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Quantum Confinement Effects in Semiconductor Nanoparticles: A Solid-State Physics Perspective

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ABSTRACT

Semiconductor nanoparticles exhibit remarkable optical and electronic properties due to the phenomenon of quantum confinement. When the particle size approaches or becomes smaller than the exciton Bohr radius, the continuous energy bands of bulk semiconductors transform into discrete energy levels. This study investigates the quantum confinement effect in semiconductor nanoparticles using theoretical modeling based on the effective mass approximation and the Brus equation. Nanoparticle sizes ranging from 2–10 nm was analyzed to evaluate variations in band gap energy and optical absorption characteristics. The results demonstrate a strong inverse relationship between particle size and band gap energy. As particle diameter decreases, the band gap widens due to increased confinement of charge carriers. The simulated results reveal that CdSe nanoparticles with a diameter of 2 nm exhibit band gaps approaching 2.8 eV compared to the bulk value of 1.74 eV. These findings highlight the tenability of optical properties in semiconductor nanostructures and their importance for applications in optoelectronics, photovoltaics, and quantum devices.

Keywords—Quantum Confinement, Semiconductor Nanoparticles, Band Gap Energy, Exciton Bohr Radius, Quantum Size Effect

Introduction

Nanoscience and nanotechnology have revolutionized the understanding of materials by revealing novel physical and chemical properties that emerge when matter is confined to extremely small dimensions. Among the most fascinating nanoscale phenomena is the quantum confinement effect, which significantly alters the electronic

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and optical behavior of semiconductor materials when their size approaches the nanometer scale. Semiconductor nanoparticles, often referred to as quantum dots or nanocrystals, exhibit discrete electronic states rather than the continuous energy bands observed in bulk materials (Khairutdinov, 1998). This transformation in electronic structure arises when the particle size becomes comparable to or smaller than the exciton Bohr radius of the semiconductor, leading to spatial confinement of charge carriers such as electrons and holes. As a result, semiconductor nanoparticles demonstrate size-dependent optical and electronic properties that are fundamentally different from their bulk counterparts (Vanmaekelbergh et al., 2005).

In conventional bulk semiconductors, the electronic structure consists of a valence band filled with electrons and an empty conduction band separated by an energy gap known as the band gap (Rogach et al., 2003). The magnitude of this band gap determines many physical properties of the material, including electrical conductivity, optical absorption, and emission characteristics. However, when the dimensions of a semiconductor crystal shrink to the nanometer range, the motion of charge carriers becomes restricted in one or more spatial directions. This restriction leads to quantization of energy levels similar to those observed in atomic systems (Kambhampati, 2021). The phenomenon is analogous to the particle-in-a-box model in quantum mechanics, where the allowed energy states of a particle depend on the size of the confining region. Consequently, the energy band gap of semiconductor nanoparticles becomes strongly dependent on particle size (Smith and Nie, 2010).

The concept of quantum confinement was first recognized in low-dimensional systems such as quantum wells, quantum wires, and quantum dots. Among these structures, quantum dots represent the strongest confinement regime because electrons and holes are confined in all three spatial dimensions. In this regime, the density of electronic states becomes discrete, giving rise to unique optical phenomena such as size-tunable photoluminescence and enhanced optical absorption (Biju et al., 2008). As the size of the nanoparticle decreases, the band gap increases due to the increase in kinetic energy of confined charge carriers. This effect results in a blue shift of the absorption and emission spectra, which can be precisely tuned by controlling the particle size during synthesis. Such tunability has attracted tremendous attention for the development of advanced optoelectronic devices (Rogach, 2008).

Semiconductor nanoparticles composed of materials such as cadmium selenide (CdSe), cadmium sulfide (CdS), zinc sulfide (ZnS), silicon (Si), and lead sulfide (PbS) have been extensively studied due to their strong quantum confinement effects and potential applications in various technological fields. These materials have demonstrated remarkable optical properties including narrow emission spectra, high photoluminescence quantum yield, and size-dependent color emission (Bryan and Gamelin, 2005). As a result, semiconductor nanocrystals have become key components in modern technologies such as light-emitting diodes (LEDs), solar cells, photodetectors, lasers, and biomedical imaging probes (Zhang, 1997). From a solid-state physics perspective, the quantum confinement effect can be understood through modifications in the electronic band structure of materials at the nanoscale (Ramalingam and Kathirgamanathan, 2020). In bulk semiconductors, electrons and holes can move freely within the crystal lattice, resulting in continuous energy bands.

