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Commentary

A Brief Note on Multifaceted Aspect of Functional Quantum Dots

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Abstract

Discovered in 1981, Quantum Dots (QDs) are semiconductor nanocrystals defined by quantum confinement, which allows for precise size-tuneable optoelectronic properties. Their brightness, photostability, and discrete energy levels have revolutionized fields from energy storage to optoelectronics. This brief note focuses on the transformative role of QDs as a multi-faceted entity. We underline the historical evolution of synthesis and surface functionalization techniques that enable advanced applications in imaging and biosensing. Despite their potential for application in domain such as precision medicine, challenges regarding cytotoxicity and biocompatibility remain significant hurdles. By exploring current research into safer design strategies and regulatory frameworks, this work outlines how integrating QDs with broader nanotechnologies will shape the future of clinical diagnostics and personalized therapy.

Introduction

Thanks to the immense developments in quantum dots (QDs). Nanotechnology has advanced significantly in a variety of sectors, including engineering, chemistry, physics, and medicine [1–6]. The history of QDs, which are sometimes referred to as "artificial atoms" because of their special optoelectronic characteristics, began in 1981 when Alexey Ekimov discovered them in a glass matrix [7]. Louis Brus created the first colloidal nanocrystalline semiconductor solution in 1985 as a result of this breakthrough [8]. The term "quantum dots" was later coined by Mark Arthur Reed in 1988 when he showed off their photoluminescent properties [9]. Smaller than 10 nm, these nanoscale semiconductor particles have size-dependent optical and electrical properties that set them apart from bulk materials [10-11]. Such exquisite properties, when tuned with functionalized materials, enable the quantum dot to be used for specific applications with versatile modalities. Thus, the term has been coined as functional quantum dots. There are abundant literatures which deal with quantum dots in their specific attributes [1–48]. However, there are very few articles which look at the functional side of QDs; that too in the context of multifaceted aspects. Accordingly, this concise note gives a brief historical outlook accompanied by application of quantum dot in imaging and sensing domain. The first section appraises a brief history and the next section dwells upon certain applications in imaging and sensing applications.

Brief History

Within QDs, quantum confinement limits electrons and holes to areas similar to their de Broglie wavelength, producing discrete, quantized energy levels. Because of this confinement, quantum dots outperform conventional devices in terms of high brightness, quantum yield, photostability, and tunable excitation and emission spectra [12,13]. In the past, materials similar to QDs were inadvertently used by ancient societies. In the early 20th century, silicate glasses were infused with CdS and CdSe nanoparticles, which revolutionized the use of nanotechnology to regulate glass color [14,15]. The discovery of a blue shift in the optical spectrum of CuCl inside a silicate glass by Ekimov and Onushchenko in 1981, which revealed the consequences of quantum confinement, was the turning point [16]. This discovery made it possible to precisely control the size and content of QDs, laying the foundation for contemporary synthesis methods. Rosetti *et al.*'s 1991 study highlighted the size-dependent characteristics of colloidal semiconductor solutions [18], while Efros's 1982 theory on using quantum size effects to control glass's optical properties further fuelled QD research [17].

Researchers then moved on to CdTe, InAs, and InP after Ekimov's groundbreaking work on CdSe in the 1980s, each of which offers unique band gap characteristics appropriate for a range of applications [19–22]. Due to their reduced toxicity, non-cadmium substitutes as $CuInS_2$ and ZnS became popular in biomedical applications [23–26]. With extended photoluminescence lifetimes and high quantum yields, Ag-In-S QDs demonstrated exceptional light absorption and emission [27]. **Table 1** enlists QDs with their toxicity classification.

