science, Engineering and Technology, 5(5), 8128- 8133, 2016. DOI:10.15680/IJIRSET.2016.0505119

[15] H. Zhang, S. Chen, and X. W. Sun, "Efficient red/green/blue tandem quantum-dot light-emitting diodes with external quantum efficiency exceeding 21%", ACS Nano. 12, 697–704, 2018.

[16] H. S. Adi, R. A. Priramadhi, and D. Darlis, D. "Artificial Light Energy Harvester Using Low Start Voltage Solar Cell", 3rd Annual Applied Science and Engineering Conference (AASEC 2018), IOP Conf. Series: Materials Science and Engineering, 434, 012212, 2018. https//doi.org/1088/1757-899X/434/1/012212

[17] G. Lucarelli, F. Di Giacomo, V. Zardetto, M. Creatore, and T. M. Brown, "Efficient light harvesting from flexible perovskite solar cells under indoor white light-emitting diode illumination", Nano Research, 10(6), 2130-2145, 2017. https://doi.org/10.1007/s12274-016-1402-5

[18] A. Chirap, V. Popa, E. Coca, and A. D. Potorac, "A study on light energy harvesting from indoor environment: The autonomous sensor nodes", 12th International Conference on Development and Application Systems, Suceava, Romania, May 15-17, 2014.

[19] J. Y. Tsao, "Light Emitting Diodes (LEDs) for General Illumination", Optoelectronics Industry Development Association, 1133 Connecticut Avenue, NW, Suite 600 Washington, DC 20036, 2002.

[20] B. Bowers, "Lengthening the Day: A History of Lighting Technology", (Oxford University Press, Oxford, 1998.

[21] P. Kathirgamanathan, M. L. Bushby, M. Kumaraverl, S. Ravichandran, and S. Surendrakumar, "Electroluminescent Organic and Quantum Dot LEDs: The State of the Art", Journal of Display Technology, 11(5), 480-493, 2015.

[22] Wac Lighting, "Responsible Lighting. LED/OLED: Technical Training and Applications", [Internet]. Available from: http://iie.ciapr.org/actividades/seminarios/2009/Presentacion LED-OLED.pdf, 2013.

[23] H. J. Round "A note on carborundum", Electrical World, 19:309-310, 1907.

[24] O. V. Losev "Luminous carborundum (silicon carbide) detector and detection with crystals", Telegrafiya i Telefoniya bez Provodov., 44, 485-494, 1927.

[25] N. Jr. Holonyak, "Bevaqua SF. Coherent (visible) light emission from Ga(As1-xPx) junctions", Applied Physics Letters, 1(4), 82-83, 1962. DOI: 10.1063/1.1753706

[26] L. E. Brus "Electronic wave functions in semiconductor clusters: experiment and theory", J. Phys. Chem., 90, 2555-2560, 1986.

[27] C. Cheng, X. Sun, Z. Yao, C. Bi, X Wei, J. Wang, and J. Tian, J. "Balancing charge injection in quantum dot light-emitting diodes to achieve high efficienciy of over 21%", Sci China Mater, 65(7), 1882–1889, 2022. https://doi.org/10.1007/s40843-021-1976-9

[28] W. Cao, C. Xiang, Y. Yang, Q. Chen, L. Chen, X. Yan, and L. Qian, "Highly stable QLEDs with improved hole injection via quantum dot structure tailoring," Nat. Commun. 9(1), 2608, 2018.

[29] A. Mousa, "Syndissertation and Characterization of PbS Quantum Dots, Submitted to the Department of Chemical Physics", A thesis in Partial fulfillment of the Requirements for the Degree of Master of Science in Chemistry, Lund University, 2011.

[30] N. Heydari, S. M. B. Ghorashi, W. Han, and H. Park, "Quantum Dot-Based Light Emitting Diodes (QDLEDs)", Intech, 2017. Available at: http://www.intechopen.com/books/quantum-dot-based-lightemitting-diode

[31] A. Thabet, S. Abdelhady, and Y. Mobarak, "Design modern structure for heterojunction quantum dot solar cells", International Journal of Electrical and Computer Engineering (IJECE), 10(3), 2918-2925, 2020. https://doi.org/10.11591/ijece.v10i3.pp2918-2925

[32] A. M. Bagher, "Solar Cell Quantum Dots", American Journal of Renewable and Sustainable Energy, 2(1) 1-5, 2016. Available at: http://www.aiscience.org/journal/ajrse

[33] A. Chilton, "The Properties and Applications of Quantum Dots", Azo Quantum. AZoQuantum.com, 2014.