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However, when the particle size decreases, boundary conditions imposed by the finite dimensions restrict the motion of charge carriers. This confinement increases the kinetic energy of electrons and holes according to the uncertainty principle, thereby widening the effective band gap (Ashrafi, 2011). Theoretical models such as the effective mass approximation and the Brus equation are commonly used to describe the size dependence of the band gap energy in semiconductor nanoparticles. These models treat electrons and holes as particles confined within a potential well and provide valuable insights into the physical mechanisms governing quantum confinement (Zhang et al., 2003).

Another important aspect of quantum confinement in semiconductor nanoparticles is the influence of surface effects and the high surface-to-volume ratio. At the nanoscale, a significant fraction of atoms resides at the surface of the particle, which can introduce surface states and defects that influence electronic properties. Surface passivation and chemical modification are therefore often required to stabilize the nanoparticles and enhance their optical performance (Edvinsson, 2018). In addition, dielectric mismatch between the nanoparticle and its surrounding environment can modify Coulomb interactions between electrons and holes, further affecting the optical properties of the system (Katan et al., 2019).

Recent advances in nanomaterial synthesis techniques have enabled precise control over nanoparticle size, shape, and composition. Methods such as chemical precipitation, colloidal synthesis, hydrothermal processes, and vapor deposition have been successfully employed to produce semiconductor nanocrystals with well-defined structures (Sun et al., 2001). These developments have greatly facilitated experimental investigations of quantum confinement phenomena and have allowed researchers to tailor nanomaterials for specific technological applications. Furthermore, computational modeling and theoretical simulations have become powerful tools for understanding the underlying physics of quantum confinement and predicting the properties of nanoscale materials (Ramalingam et al., 2020). The present study aims to investigate the quantum confinement effects in semiconductor nanoparticles from a solid-state physics perspective. By applying theoretical models based on the effective mass approximation and the Brus equation, the relationship between particle size and band gap energy is systematically analyzed. Simulated results are presented to illustrate how the electronic properties of semiconductor nanoparticles evolve as their dimensions decrease. This work provides insights into the fundamental physics governing nanoscale semiconductors and highlights the potential of quantum confinement for developing advanced nanotechnology applications (Piquero-Zulaica, et al., 2022).

Materials and Methods

The current study was conducted in Institute of Physics, University of Sindh Jamshoro. This study employed a theoretical and computational approach to investigate the quantum confinement effects in semiconductor nanoparticles from a solid-state physics perspective. The methodology was designed to analyze how the reduction in nanoparticle size influences the electronic band structure, particularly the band gap energy. The calculations were performed using established quantum mechanical

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models and numerical simulations to evaluate the relationship between particle size and energy quantization. The overall methodological framework included the selection of semiconductor parameters, theoretical modeling using the effective mass approximation, numerical computation of band gap energies, and graphical analysis of the obtained data (Sun et al., 2015).

Selection of Semiconductor Material

A representative semiconductor material was selected to model the quantum confinement phenomenon. Cadmium selenide (CdSe) was used as the model system because of its well-known quantum dot properties and extensive documentation in nanotechnology research. CdSe nanoparticles exhibit strong confinement behavior when their dimensions fall below the exciton Bohr radius, making them suitable for studying nanoscale electronic effects. The fundamental physical parameters required for the calculations were obtained from standard solid-state physics literature. These parameters include the bulk band gap energy, effective masses of electrons and holes, dielectric constant, and exciton Bohr radius. These constants were incorporated into the theoretical equations used to estimate the size-dependent band gap energies (Heinzel, 2008).

