Quantum Confinement and Electronic Transport in II–IV Semiconductor Quantum Dots

Ratneshwar Kumar Ratnesh[1*] *and Abhinav Sharma*[2]
[1]Lincoln University College, Petaling Jaya, Selangor Darul Ehsan, 47301, Malaysia
[2]Institute of Post-LED Photonics, Tokushima University, 2-1 Minami-Josanjima, Tokushima, 770-8506, Japan
Email ID: ratnes123@gmail.com, pdf.ratneshwar@lincoln.edu.my, abhisharma.75@gmail.com

---

Abstract: II–IV semiconductor quantum dots (QDs) have emerged as promising nanomaterials for next-generation electronic and optoelectronic applications due to their size-dependent tunable properties and enhanced carrier dynamics. This paper presents an overview of the synthesis approaches, structural characteristics, and electronic properties of II–IV QDs, emphasizing their role in nanoscale device engineering. The influence of quantum confinement on bandgap modulation, charge transport, and optical response is critically discussed. Furthermore, the integration of these QDs into advanced electronic devices is examined, highlighting their potential for low-power, high-speed, and miniaturized systems. Key challenges related to material uniformity, stability, and large-scale fabrication are also addressed. The study concludes by outlining future research directions aimed at improving device performance and enabling the practical deployment of II–IV quantum dot-based technologies in modern electronics.

Keywords: Quantum-dot, Quantum confinement, Carrier dynamics, Device fabrication technique.

---

1. Introduction

QDs are zero-dimensional nanostructures whose low-energy levels are a result of quantum confinement and have tunable bandgaps, high photoluminescence efficiency, and improved carrier dynamics [1]. CdSe, ZnS, CdS/ZnS core-shell structures and QDs II-VI with their high optical properties are commonly studied because of their ease of synthesis [2], [3], and alloyed QDs additionally allow compositional and emission manipulation [2]. The size reduction in quantum confinement boosts bandgap energy [3] and optical emission and the device performance are controlled by exciton generation and recombination [1]. Heterostructures Type-I and type-II Advanced heterostructures allow controlled band alignment of charge separation and transport in optoelectronic and photovoltaic devices [4], and external electric and magnetic fields allow further control of electronic and optical behavior [5]. These mechanisms of fabricating methods, which are utilized top-down, bottom-top, and top-down, would consist of molecular beam epitography, chemical vapor deposition, microwave creation and colloidal techniques [6], and surface passivation enhances stability and minimizes defects [7]. QDs are also being incorporated in QLEDs, photodetectors, and spintronic devices [8-10], albeit more remains to be done e.g. in terms of toxicity, stability and scalability, there should be comparative analysis of materials and fabrication strategies to be applied in high performance.

2. Working Principles of Semiconductor Quantum Dots

The operation of semiconductor quantum dots can be governed by a range of fundamental approaches to physics, and the approaches are compared to a certain degree below.

2.1. Quantum Confinement Effect

The primary mechanism determining the properties of QDs is quantum confinement: on the one hand, as the size of the dot decreases to the scale of the exciton Bohr radius, continuous bulk-bandgap levels are quantized to discrete levels, and a size-dependent bandgap is realized [3], [9]. The larger confinement of smaller QDs results in an increased bandgap energy and shorter wavelength (blue) emission, whereas the smaller confinement of larger QDs results in a reduced bandgap and longer wavelength (red) emission. As depicted, bulk materials are continuous CB and VB materials, but QDs are discrete and the variation of the bandgap is proportional to $1/R^2$. This trend was found in experimental photoluminescence with emission peaks blue-shifting as the size decreased. Therefore, the optical and electronic behavior of quantum dots is directly controllable through size-controlled confinement as Fig.1.