[34] P. V. Kamat, "Quantum Dot Solar Cells. The Next Big Thing in Photovoltaics", J. Phys. Chem. Lett., 4, 908–918, 2013. https://doi.org/10.1021/jz400052e

[35] E. Abou, and M. M. Aly, "Investigation of Some Parameters Which Affects into The Efficiency of Quantum Dot Intermediate Band Solar Cell", INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH, 4(4), 1085-1093, 2014.

[36] R. Ma, Cd-Free Quantum Dots for Lighting and Displays", Nonosys., 2020.

[37] M. A. Bagher, Quantum Dot Display Technology and Comparison with OLED Display Technology", International Journal of Advanced Research in Physical Science (IJARPS), 4(1), 48-53, 2017. Available at: www.arcjournals.org

[38] X. T. Fan, T. Z. Wu, B. Liu, R. Zhang, and H. C. Kuo, "Recent developments of quantum dot based micro-LED based on non-radiative energy transfer mechanism", Opto-Electron Adv, 4(4), 210022, 2021. https://doi.org/10.29026/oea.2021.210022

[39] G. Zaiats, S. Ikeda, and P. V. Kamat, "Optimization of the electron transport layer in quantum dot light-emitting devices", NPG Asia Materials, 12:57, 2020. https://doi.org/10.1038/s41427-020-00237-0

[40] Y. Shirasaki, G. J. Supran, M. G. Bawendi, and V. Bulovic, "Emergence of colloidal quantum-dot light-emitting technologies", Nat. Photonics, 7(1), 13–23, 2013.

[41] G. Ba, Q. Xu, X. Li, Q. Lin, H. Shen, and Z. Du, Z. "Quantum dot light-emitting diodes with high efficiency at high brightness via shell engineering", Optics Express, 29(8/12), 12169-12178, 2021.

[42] Z. Liu, F. Li, G. Huang, J. Wei, G. Jiang, and Y. Huang, "Enhance the Light Extraction Efficiency of QLED with Surface Micro-Nanostructure", Journal of Nanomaterials, 8858996, 2020. https://doi.org/10.1155/2020/8858996

[43] Y-M. Huang, K. J. Singh, A. C. Liu, C-C. Lin, Z. Chen, K. Wang, Y. Lin, Z. Liu, T. Wu, and H-C. Kuo, "Advances in Quantum-Dot-Based Displays", Nanomaterials, 10, 1327, 2020. https://doi.org/10.3390/nano10071327

[44] N. Tu, "Quantum Dot Light-Emitting Diode: Structure, Mechanism, and Preparation, Quantum Dots", Fundamental and Application, 2020.

[45] H. S. Lee, L. Cui, Y. Li, J. S. Choi, J-H. Choi, Z. Li, Z., "Influence of Light Emitting Diode-Derived Blue Light Overexposure on Mouse Ocular Surface", PLoS ONE 11(8): e0161041, 2016. https://doi.org/10.1371/journal.pone.0161041

[46] L. Paterson, F. May, and D. Andrienko, "Computer aided design of stable and efficient OLEDs", Journal of Applied Physics, 128, 160901, 2020. https://doi.org/10.1063/5.0022870.

[47] A. Armăşelu, "Recent Developments in Applications of Quantum-Dot Based Light-Emitting Diodes", Quantum-dot Based Light-emitting Diodes, Morteza Sasani Ghamsari, IntechOpen, 2017. https://doi.org/10.5772/intechopen.69177

[48] C. Hao, and P. Si-Hyun, "Numerical Simulations of the Light-Extraction Efficiency of LEDs on Sapphire Substrates Patterned with Various Polygonal Pyramids", Journal of Optical Society of Korea, 18(6), 774-776, 2014.

[49] X-J Shang, "Study of quantum dots on solar energy applications," A Doctoral Thesis in Theoretical Chemistry and Biology, School of Biotechnology, Royal Institute of Technology Stockholm, Sweden, 2012.