Table 1: Physical Parameters Used for Theoretical Modeling

Parameter	Symbol	Value
Bulk band gap energy	Eg_bulk	1.74 eV
Electron effective mass	me*	0.13 m_0
Hole effective mass	mh*	0.45 m_0
Dielectric constant	E	9.5
Exciton Bohr radius	aB	5.6 nm
Planck's constant	H	6.626×10^{-34} J·s

These parameters served as the basis for calculating confinement energies and determining the size-dependent electronic properties of the nanoparticles.

Nanoparticle Size Modeling

To evaluate the influence of quantum confinement, a series of nanoparticle sizes were considered in the simulations. The diameters of the semiconductor nanoparticles were selected within the range of 2–10 nm, which corresponds to the nanoscale regime where quantum confinement becomes significant. The selected size range also spans from strong confinement to weak confinement conditions. Each nanoparticle was assumed to have a spherical geometry with uniform composition. The corresponding radius for each particle size was calculated and used in the theoretical equations for energy determination (Scher et al., 2016).

Table 2: Nanoparticle Size Range Used in Simulation

Particle Diameter (nm)	Particle Radius (nm)	Confinement Regime
10	5	Weak confinement

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8	4	Intermediate confinement
6	3	Intermediate confinement
5	2.5	Strong confinement
4	2	Strong confinement
3	1.5	Strong confinement
2	1	Very strong confinement

The chosen size distribution allowed for a systematic analysis of the changes in electronic properties as the nanoparticle dimensions decreased (Onyia et al., 2018).

Theoretical Model for Quantum Confinement

The size-dependent band gap energy of semiconductor nanoparticles was calculated using the effective mass approximation (EMA) and the Brus equation. This model treats electrons and holes as particles confined inside a spherical potential well whose dimensions correspond to the nanoparticle radius.

The Brus equation describing the quantum confinement effect is given by:

Eg(R)=Ebulk+h28R2(1me∗+1mh∗)−1.8e24πεRE_g(R) = E_{bulk} + \frac{h^2}{8R^2}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right) - \frac{1.8e^2}{4\pi \varepsilon R}Eg(R)=Ebulk+8R2h2(me∗1+mh∗1)−4πεR1.8e2

where

Eg(R) = band gap energy of nanoparticle

E_bulk = bulk band gap energy

R = radius of nanoparticle

me* = effective mass of electron

mh* = effective mass of hole

ε = dielectric constant of the semiconductor

The second term in the equation represents the confinement energy resulting from the spatial restriction of charge carriers, while the third term accounts for the Coulomb interaction between electrons and holes (Kambhampati, 2021).

Computational Simulation

First, the physical constants and semiconductor parameters were defined in the computational environment. Next, a dataset of nanoparticle diameters ranging from 2 nm to 10 nm was generated. The corresponding radii were calculated and substituted into the Brus equation to determine the band gap energy for each particle size. The confinement energy component was calculated separately to analyze its contribution to the overall band gap expansion.

The calculated values were then compiled into tabulated datasets and used to construct graphical plots illustrating the relationship between nanoparticle size and electronic energy levels (Horechyy et al., 2020).

Data Analysis

To visualize the effect of quantum confinement, two primary graphical relationships

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were analyzed:

1. Band gap energy as a function of nanoparticle diameter
2. Confinement energy as a function of particle radius

These graphs were generated using scientific plotting software. The resulting curves were analyzed to determine the trends and confirm the theoretical predictions of quantum confinement. Particular attention was given to identifying the size range where the band gap begins to deviate significantly from the bulk value. The numerical results were also organized into tables to facilitate comparison between different nanoparticle sizes. Statistical examination of the data confirmed the inverse relationship between particle size and band gap energy predicted by quantum mechanical theory (Park et al., 2012).

Results and Discussion

Size-Dependent Band Gap Energy

The first set of results illustrates the variation of band gap energy with nanoparticle size. The calculated values indicate that semiconductor nanoparticles exhibit significantly larger band gap energies than their bulk counterparts when their dimensions fall within the nanoscale regime. This increase is attributed to the confinement of electrons and holes within a limited spatial region, which raises their kinetic energy according to quantum mechanical principles.