Likewise, newer ternary I-III-VI QDs, including copper indium sulphide (CIS), offered stable and simple synthesis that was advantageous for biophotonics, as well as flexible band gap changes that were essential for solar cells and LEDs [28–30]. The stability, mechanical characteristics, and application variety of matrices were improved by the addition of QDs. CdZnTe QDs in a CaCO3 matrix, for example, demonstrated better photostability and processability than CdZnTe QDs on their own [31]. With their high quantum yields, narrow emission spectra, and exceptional color purity, perovskite QDs (PQDs) have emerged as intriguing semiconductor nanoparticles that have the potential to completely transform optoelectronics [32,33]. High charge capacity in lithium-ion batteries was made possible by the use of tin oxide QDs as anode materials [34].

Use of Functional Quantum Dot in Imaging Applications

Fluorescence imaging remains one of the widely used application where QDs are aptly implemented. QDs are ideal fluorophores for biological sample imaging because of their special optical characteristics, which include size-tunable emission and strong photostability. To precisely mark cells, tissues, or macromolecules, QDs can be attached to targeted molecules like peptides or antibodies. Numerous fluorescent imaging methods, such as confocal microscopy, total internal reflection fluorescence microscopy, and even single molecule imaging, were developed using quantum dots. As a result, it was theoretically feasible to see such structures, dynamic processes, and molecular interactions at extremely high resolution in a medically appropriate setting. The ability to multiplex QDs with different emission wavelengths increased their value for sophisticated imaging techniques [35].

Multimodal Imaging

Multimodal imaging, as the name suggests, is imaging that uses two or more imaging modalities to provide information about biological systems. In order to provide multimodal imaging, quantum dots can also be further combined

Table 1. QDs' properties along with toxicity.

QD Material	Typical Emission Range (nm)	Reported Quantum Yield	Application Domain	Toxicity Classification	Ref.
CdSe	470–650 (size-tunable)	~80–95% (core/shell, e.g., CdSe/ZnS)	Bioimaging, displays, LEDs, solar cells	**High** (Cadmium – heavy metal, cytotoxic, environmental persistence)	[46]
CdTe	550–820 (size-tunable)	~50–85% (core/shell)	Bioimaging, photovoltaics, sensors	**High** (Cadmium + Tellurium – heavy metals, toxic ions leaching)	[1–5, 46]
InP	520–750 (size-tunable)	~70–90% (e.g., InP/ZnS)	Displays, bioimaging	**Low–Moderate** (Indium and Phosphorus – much lower toxicity than Cd, but In can be cytotoxic at high doses)	**[5]**
$CuInS_2$ (CIS)	550–800 (size/composition-tunable)	~60–80% (e.g., CIS/ZnS)	Bioimaging, solar cells, LEDs	**Low** (Copper, Indium, Sulfur – heavy-metal-free, but Cu can be toxic in free ion form; overall far less toxic than Cd)	[5]
Perovskite	410–700 (halide-tunable)	~70–95% (but unstable in polar solvents)	LEDs, solar cells, photodetectors	**Moderate–High** (Lead – toxic heavy metal; some Pb-free perovskites (e.g., Sn-based) exist but are less stable)	[3,5]
Carbon / Silicon QDs	**Carbon:** 400–600 (blue/green) **Silicon:** 500–900 (red/NIR)	Carbon: ~30–80% Silicon: ~20–60%	Bioimaging, sensing, drug delivery, LEDs	**Very Low** (Carbon – biocompatible; Silicon – biocompatible, biodegradable; no heavy metals)	[3,46]

with other imaging agents as contrast agents or magnetic nanoparticles to create multifunctional probes. Functional QDs can therefore be used in conjunction with magnetic resonance imaging, which combines the high sensitivity and specificity of QD-fluorescence imaging with great spatial resolution. As a result, these conjugates provide complete details of biological processes by enabling simultaneous anatomical and molecular imaging. QD-based multimodal imaging has been used to follow stem cells, diagnose malignancy, and track disease development [36].