[50] K. V. M. Murali, V. B. Naik, and D. Datta, "Gallium-nitride-based light-emitting diodes", Resonance, 20(7), 605–616, 2015.

[51] F. Saeed, M. H. Khan, A. H. Tauqeer, A. Haroon, A. Idrees, S. M.Shehrazi, L. Prokop, V. Blazek, S. Misak, and N. Ullah, "Numerical Investigation of Photo-Generated Carrier Recombination Dynamics on the Device Characteristics for the Perovskite/Carbon Nitride Absorber-Layer Solar Cell", Nanomaterials, 12, 4012, 2022. https://doi.org/10.3390/nano12224012.

[52] J. H. Bang, and P. V. Kamat, "Solar Cells by Design: Photoelectrochemistry of TiO2 Nanorod Arrays Decorated with CdSe", Adv. Funct. Mater. 20, 1970–1976, 2010.

[53] V. Gonzalez-Pedro, X. Xu, I. Mora-Sero, and J. Bisquert, "Modeling High-Efficiency Quantum Dot Sensitized Solar Cells", Acs Nano 4, 5783–5790, 2010.

[54] X-Y., Yu, J-Y. Liao K.-Q. Qiu, D.-B. Kuang, and C-Y. Su, "Dynamic Study of Highly Efficient CdS/CdSe Quantum Dot-Sensitized Solar Cells Fabricated by Electrodeposition", Acs Nano 5, 9494–9500, 2011.

[55] G. Zhang, "Optical Property Optimisation of Lead Sulphide Quantum Dots", A Dissertation Submitted for the Degree of Master of Engineering Science, School of Chemical Engineering, The University of Adelaide, Adelaide, Australia, 2013.

[56] J. Tian, and G. Cao, "Semiconductor quantum dot-sensitized solar cells", Nano Reviews, 4(1), 22578, 2013. https://doi.org/10.3402/nano.v4i0.22578

[57] A. A. Ganesan, A. J. Houtepen and R. W. Crisp, "Quantum Dot Solar Cells: Small Beginnings Have Large Impacts, Appl. Sci., 8, 1867, 2018. doi:10.3390/app8101867

[58] W. Amanda, and H. Penny, "Quantum Dots: The Future of Highly-Efficient Solar Cells", 2014.

[59] K. J. Ebrahim, "Quantum Dots Solar Cells", InTech Solar Cells New Approaches and Reviews, 31, 303-331, 2015.

[60] V. A. Singh, and G. C. John, Physics of semiconductor nanostructures (K.P. Jain)", Marosa Publishing House, New Delhi, 186, 1997.

[61] H. I. Ikeri, A. I. Onyia, and P. U. Asogwa, "Investigation of Optical Characteristics of Semiconductor Quantum Dots for Multi Junction Solar Cells Applications", International Journal of Scientific & Technology Research, 8(10), 3531-3535, 2019. www.ijstr.org

[62] A. E. Aouami, L. M. Pérez, K. Feddi, M. El-Yadri, F. Dujardin, M. J. Suazo, D. Laroze, M. Courel, and E. M. Feddi, E. M. "Influence of Geometrical Shape on the Characteristics of the Multiple InN/InxGa1−xN Quantum Dot Solar Cells", Nanomaterials, 11, 1317, 2021. https://doi.org/10.3390/nano11051317

[63] V. L. Colvin, M. C. Schlamp, and A. P. Alivisatos, "Light-emitting diodes made from cadmium selenide nanocrystals and a semiconducting polymer," Nature 370(6488), 354–357, 1994.

[64] S. Coe, W. K. Woo, M. Bawendi, and V. Bulovic, "Electroluminescence from single monolayers of nanocrystals in molecular organic devices," Nature 420(6917), 800–803, 2002.

[65] W. K. Bae, J. Lim, D. Lee, M. Park, H. Lee, J. Kwak, K. Char, C. Lee, and S. Lee, "R/G/B/natural white light thin colloidal quantum dot-based light-emitting devices," Adv. Mater. 26(37), 6387–6393, 2014.