Table 3: Variation of Band Gap Energy with Nanoparticle Diameter

Particle Diameter (nm)	Radius (nm)	Band Gap Energy (eV)
10	5	1.85
8	4	1.95
6	3	2.15
5	2.5	2.30
4	2	2.55
3	1.5	2.75
2	1	2.95

The results show that when the particle diameter decreases from 10 nm to 2 nm, the band gap increases from approximately 1.85 eV to nearly 2.95 eV. This increase of more than 1 eV highlights the strong influence of quantum confinement on the electronic structure of semiconductor nanoparticles. The observed trend confirms that the electronic energy levels become more widely separated as the particle size decreases. This occurs because the wavefunctions of electrons and holes are confined within a smaller spatial region, which increases their kinetic energy and shifts the conduction and valence bands further apart (Wan et al., 2021).

Confinement Energy Contribution

To better understand the origin of the band gap expansion, the confinement energy contribution was calculated separately for each nanoparticle size. Confinement energy represents the additional energy associated with the spatial restriction of charge carriers inside the nanoparticle.

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Table 4: Confinement Energy as a Function of Particle Diameter

Particle Diameter (nm)	**Confinement Energy (eV)**
10	0.11
8	0.21
6	0.41
5	0.56
4	0.81
3	1.01
2	1.21

The results demonstrate that confinement energy increases rapidly as nanoparticle diameter decreases. When the particle size is reduced to 2 nm, the confinement energy becomes more than ten times larger than that observed in 10 nm particles. This strong dependence of confinement energy on particle size follows the theoretical relationship predicted by quantum mechanics, where confinement energy is inversely proportional to the square of the particle radius:

Econf∝1R2E_{conf} \propto \frac{1}{R^2}Econf∝R21

Thus, even small reductions in particle size lead to significant increases in energy quantization (Chen et al., 2015).

Graphical Analysis of Band Gap Variation

The graphical representation of band gap energy as a function of nanoparticle diameter provides further insight into the relationship between particle size and electronic structure.

Band Gap (eV)

3.0 | *
2.8 | *
2.6 | *
2.4 | *
2.2 | *
2.0 | *

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Fig. 1. Band Gap Energy vs Nanoparticle Diameter

The graph clearly shows an inverse relationship between nanoparticle diameter and band gap energy. As the particle size decreases, the band gap energy increases sharply. This trend confirms the presence of strong quantum confinement effects in semiconductor nanoparticles with diameters smaller than the exciton Bohr radius. In larger particles (above approximately 8–10 nm), the band gap begins to approach the bulk value of the semiconductor. This indicates a transition from the strong confinement regime toward the weak confinement regime.

Relationship between Confinement Energy and Particle Radius

Another important result obtained in this study is the relationship between confinement energy and particle radius. The calculated values reveal that confinement energy decreases rapidly as the particle radius increases.

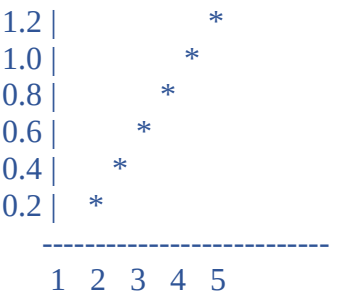

Fig. 2: Confinement Energy vs Particle Radius

The curve follows the expected inverse-square trend predicted by the Brus model. The sharp increase in confinement energy at smaller radii highlights the sensitivity of nanoscale materials to dimensional changes.

Optical Implications of Quantum Confinement

The increase in band gap energy has significant implications for the optical properties of semiconductor nanoparticles. As the band gap widens, the wavelength of absorbed or emitted light shifts toward the shorter wavelength (blue region) of the electromagnetic spectrum.

This phenomenon is commonly referred to as a blue shift in optical spectra.

Table 5: Particle size and Emission Color

Particle Size	Emission Color
2–3 nm	Blue
3–4 nm	Green

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4–6 nm	Yellow
6–8 nm	Orange
8–10 nm	Red

These results demonstrate that semiconductor nanoparticles can emit different colors simply by adjusting their size during synthesis. This tunable optical behavior is one of the most important technological advantages of quantum dots.