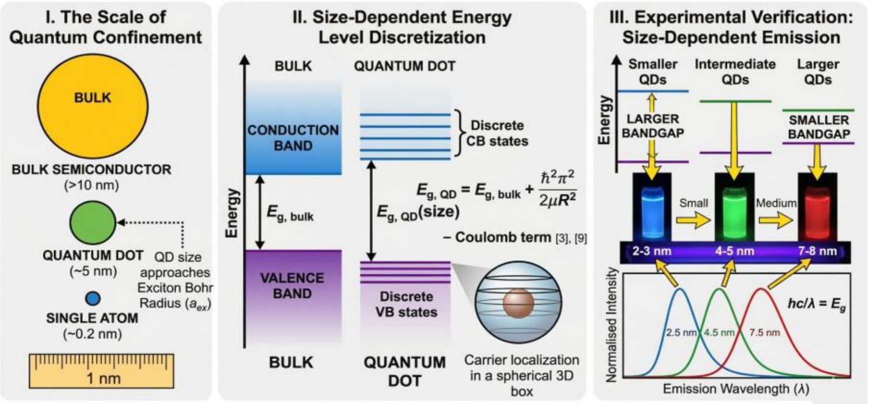

Fig. 1 Quantum Confinement Effect

2.2. Carrier Dynamics and Exciton Behavior

Carrier dynamics in II–VI semiconductor quantum dots are governed by ultrafast processes such as exciton generation, recombination, and Auger interactions. Upon optical excitation, electron–hole pairs (excitons) are generated, followed by competing recombination pathways, including radiative emission and non-radiative decay mechanisms [1]. Multiple exciton generation (MEG) and nonlinear optical processes play a significant role in enhancing device performance, particularly in photovoltaic and optoelectronic applications. The recombination dynamics typically exhibit multi-exponential behavior, consisting of fast, intermediate, and slow decay components. Fast decay is mainly associated with Auger recombination and other non-radiative processes, intermediate decay arises from carrier trapping, while slow decay corresponds to intrinsic radiative recombination (Fig.2) provides a comprehensive illustration of these processes, depicting exciton generation through light absorption, radiative and non-radiative recombination pathways, and time-resolved carrier decay mechanisms. It also highlights the role of MEG in generating multiple excitons, which is crucial for improving energy conversion efficiency. Overall, understanding carrier and exciton dynamics is essential for optimizing the performance of II–VI quantum dot-based electronic and optoelectronic devices.

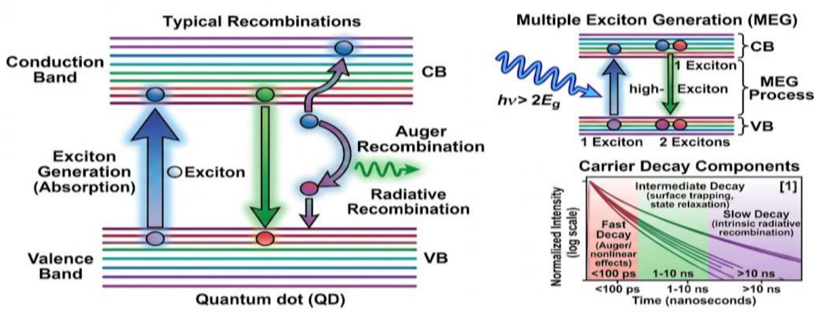

Fig. 2 Carrier Dynamics and Exciton Behavior

2.3. Bandgap Engineering and Alloying

Bandgap tuning in alloyed QDs such as CdSeS/ZnS is achieved through compositional modification, as shown in Figure 2.3, where crystal lattice alloying enables a continuous variation of bandgap between CdS (larger bandgap) and CdSe (smaller bandgap), allowing emission tuning across ~510–710 nm [2]. The figure also illustrates discrete CB and VB states in the alloyed core, confirming composition-dependent energy control. Further, (Fig. 3) demonstrates that alcohol-based processing enables controlled size reduction from $D_{initial}$ to $D_{reduced}$, resulting in spectral tuning. This is experimentally verified by the photoluminescence plot, where processed QDs show a blue-shifted and narrower emission peak (~550 nm), indicating improved uniformity and quantum yield. Thus, the figure confirms that both compositional alloying and post-processing provide precise control over QD optical properties [2].