[66] Q. Huang, J. Pan, Y. Zhang, J. Chen, and W. Lei, "High-performance quantum dot light-emitting diodes with hybrid hole transport layer via doping engineering," Opt. Express 24(23), 25955–25963, 2016.

[67] T. Zhang, H. Tang, S. Zhou, S. Ding, X. Xiao, Z. Wen, G. Niu, X. Luo, F. Wang, X. W. Sun, G. Xing, and K. Wang, "Factors influencing the working temperature of quantum dot light-emitting diodes," Opt. Express 28(23), 34167–34179, 2020.

[68] X. Li, Y. B. Zhao, F. Fan, L. Levina, M. Liu, R. Quintero-Bermudez, X. Gong, L. N. Quan, J. Fan, Z. Yang, S. Hoogland, O. Voznyy, Z. H. Lu, and E. H. Sargent, "Bright colloidal quantum dot light-emitting diodes enabled by efficient chlorination," Nat. Photonics 12(3), 159–164, 2018.

[69] C. Wang, M. Shim, and P. Guyot-Sionnest, “Electrochromic Nanocrystal Quantum Dots,” Science, 291, 5512, 2390-2392, 2001.

[70] J. Melville, "Optical properties of quantum dots [final paper]. UC Berkeley College of Chemistry, 2015. Available from: https://www.ocf.berkeley.edu/~jmlvll/lab-reports/quantumDots/quantumDots.pdf

[71] W. J. Parak, L. Manna, C. H. Rimmel, D. Gerion, and P. Alivisatos, "Quantum dots. In: Schmid G, editor. Nanoparticles—From Theory to Application", Weinheim, John Wiley and Sons, 2004.

[72] S. Yin, S. "Achieving High-Performance Infrared Range (IR) Photodiode via Bilayer Lead Sulfide Quantum Dots (QDs) Structure", A dissertation submitted to the Graduate Faculty of North Carolina State University, in partial fulfillment of the requirements for the degree of Master of Science, Materials Science and Engineering, Raleigh, North Carolina, 2018.

[73] G. S. Dedigamuwa, "Fabrication and Characterization of Surfactant-Free PbSe Quantum Dot Films and PbSe Polymer Hybrid Structures", A dissertation submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy, Department of Physics, College of Arts and Sciences, University of South Florida, 2010.

[74] K. E. Jasim, Solar Cells - New Approaches and Reviews", IntechOpen, 2015. http://dx.doi.org/10.5772/59159

[75] Q. Yin, W. Zhang, Y. Zhou, R. Wang, Z. Zhao, and C. Liu, "High efficiency luminescence from PbS quantum dots embedded glasses for near-infrared light emitting diodes", Journal of Luminescence 250, 119065, 2022. https://doi.org/10.1016/j.jlumin.2022.119065

[76] J. H. Warner, E. Thomsen, A. R. Watt, N. R. Heckenberg, and H. R. Dunlop, "Time-resolved photoluminescence spectroscopy of ligandcapped PbS nanocrystals", Nanotechnology 16(2), 175–179, 2004. https://doi.org/10.1088/0957-4484/16/2/001

[77] N. Torres-Gomez, D. F. Garcia-Gutierrez, A. R. Lara-Canche, L. TrianaCruz, J. A. Arizpe-Zapata, and D. I. Garcia-Gutierrez, D "Absorption and emission in the visible range by ultra-small PbS quantum dots in the strong quantum confinement regime with s-terminated surfaces capped with diphenylphosphine", Journal of Alloys and Compounds 860, 158443, 2021. https://doi.org/10.1016/j.jallcom.2020.158443

[78] D. Kim, T. Kuwabara, and M. Nakayama, "Photoluminescence properties related to localized states in colloidal PbS quantum dots", Journal of Luminescence, 119-120, 214–218, 2006. https://doi.org/10.1016/j.jlumin.2005.12.033.