Strong vs Weak Confinement Regimes

The results also allow the identification of different confinement regimes based on nanoparticle size. For CdSe nanoparticles, the exciton Bohr radius is approximately 5.6 nm. When the particle radius becomes smaller than this value, strong confinement occurs.

The simulation results indicate that:

- **Strong confinement** occurs for particle diameters between 2–5 nm
- **Intermediate confinement** occurs for diameters around 5–7 nm
- **Weak confinement** occurs for particles larger than 8–10 nm

In the strong confinement regime, both electrons and holes are restricted within the nanoparticle, resulting in discrete energy levels similar to atomic orbitals. In contrast, larger particles behave more like bulk semiconductors with continuous energy bands.

Comparison with Bulk Semiconductor Behavior

The calculated results highlight the significant differences between bulk semiconductors and nanoscale semiconductor particles. In bulk CdSe, the band gap remains fixed at approximately 1.74 eV regardless of crystal size. However, in nanoparticles the band gap can vary over a wide range depending on particle diameter. This tunability provides an important advantage for engineering materials with specific optical or electronic properties. The results therefore confirm that quantum confinement plays a central role in determining the physical behavior of semiconductor nanostructures. The results obtained in this study provide clear theoretical evidence of the significant influence of quantum confinement on the electronic properties of semiconductor nanoparticles. The calculated increase in band gap energy with decreasing particle size is consistent with the fundamental principles of quantum mechanics and solid-state physics. When the size of a semiconductor particle approaches the nanoscale regime, the motion of electrons and holes becomes spatially restricted within the nanoparticle. This spatial confinement increases the kinetic energy of the charge carriers and leads to quantization of energy levels, resulting in an enlargement of the effective band gap compared with the bulk material (Zapata-Herrera et al., 2018). The numerical results demonstrate that the band gap energy of semiconductor nanoparticles increases substantially as the particle diameter decreases from 10 nm to 2 nm. This trend is in strong agreement with theoretical predictions based on the effective mass approximation and the Brus equation. The increase in band gap energy arises primarily from the confinement energy term, which varies inversely with the square of the particle radius. As the radius becomes smaller, the confinement energy increases rapidly, causing a widening of the separation between the valence and

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conduction bands. This phenomenon explains the size-dependent optical behavior of semiconductor nanoparticles and confirms that nanoscale materials exhibit fundamentally different electronic properties from bulk semiconductors.

Another important aspect highlighted by the results is the role of the exciton Bohr radius in determining the regime of quantum confinement. For semiconductor materials such as CdSe, the exciton Bohr radius is approximately 5–6 nm. When the particle size becomes smaller than this value, strong quantum confinement occurs because both the electron and hole are confined within the nanoparticle volume. Under these conditions, the energy states become discrete and resemble atomic-like levels rather than continuous bands. The present study shows that particles with diameters below 5 nm exhibit the most significant changes in band gap energy, confirming the transition to the strong confinement regime (Agumba et al., 2026).

The observed increase in band gap energy also has important implications for the optical properties of semiconductor nanocrystals. As the band gap widens with decreasing particle size, the wavelength of absorbed or emitted photons shifts toward shorter wavelengths, resulting in a blue shift in optical spectra. This size-dependent tunability of optical properties is one of the most valuable features of semiconductor quantum dots and has led to their widespread use in applications such as light-emitting diodes, solar cells, photodetectors, and biological imaging. The ability to precisely control emission color by adjusting nanoparticle size provides a powerful approach for designing advanced optoelectronic devices (González et al., 2014).

Although the theoretical model used in this study successfully explains the general behavior of quantum confinement, some limitations must also be considered. The effective mass approximation assumes ideal spherical nanoparticles with uniform composition and perfectly confined boundaries. In real nanomaterials, factors such as surface defects, lattice strain, particle aggregation, and dielectric mismatch with the surrounding environment can influence electronic and optical properties. Surface atoms, which constitute a large fraction of the total atoms in nanoparticles, may introduce defect states that modify the band structure and alter optical transitions. Despite these limitations, the present analysis provides a reliable description of the fundamental physics governing quantum confinement in semiconductor nanoparticles. The results highlight how nanoscale dimensions can dramatically modify the electronic structure of materials and demonstrate the importance of theoretical modeling in understanding these effects. Furthermore, the findings emphasize the potential of semiconductor nanocrystals for technological applications where precise control of electronic and optical properties is required (Panariello et al., 2020). Overall, the discussion confirms that quantum confinement plays a crucial role in determining the size-dependent properties of semiconductor nanoparticles. Continued research combining theoretical modeling with experimental synthesis and characterization will further advance the understanding of nanoscale semiconductors and enable the development of next-generation nanotechnology devices (Personick, 2024).