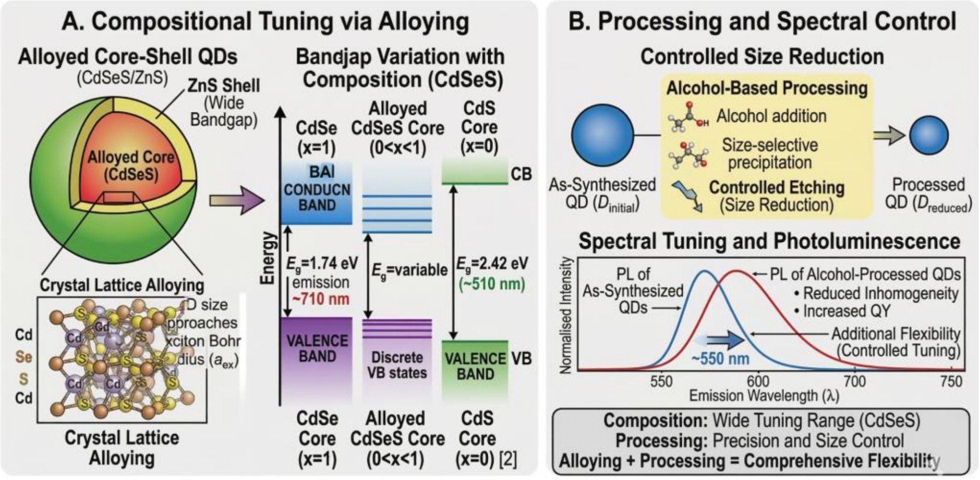

Fig. 3 Bandgap Engineering A) Compositional Tuning via Alloying, B) Processing and spectral control

2.4. Band Alignment and Coupled Quantum Dots

In interfaces of coupled quantum dots, charge distribution and transport depends on the band offsets. Typical application of Type-II heterostructures facilitates electron and hole spatial separation which leads to enhanced photovoltaic performance [4]. Strain and interfacial effects go further to affect band alignment.

2.5 External Field and Impurity Effects

The application of electric and magnetic fields alters the energy spectrum and optical properties of QDs. Donor impurities introduce additional energy states within the bandgap, modifying absorption and emission characteristics [5].

2.6 Spin and Magnetic Effects

Dilute magnetic semiconductor QDs exhibit spin-dependent electronic properties, enabling applications in spintronics. The incorporation of magnetic impurities allows control over spin polarization and magneto-optical behavior [10]. A comparative summary of the underlying working principles of semiconductor quantum dots in various material systems is given in Table 1. It is clear that quantum confinement remains to be the leading mechanism that affects the bandgap tunability and optical response, especially in II-VI quantum dots [3], [9]. The carrier dynamics such as multiple exciton generation, Auger recombination, etc. are also a pivotal factor in the behavior of ultrafast devices such as the CdSeTe quantum dots [1]. Also, band alignment engineering of coupled quantum dot can result in a higher level of charge separation, which is very advantageous to photovoltaic [4]. This new addition of external electric and magnetic fields also allows dynamic tuning of optical and electronic properties [5]. Additionally, spintronic applications of magnetically quantum dots may be expanded, as magnonic quantum dots permit transport to be spin-dependent [10]. On the whole, as observed in the table, several mechanisms (including confinement, band engineering, and external modulation) need to be combined to make quantum dots best in working with electronic devices.

Table 1: Comparative Analysis of Working Principles in Quantum Dots

Material/System	Core Working Principle	Key Mechanism	Impact on Electronics
CdSeTe QDs [1]	Carrier dynamics	MEG, Auger recombination	Enables optical switching and ultrafast devices
CdSeS/ZnS alloy QDs [2]	Bandgap engineering	Composition + size tuning	Tunable emission for LEDs and sensors
ZnS QDs [3]	Quantum confinement	Type-I / Type-II heterostructures	Improved optoelectronic efficiency
Coupled II–VI QDs [4]	Band alignment	Electric & magnetic field modulation	Enhanced charge separation (PV devices)
CdS/ZnS QDs [5]	External field effects	Electric & magnetic field modulation	Tunable optical absorption
II–VI / III–V QDs [9]	Exciton recombination	Radiative recombination control	High-efficiency QLED emission
Magnetic QDs [10]	Spintronics	Magnetic impurity interaction	Spin-based electronic devices

3. Tools and Techniques: Comparative Analysis

A detailed comparison of synthesis and analysis techniques across the selected papers is presented below.