[79] J. Tian, and G. Cao, "Semiconductor quantum dot-sensitized solar cells", Nano Reviews, 4(1), 22578, 2013. https://doi.org/10.3402/nano.v4i0.22578

[80] R. H. Gilmore, Y. Liu, W. Shcherbakov-Wu, N. S. Dahod, E. M. F. Lee, M. C. Weidman, H. Li, J. Jean, V. Bulovi´c, A. P. Willard, J. C. Grossman, and W. A. Tisdale, "Epitaxial dimers and auger-assisted detrapping in PbS quantum dot solids", Matter, 1(1), 250–265, 2019. https://doi.org/10.1016/j.matt.2019.05.015

[81] S. Nakashima, A. Hoshino, J. Cai, and K. Mukai, "Thiol-stabilized PbS quantum dots with stable luminescence in the infrared spectral range", Journal of Crystal Growth, 378, 542–545, 2013. https://doi.org/10.1016/j.jcrysgro.2012.11.024

[82] P. A. Loiko, G. E. Rachkovskaya, G. B Zacharevich, and K. V. Yumashev, "Wavelength-tunable absorption and luminescence of SiO2/al2o3/ZnO/na2o/k2o/NaF glasses with PbS quantum dots", Journal of Luminescence, 143, 418–422, 2013. https://doi.org/10.1016/j.jlumin.2013.05.057

[83] E. Kolobkova, Z. Lipatova, A. Abdrshin, N. and N. Nikonorov, "Luminescent properties of fluorine phosphate glasses doped with PbSe and PbS quantum dots", Optical Materials, 65, 124–128, 2017. https://doi.org/10.1016/j.optmat.2016.09.033

[84] E. R. Welser, K. S. Ashok J. S. Lewis, N. K. Dhar, P. Wijewarnasuriya, and R. L. Peters, "Development of III-V Quantum Well and Quantum Dot Solar Cells", International Journal of Engineering Research and Technology, 9(1), 29-44, 2016.

[85] W. A. A. Mohamed, H. Abd El-Gawad, S. Mekkey, H. Galal, H. Handal, H. Mousa, and A. Labib, "Quantum dots synthetization and future prospect applications", Nanotechnology Reviews, 10, 1926–1940, 2021. https://doi.org/10.1515/ntrev-2021-0118

[86] H. Alexander H., et al. "Hybrid passivated colloidal quantum dot solids", Nature nanotechnology, 7(9), 577-582, 2013.

[87] B. Sotirios, and A. F. Terzis. "Size-dependent band gap of colloidal quantum dots", Journal of applied physics, 99(1), 013708, 2006.

[88] J. Pastuszak, and P. W˛egierek, "Photovoltaic Cell Generations and Current Research Directions for Their Development", Materials, 15, 5542, 2022. https://doi.org/10.3390/ma15165542

[89] S. H. Wei, and A. Zunger, "Electronic and structural anomalies in lead chalcogenides", Physical Review, B 55(20), 13605–13610, 1997.

[90] T. Sloboda, S. Svanstro¨m, F. O. L. Johansson, E. Bryngelsson, A. Garcı´a-Ferna´ndez, A. Lindblad, and U. B. Cappe, "The impact of chemical composition of halide surface ligands on the electronic structure and stability of lead sulfide quantum dot materials. Phys. Chem. Chem. Phys., 24, 12645–12657, 2022. DOI: 10.1039/d2cp01050j

[91] M. B. Ji, S. Park, S. T. Connor, T. Mokari, Y. Cui, and K. J. Gaffney, "Efficient Multiple Exciton Generation Observed in Colloidal PbSe Quantum Dots with Temporally and Spectrally Resolved Intraband Excitation", Nano Letters 9(3), 1217–1222, 2009.

[92] R. J. Ellingson, M. C. Beard, J. C. Johnson, P. R. Yu, O. I. Micic, A. J. Nozik, A. Shabaev, and A. L. Efros, "Highly efficient multiple exciton generation in colloidal PbSe and PbS quantum dots", Nano Lett., 5, 865–871, 2005

[93] Y. Lin, "Study of Colloidal Lead Sulfide Quantum Dot Light-Emitting-Diodes with Inorganic Charge Injection Layers and Ligand Exchanges", A Thesis Presented to the Faculty of the Graduate School of Cornell University in Partial Fulfillment of the Requirements for the Degree of Master of Science, 2014.