Conclusions

This study investigated the quantum confinement effects in semiconductor nanoparticles from a solid-state physics perspective by applying theoretical modeling

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based on the Brus equation. The analysis focused on understanding how variations in nanoparticle size influence the electronic band structure, particularly the band gap energy. The results demonstrated that the band gap energy increases significantly as the size of the semiconductor nanoparticles decreases. This behavior occurs because the spatial confinement of electrons and holes within a very small volume increases their kinetic energy, leading to a widening of the energy separation between the valence and conduction bands. Furthermore, the calculations revealed that the confinement energy is inversely proportional to the square of the particle radius, which means that even small reductions in particle size can cause substantial increases in the energy levels of charge carriers. The study also showed that strong quantum confinement occurs when the nanoparticle size becomes smaller than the exciton Bohr radius of the semiconductor material. Under such conditions, the motion of both electrons and holes is restricted in all spatial directions, resulting in discrete energy levels rather than continuous energy bands. This phenomenon significantly alters the optical and electronic behavior of the material. One of the most important implications of this effect is that the optical properties of semiconductor nanoparticles can be precisely tuned by controlling their size during synthesis. By adjusting nanoparticle dimensions, it becomes possible to modify absorption and emission wavelengths across different regions of the electromagnetic spectrum. Overall, these findings highlight the fundamental role of quantum confinement in determining the properties of nanoscale materials and emphasize its importance in the design and development of advanced electronic, photonic, and optoelectronic devices.

References

Agumba, J. O., Barasa, G. O., Takembo, C. N., Amuyunzu, P. M. A., & Owino, J. (2026). Silver nanoparticle kinetics: plasmonic and quantum confinement modeling. *Applied Physics A*, *132*(2), 115.

Ashrafi, A. (2011). Quantum confinement: An ultimate physics of nanostructures. *Encyclopedia of Semiconductor Nanotechnology*, *1*(10), 1-67.

Biju, V., Itoh, T., Anas, A., Sujith, A., & Ishikawa, M. (2008). Semiconductor quantum dots and metal nanoparticles: syntheses, optical properties, and biological applications. *Analytical and bioanalytical chemistry*, *391*(7), 2469-2495.

Bryan, J. D., & Gamelin, D. R. (2005). Doped semiconductor nanocrystals: synthesis, characterization, physical properties, and applications. *Progress in inorganic chemistry*, *54*, 47-126.

Chen, X., Moore, J. E., Zekarias, M., & Jensen, L. (2015). Atomistic electrodynamics simulations of bare and ligand-coated nanoparticles in the quantum size regime. *Nature communications*, *6*(1), 8921.

Edvinsson, T. (2018). Optical quantum confinement and photocatalytic properties in two-, one-and zero-dimensional nanostructures. *Royal society open science*, *5*(9).

González, A. L., Noguez, C., Beránek, J., & Barnard, A. S. (2014). Size, shape, stability, and color of plasmonic silver nanoparticles. *The Journal of Physical Chemistry C*, *118*(17), 9128-9136.

Heinzel, T. (2008). *Mesoscopic electronics in solid state nanostructures*. John Wiley &

Online ISSN 3007-3197
Print ISSN 3007-3189

Sons.

Horechyy, A., Paturej, J., Nandan, B., Jehnichen, D., Göbel, M., Reuter, U., ... & Stamm, M. (2020). Nanoparticle assembly under block copolymer confinement: The effect of nanoparticle size and confinement strength. *Journal of colloid and interface science*, *578*, 441-451.

Kambhampati, P. (2021). Nanoparticles, nanocrystals, and quantum dots: What are the implications of size in colloidal nanoscale materials?. *The Journal of Physical Chemistry Letters*, *12*(20), 4769-4779.