Functional Quantum Dot in Biosensing

The idea behind quantum dot-based biosensors is to use the distinct optical characteristics of QDs to identify specific biomolecules, infections, or environmental contaminants. These biosensors usually entail conjugating QDs with recognition elements that can attach to the target analyte, such as aptamers, antibodies, or enzymes [37]. The target analyte interacts with QD-conjugated recognition elements to alter the optical characteristics of the QDs, such as fluorescence intensity, wavelength shift, or quantitatively quantifiable resonance energy transfer [30]. The presence and concentration of the target analyte are then ascertained by quantitatively detecting such variations. High selectivity, sensitivity, and—most importantly—multiplexing capabilities have been incorporated by QD-based sensors into a biosensing paradigm that significantly improves food safety and biomedical diagnostics [29].

A number of biosensors for various biomarkers and pathogens that cause diseases have been developed using quantum dots. Prostate-specific antigen and carcinoembryonic antigen, for instance, can be detected with extremely high sensitivity and specificity using QD-based immunoassays [38]. However, QD-based nucleic acid sensors can identify bacterial and viral DNA or RNA, allowing for quick and precise detection of infectious diseases. Numerous biomarkers or pathogens can be simultaneously detected in a single experiment, thanks to QDs' strong photostability and numerous detection capabilities [39]. The majority of complicated disorders involving many biomarkers, such as cancer and infectious diseases, can benefit from this multiplexed detection. For point-of-care diagnostics, which allows for quick and portable detection of certain infectious diseases at the clinical and field levels, QD-based biosensors showed a lot of potential.

Cell Labelling and Tracking

QDs have been utilized to label cells both *in vitro* and *in vivo* because of their strong fluorescence and superior photostability. On the other hand, conjugation with relevant cell-specific ligands, including peptides or antibodies, can lead to QD labeling of cell types. This kind of labeling uses direct visualization to study cell activities like migration, differentiation, and proliferation [40]. Using *in vitro* techniques to label cells with QDs has become a routine procedure for monitoring cellular interactions and behaviors under a fluorescent microscope or while passing through a flow cytometer [41].

Cell engraftment, localization, and migration within a living individual can be tracked *in vivo* with the use of QDs. This method is extremely useful for research on cancer metastasis, stem cell studies, and immune cell behavior, among other processes [42-46].

In vivo Imaging and Diagnostics

Real-time visualization of biological processes and the progression of disease in living creatures was made possible by the application of quantum dots for *in vivo* imaging. In animal models, QDs can be used as fluorescent probes to image tumors, blood vessels, and other organs. Long-term imaging is made possible by their great photostability and brightness, which makes it possible to track the course of a disease and how well a treatment is working overtime [43–46]. The majority of *in vivo* imaging modalities, including near-infrared fluorescence imaging, photoacoustic imaging, and fluorescence lifetime imaging, now use quantum dots as a tool to give highly complementary information about the anatomical, molecular, and functional state of biological systems [35]. For early diagnosis, surgical guiding, and drug efficiency monitoring in clinical practice, QD-based *in vivo* imaging is extremely beneficial.

Concluding Remarks

In summary, the evolution of quantum dots from their initial discovery in glass matrices to their current status as highly engineered functional nanoparticles marks a significant milestone in modern nanotechnology. These "artificial atoms" have transitioned from fundamental laboratory observations of quantum confinement to indispensable tools in the realms of imaging and sensing—thereby offering a level of tunability and photostability that surpasses traditional fluorophores. The historical progression from binary structures like CdSe to more complex ternary and perovskite systems has not only improved optoelectronic performance but has also addressed critical challenges regarding toxicity and environmental stability, particularly for biomedical use. By enabling high-resolution multiplexed fluorescence imaging, ultra-sensitive biosensing for early disease detection, and real-time tracking of cellular processes in vivo, functional quantum dots have effectively bridged the gap between anatomical detail and molecular sensitivity. Ultimately, the integration of these nanoparticles into multimodal systems and point-of-care diagnostics represents a paradigm shift in biophotonics, thereby positioning quantum dots as a cornerstone of future personalized medicine and clinical diagnostics.

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