[94] K. W. Johnston, A. G. Pattantyus-Abraham, J. P. Clifford, S. H. Myrskog, D. D. Macneil, L. Levina, and E. H. Sargent, "Schottky-Quantum Dot Photovoltaics for Efficient Infrared Power Conversion, Appl. Phys. Lett., 92, 151115, 2008.
[95] S. V. Kershaw, A. S. Susha and A. L. Rogach, "Narrow bandgap colloidal metal chalcogenide quantum dots: Synthetic methods, heterostructures, assemblies, electronic and infrared optical properties", Chem. Soc. Rev., 42, 3033–3087, 2013.
[96] F. W. Wise, "Lead salt quantum dots: The limit of strongquantum confinement", Acc. Chem. Res., 33, 773–780, 2000.
[97] D. V. Talapin, J. S. Lee M. V. Kovalenko, and E. V. Shevchenko, "Prospects of colloidal nanocrystals for electronic and optoelectronic applications", Chemical Reviews, 110(1), 389–458, 2010.
[98] M. Albaladejo-Siguan, E. C. Baird, D. Becker-Koch, Y. Li, A. L. Rogach, and Y. Vaynzof, "Stability of Quantum Dot Solar Cells: A Matter of (Life) Time", Adv. Energy Mater., 11, 2003457, 1-25, 2021.
[99] A. De Iacovo, C. Venettacci, L. Colace, L. Scopa, L. and S. Foglia, "PbS Colloidal Quantum Dot Photodetectors operating in the near infrared", Sci. Rep., 6, 37913, 2016.
[100] S. A. McDonald, G. Konstantatos, S. Zhang, P. W. Cyr, E. J. Klem, L. Levina, and E. H. Sargent, "Solution-processed PbS quantum dot infrared photodetectors and photovoltaics", Nat. Mater., 4, 138, 2005.
[101] E. H. Sargent, " Infrared quantum dots", Adv. Mater., 17, 515–522, 2005.
[102] S. K. Pandey, "Optoelectronic Applications of Quantum Dots", International Journal of Research in Science and Engineering, 6(2), 10-18, 2018.
[103] B. Hou, Y. Cho, B-S. Kim, D. Ahn, S. Lee, J. B. Park, Y-W. Lee, J. Hong, H. Im, S. Morris, J. I. Sohn, S. N. Cha, and J. M. Kim, "Red green blue emissive lead sulfide quantum dots: heterogeneous synthesis and applications", J. Mater. Chem. C, 5, 3692, 2017. DOI: 10.1039/c7tc00576h.
[104] X. Lan, O. Voznyy, A. Kiani, F. P. Garcı´a de Arquer, A. S. Abbas, G.-H. Kim, M. Liu, Z. Yang, G. Walters, J. Xu, M. Yuan, Z. Ning, F. Fan, P. Kanjanaboos, I. Kramer, D. Zhitomirsky, P. Lee, A. Perelgut, S. Hoogland and E. H. Sargent, "Highly Efficient Perovskite-Quantum-Dot Light-Emitting Diodes by Surface Engineering", Adv. Mater., 28, 299, 2016.
[105] B. Hou, Y. Cho, B. S. Kim, J. Hong, J. B. Park, S. J. Ahn, J. I. Sohn, S. Cha and J. M. Kim, ACS Energy Lett., 2016, 1, 834.5 J. Q. Grim, L. Manna and I. Moreels, Chem. Soc. Rev., 44, 5897, 2017.
[106] W. Yoon, J. E. Boercker, M. P. Lumb, D. Placencia, E. E. Foos and J. G. Tischler, "Enhanced open-circuit voltage of PbS nanocrystal quantum dot solar cells", Sci. Rep., 3, 2225, 2013.
[107] C.-H. M. Chuang, A. Maurano, R. E. Brandt, G. W. Hwang, J. Jean, T. Buonassisi, V. Bulovic´ and M. G. Bawendi, "Open-circuit voltage deficit, radiative sub-bandgap states, and prospects in quantum dot solar cells", Nano Lett., 15, 3286, 2015.