3.1 Synthesis Techniques for II-VI Quantum dots

Microwave-assisted synthesis offers rapid and uniform heating, enabling precise control over particle size distribution in II–VI semiconductor quantum dots such as ZnS, CdSe, and CdS [3]. Chemical methods, particularly hot-injection, provide excellent control over composition, size, and morphology, making them highly suitable for alloyed and core-shell II–VI QDs [2]. In contrast, advanced techniques like molecular beam epitaxy and lithography deliver atomic-level precision but are limited by high cost and poor scalability [6]. Microwave and chemical techniques effectively control size and shape, directly influencing quantum confinement and optical properties. Top-down approaches are more suitable for precise device integration despite scalability challenges. Hybrid methods, such as Metal-Organic Framework (MOF) encapsulation, further improve stability by reducing surface defects and enhancing photoluminescence efficiency [7]. Overall, no single synthesis method is universally optimal for II–VI quantum dots; the selection depends on the required balance between precision, scalability, cost, and material quality.

3.2 Computational and Modeling Techniques

Density functional algorithm (DFT) is now standard tool of exploration of band structure, band gaps, optical properties of isolated quantum dots in pairs [4]. Finite element analysis is used to misuse the analysis of the effects of impurity and external field interactions [5]. The significant computational and experimental methods employed in the study of the electronic and optical properties of quantum dots. Density functional theory (DFT) is important to compute both band structures and band offsets, which will be used to design devices based on heterostructures [4]. Finite element techniques also give useful information on the influence of external electric and magnetically driven fields, impurity generated states of energy [5]. The use of experimental methods including pump-probe spectroscopy can be used to investigate ultrafast dynamics of carriers and recombination processes which are important in high-speed optoelectronic applications [1]. Also, bandgap variations in alloyed quantum dots are most commonly estimated using theoretical methods including the effective mass approximation [2]. As it can be seen in the table, both theoretical modelling and experimental validation are required to complete the insight and optimization of the quantum dot behavior.

3.3 Device Fabrication Techniques

Device fabrication using II–VI semiconductor quantum dots (e.g., CdSe, ZnS, CdS) critically depends on the optimization of charge transport layers and interface engineering. In QLED structures, the electron transport layer (ETL) plays a key role, where sputtered SnO_2 films provide improved uniformity, enhanced charge injection, and better transport compared to solution-processed layers [8].

Ligand engineering and core–shell structuring of II–VI QDs significantly influence device efficiency by minimizing surface trap states and improving carrier recombination [9]. Although solution-processed QLEDs offer cost-effective fabrication, they often suffer from ligand-induced charge trapping and reduced efficiency. Advanced integration strategies, such as MOF-based encapsulation, enhance device stability by protecting II–VI QDs from environmental degradation [7]. Furthermore, coupled quantum dot systems improve charge separation through band engineering, leading to enhanced device performance [4].

Additionally, magnetic II–VI quantum dots enable emerging device architectures in spintronics by exploiting spin-dependent transport properties [10].

Overall, device performance is strongly governed by both material engineering and fabrication techniques.

3.4 Comparative Discussion

For II–VI semiconductor quantum dots, microwave-assisted synthesis offers simplicity, scalability, and uniform particle distribution, but provides limited compositional control. In contrast, chemical methods such as hot-injection enable superior tunability of size, composition, and morphology, though they involve greater process complexity. Advanced computational techniques, including DFT and numerical modeling, significantly improve the understanding and prediction of electronic properties; however, they are computationally intensive. From a device fabrication perspective, sputtering-based approaches enhance uniformity and are more suitable for industrial-scale integration compared to solution-based methods. Overall, the best device performance in II–VI quantum dots is achieved through a hybrid approach that combines precise synthesis, effective surface engineering, and advanced modeling techniques, balancing scalability, accuracy, and material quality.