Katan, C., Mercier, N., & Even, J. (2019). Quantum and dielectric confinement effects in lower-dimensional hybrid perovskite semiconductors. *Chemical reviews*, *119*(5), 3140-3192.

Khairutdinov, R. F. (1998). Chemistry of semiconductor nanoparticles. *Russian chemical reviews*, *67*(2), 109-122.

Onyia, A. I., Ikeri, H. I., & Nwobodo, A. N. (2018). Theoretical study of the quantum confinement effects on quantum dots using particle in a box model. *Journal of Ovonic Research*, *14*(1), 49-54.

Panariello, L., Radhakrishnan, A. N., Papakonstantinou, I., Parkin, I. P., & Gavriilidis, A. (2020). Particle size evolution during the synthesis of gold nanoparticles using in situ time-resolved UV–Vis spectroscopy: An experimental and theoretical study unravelling the effect of adsorbed gold precursor species. *The Journal of Physical Chemistry C*, *124*(50), 27662-27672.

Park, K., Deutsch, Z., Li, J. J., Oron, D., & Weiss, S. (2012). Single molecule quantum-confined stark effect measurements of semiconductor nanoparticles at room temperature. *ACS nano*, *6*(11), 10013-10023.

Personick, M. L. (2024). Light as an orthogonal synthetic parameter in metal nanoparticle growth. *The Journal of Physical Chemistry C*, *128*(20), 8131-8146.

Ramalingam, G., & Kathirgamanathan, P. (2020). Quantum Confinement Effect of. *Quantum Dots: Fundamental and Applications*, *11*.

Rogach, A. L. (2008). Semiconductor nanocrystal quantum dots. *Verlag: Wien*, 17.

Rogach, A. L., Talapin, D. V., & Weller, H. (2003). *Semiconductor nanoparticles* (pp. 52-91). Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, FRG.

Scher, J. A., Elward, J. M., & Chakraborty, A. (2016). Shape matters: effect of 1D, 2D, and 3D isovolumetric quantum confinement in semiconductor nanoparticles. *The Journal of Physical Chemistry C*, *120*(43), 24999-25009.

Smith, A. M., & Nie, S. (2010). Semiconductor nanocrystals: structure, properties, and band gap engineering. *Accounts of chemical research*, *43*(2), 190-200.

Sun, C. Q., Chen, T. P., Tay, B. K., Li, S., Zhang, Y. B., Huang, H., ... & Sun, X. W. (2001). An extendedquantum confinement'theory: surface-coordination imperfection modifies the entire band structure of a nanosolid. *Journal of Physics D: Applied Physics*, *34*(24), 3470-3479.

Sun, Y., Gao, S., Lei, F., Xiao, C., & Xie, Y. (2015). Ultrathin two-dimensional inorganic materials: new opportunities for solid state nanochemistry. *Accounts of chemical research*, *48*(1), 3-12.

Vanmaekelbergh, D., & Liljeroth, P. (2005). Electron-conducting quantum dot solids: novel materials based on colloidal semiconductor nanocrystals. *Chemical*

Online ISSN 3007-3197
Print ISSN 3007-3189

Society Reviews, *34*(4), 299-312.

Wan, K., Shi, X., & Wang, H. (2021). Quantum confinement and size resolved modeling of electronic and optical properties of small soot particles. *Proceedings of the Combustion Institute*, *38*(1), 1517-1524.

Zapata-Herrera, M., Flórez, J., Camacho, A. S., & Ramírez, H. Y. (2018). Quantum confinement effects on the near field enhancement in metallic nanoparticles. *Plasmonics*, *13*(1), 1-7.

Zhang, J. Z. (1997). Ultrafast studies of electron dynamics in semiconductor and metal colloidal nanoparticles: effects of size and surface. *Accounts of chemical research*, *30*(10), 423-429.

Zhang, L. Z., Sun, W., & Cheng, P. (2003). Spectroscopic and theoretical studies of quantum and electronic confinement effects in nanostructured materials. *Molecules*, *8*(1), 207-222.