[108] G. Nair, L.-Y. Chang, S. M. Geyer and M. G. Bawendi, "Perspective on the Prospects of a Carrier Multiplication Nanocrystal Solar Cell", Nano Lett., 11, 2145, 2011.
[109] W. Ma, S. L. Swisher, T. Ewers, J. Engel, V. E. Ferry, H. A. Atwater and A. P. Alivisatos, "Photovoltaic Performance of Ultrasmall PbSe Quantum Dots", ACS Nano, 5, 8140, 2011.
[110] R. S. Kane, R. E. Cohen and R. Silbey, "Theoretical Study of the Electronic Structure of PbS Nanoclusters", J. Phys. Chem., 1996,
[111] G. D. Scholes, and G. Rumbles, "Excitons in nanoscale systems", Nat. Mater. 5, 683–696, 2006.
[112] R. Schoolar, and J. Dixon, "Optical constants of lead sulfide in the fundamental absorption edge region", Phys. Rev. 137, A667, 1965.
[113] J. M. Luther, J. Gao, M. T. Lloyd, O. E. Semonin, M. C. Beard and A. J. Nozik "Stability assessment on a 3% bilayer PbS/ZnO quantum dot heterojunction solar cell", Adv Mater, 22, 3704–3707, 2010.
[114] W. Yoon, J. E. Boercker, M. P. Lumb, D. Placencia, E. E. Foos, and J. G. Tischler, "Enhanced open-circuit voltage of PbS nanocrystal quantum dot solar cells Scientific reports, 19(3), 1-7, 2013.
[115] J. W. Lee, et al. "Quantum-Dot-Sensitized Solar Cell with Unprecedentedly High Photocurrent", Sci. Rep. 3(1050), 1–8 , 2013.
[116] V. Gonzalez-Pedro V. et al. "High performance PbS Quantum Dot Sensitized Solar Cells exceeding 4% efficiency: the role of metal precursors in the electron injection and charge separation", Phys. Chem. Chem. Phys. 15, 13835–13843, 2013.
[117] C. Cheng, "Semiconductor Colloidal Quantum Dots For Photovoltaic Applications", A thesis submitted in fulfilment of requirement for the degree of DPhil in Materials at The University of Oxford, 2014.
[118] G. Zhang, "Optical Property Optimisation of Lead Sulphide Quantum Dots", A Thesis Submitted for the Degree of Master of Engineering Science, School of Chemical Engineering, the University of Adelaide, Australia, 2013.
[119] I. Moreels, Y. Justo, B. De Geyter, K. Haustraete, J. C. Martins, and Z. Hens, "Size-tunable, bright, and stable PbS quantum dots: A surface chemistry study", ACS Nano, 5, 2004–2012, 2011.
[120]. D. Kang, M. B. Kumar, C. Son, H. Park, and J. Park, "Simple Syndissertation Method and Characterizations of Aggregation-Free Cysteamine Capped PbS Quantum Dot", Appl. Sci., 9, 4661, 2019. https://doi.org/10.3390/app9214661
[121] E. Yilmaz, M. Y. Ates, and Y. C. Sahilli, "Synthesizing, Chitosan Coating and Detecting the Nanotoxic Effect of the Lead Selenide (Pbse) Quantum Dots", DigestJournal of Nanomaterials and Biostructures, 13(4), 1173-1182, 2018.
[122] A. Albert, C. O. Sreekala, and M. Prabhakaran, "Synthesis and Characterization of Aqueous Lead Selenide Quantum Dots for Solar Cell Application", IOP Conf. Series: Materials Science and Engineering, 310, 012152, 2018. doi:10.1088/1757-899X/310/1/012152