4. Conclusion

This paper presents a comparative analysis of semiconductor quantum dots focusing on their operating principles and fabrication techniques. Key factors such as quantum confinement, exciton dynamics, and band alignment are identified as critical in determining QD behavior. Chemical synthesis offers superior tunability, while microwave-assisted methods enable scalable production. Surface engineering and core–shell structures significantly enhance stability and efficiency. Advanced modeling techniques improve the prediction of electronic properties. Device integration studies highlight the importance of optimizing charge transport layers for enhanced performance. Overall, the advancement of QD-based electronics requires a multidisciplinary approach combining materials design, synthesis, and device engineering. Future research should focus on reducing toxicity, improving stability, and developing scalable fabrication processes.

References

1. Wenzhi Wu, Zhijun Chai, Yachen Gao, Degui Kong, Feng He, Xianghai Meng, Yaguo Wang, "Carrier dynamics and optical nonlinearity of alloyed CdSeTe quantum dots in glass matrix," Opt. Mater. Express, vol. 7, no. 5, p. 1547, Apr. 2017, doi: 10.1364/ome.7.001547.
2. E. Kheirandish, J. C. Marnocha, and N. Kouklin, "Controlling opto-electronic characteristics of ternary II–VI alloyed quantum dots: alcohol processing assay," Mater. Res. Express, vol. 7, no. 7, p. 075008, Jul. 2020, doi: 10.1088/2053-1591/aba506.
3. N. Soltani, E. Saion, M. Erfani, Khadijeh Rezaee, G. Bahmanrokh, G. Drummen, A. Bahrami, M. Hussein, "Influence of the Polyvinyl Pyrrolidone Concentration on Particle Size and Dispersion of ZnS Nanoparticles Synthesized by Microwave Irradiation," IJMS, vol. 13, no. 10, pp. 12412–12427, Sep. 2012, doi: 10.3390/ijms131012412.
4. A. Chakraborty, B. Das, and I. Dasgupta, "Unlocking the electronic, optical and transport properties of semiconductor coupled quantum dots using first principles methods," Int J of Quantum Chemistry, vol. 123, no. 11, Feb. 2023, doi: 10.1002/qua.27101.
5. K. Hasanirokh, A. Radu, and C. A. Duque, "Donor Impurity in CdS/ZnS Spherical Quantum Dots under Applied Electric and Magnetic Fields," Nanomaterials, vol. 12, no. 22, p. 4014, Nov. 2022, doi: 10.3390/nano12224014.
6. Madhuri Singh, "A review on synthesis of quantum dots and their biomedical applications," IJBB, 2022, doi: 10.56042/ijbb.v59i12.67291.
7. A. Cortés-Villena and R. E. Galian, "Present and Perspectives of Photoactive Porous Composites Based on Semiconductor Nanocrystals and Metal-Organic Frameworks," Molecules, vol. 26, no. 18, p. 5620, Sep. 2021, doi: 10.3390/molecules26185620.
8. J. Choi and J. Kim, "Highly Efficient and Stable Quantum Dot Light-Emitting Diodes Employing Sputtered SnO2 Layer as Electron Transport Layers," Nanomaterials, vol. 16, no. 1, p. 31, Dec. 2025, doi: 10.3390/nano16010031.
9. S.-N. Li, J.-L. Pan, Y.-J. Yu, F. Zhao, Y.-K. Wang, and L.-S. Liao, "Advances in Solution-Processed Blue Quantum Dot Light-Emitting Diodes," Nanomaterials, vol. 13, no. 10, p. 1695, May 2023, doi: 10.3390/nano13101695.
10. J. M. Baruah and J. Narayan, "Dilute Magnetic Semiconducting Quantum Dots: Smart Materials for Spintronics," Nonmagnetic and Magnetic Quantum Dots. InTech, Apr. 04, 2018. doi: 10.5772/intechopen.73286.