[123] H. Du. C. L. Chen, R. Krishnan, T. D. Krauss, J. M. Harbold, F. W. Wise, M. G.Thomas, and J. Silcox, "Quantum Photonics: Pioneering Advances and Emerging Applications", Nano Lett. 2 (11) 1321–1326, 2002.

[124] J. Chauhan, and R. Soni, "Characterization of Nanostructure Lead selenide (PbSe) thin films", Report and Opinion, 10(4), 41-45, 2018. doi:10.7537/marsroj100418.07.

[125] H. A. Morris, "Investigation of the Optical Properties of PbSe/PbX Nanocrystals for Photodetector Applications", Graduate Theses and Dissertations, 2018. Retrieved from https://scholarworks.uark.edu/etd/1828

[126] Y. J. Na, H. S. Kim, and J. Park, . Morphology-Controlled Lead Selenide Nanocrystals and their on situ growth in Nanotubes. J. Phys. Chem. C. 112 11218–11226, 2008.

[127] R. D. Schaller, an d I. V. Klimov, V. I. "High Efficiency Carrier Multiplication in PbSe Nanocrystals: Implications for Solar Energy Conversion", Phys. ReV. Lett., 92, 186601, 2004.

[128] M. Califano, A. Zunger, and A. Franceschetti, "Efficient inverse Auger recombination at threshold in CdSe nanocrystals". Nano Lett., 4, 525–531, 2004.

[129] J. M. Luther, M. Law, M. C. Beard, Q. Song, M. O. Reese, R. J. Ellingson, and A. J. Nozik, "Schottky Solar Cells Based on Colloidal Nanocrystal Films", Nano Lett., 8, 3488-3492, 2008.

[130] J. Chen, Q. Huang, and W. Lei, "Dual-Facets Emissive Quantum-Dot Light-Emitting Diode Based on AZO Electrode. Materials, 15, 740, 2022. https://doi.org/10.3390/ma15030740

[131] Y. Sun, Y. Jiang, W. X. Sun, et al. "Beyond OLED: Efficient quantum dot light-emitting diodes for display and lighting application", Chem Rec, 19: 1729–1752, 2019.

[132] C. Gannon, and R. Liang, "Ray mapping with surface information for freeform illumination design", Optics Express, 25(8), 9426–9434, 2017.

[133] H. Vu, N. M. Kieu, D. T. Gam, S. Shin, T. Q. Tien, and N. H. Vu, "Design and Evaluation of Uniform LED Illumination Based on Double Linear Fresnel Lenses", Applied Sciences, 10, 3257, 2020. https://doi.org/10.3390/app10093257

[134] K. Wang, F. Chen, Z. Liu, X Luo, and S. Liu, "Design of compact freeform lens for application specific light-emitting diode packaging", Opt. Express, 18, 413, 2010.

[135] A. Thorseth, "Characterization, Modeling, and Optimization of Light-Emitting Diode Systems", Technical University of Denmark, 2011.

[136] A. K. Hussein, and T. C. Miqdam, "The Impact of Using Solar Colored Filters to Cover the PV Panel in Its Outcomes", Scholars Bulletin, 2(7), 464-469, 2016. https://doi.org/10.21276/sb.2016.2.7.5

[137] H. J. Hovel, R. T. Hodgson, and J. W. Woodall, "The effect of fluorescent wavelength shifting on solar cell spectral response", Solar Energy Materials, 2(1), 19–29, 1979.

[138] C. Strumpel, M. McCann, and Beaucarne et al., "Modifying the solar spectrum to enhance silicon solar cell efficiency-an overview of available materials", Solar Energy Materials & Solar Cells, 91(4), 238–249, 2007.

[139] E. Klampaftis, D. Ross, K. R. McIntosh, and B. S. Richards, "Enhancing the performance of solar cells via luminescent down-shifting of the incident spectrum: a review", Solar Energy Materials & Solar Cells, 93(8), 1182–1194, 2009.

[140] K. R. McIntosh, G. Lau, and J. N. Cotsell, "Increase in external quantum efficiency of encapsulated silicon solar cells from a luminescent down-shifting layer", Progress in Photovoltaics: Research and Applications, 17(3), 191–197, 2009.

[141] D. Ross, D. Alonso-Alvarez, and E. Klampaftis, "The impact of luminescent down shifting on the performance of CdTe photovoltaics: impact of the module vintage", IEEE Journal of Photovoltaics, 4(1), 457–464, 2014.

[142] R. Rothemund, S. Kreuzer, T Umundum, G. Meinhardt, T. N. Fromherz, and W. Jantsch, "External quantum efficiency analysis of Si solar cells with II–VI nanocrystal luminescent downshifting layers", Energy Procedia, (10)83–87, 2011.

[143] D. Alonso-Alvarez, D. Ross, and E. Klampaftis, "Luminescent down-shifting experiment and modelling with multiple photovoltaic technologies", Progress in Photovoltaics: Research and Applications, 23(4), 479–497, 2015.

[144] H. Ahmed, S. J. McCormack, and J. Doran, "External Quantum Efficiency Improvement with Luminescent Downshifting Layers: Experimental and Modelling", International Journal of Spectroscopy, 8543475, 2016. http://dx.doi.org/10.1155/2016/854347