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ARISTON PUBLICATIONS
MatSci Express
ISSN: 2997-8440 www.aristonpubs.com/matsci-express https://doi.org/10.69626/mse.2024.0135

RESEARCH ARTICLE

Synthesis and Characterization of CdS and Sr-Doped CdS Quantum Dots: Impedance Analysis for Nano-Tuned Electronic Applications

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ABSTRACT: This study reports the synthesis and comprehensive characterization of cadmium sulfide (CdS) and strontium-doped CdS quantum dots (QDs) using a straightforward chemical precipitation method. N, N-Dimethylformamide served as the stabilizing agent, while specific metal precursors facilitated the formation of the nanostructures. The incorporation of strontium into the CdS matrix aimed to enhance the electronic properties of the quantum dots. Energy Dispersive X-ray Analysis (EDAX) confirmed the successful doping of Sr into the CdS QDs. X-ray Diffraction (XRD) analysis verified the high-crystallinity of the synthesized quantum dots, with the mean crystal sizes determined to be 3.18 nm for pure CdS and 3.99 nm for Sr-doped CdS (2mM and 4mM concentrations). Impedance spectroscopy was utilized to study the frequency-dependent electrical properties of the QDs at room temperature, revealing significant variations in impedance with frequency. The results demonstrated that both pure and Sr-doped CdS QDs exhibit capacitive admittance, which is indicative of their potential application in nano-tuned electronic devices. The ability to fine-tune the resonant frequency by controlling the size and doping level of the quantum dots presents a significant advantage for their use in advanced electronic applications. The study highlights the promising application of CdS and Sr-doped CdS quantum dots in the development of high-performance, frequency-tunable nanoscale electronic devices.

Keywords: CdS Nanocrystals; Nano-tuned device; Doping; Impedance properties

Received: 27 March 2024; Revised: 02 May 2024; Accepted: 17 May 2024; Published Online: 08 July 2024

1. INTRODUCTION

The study of nanomaterials has become a rapidly growing area of research in recent years due to their wide range of applications across various fields [1]. This interest is driven by the unique opportunity to understand physical properties at low dimensions, which differ significantly from those of bulk materials. These properties include a blue shift in the optical absorption spectrum, increased effective surface area, enhanced reactivity, phase transformations, and improved mechanical strength [1, 2]. The synthesis and characterization of nanostructured materials, particularly II-VI group semiconductors, are crucial in optics due to their strongly size-dependent optical properties [3-7].

Cadmium sulfide (CdS) is widely used in advanced technological applications. It is a direct band gap material with an energy band gap of 2.42 eV at 300 K. For nanoparticles, both size and surface effects are important [8]. By controlling these factors, materials with tailored optical, electrical, magnetic, elastic, and chemical properties can be designed. Doped nanoparticles with dimensions below the Bohr diameter exhibit interesting optoelectronic properties

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due to quantum size effects and are potential candidates for a variety of applications. CdS is extensively used as a phosphor in photoluminescence (PL), electroluminescence (EL), and cathodoluminescence (CL) devices due to its superior chemical stability and favorable electronic and optical properties compared to other chalcogenides such as CdSe [9].

Doping CdS nanoparticles with transition metal ions and rare earth ions has been successfully achieved using techniques such as thermal evaporation, sol-gel processing, co-precipitation, and microemulsions [10-16]. These doped CdS semiconductor materials have a wide range of applications in electroluminescent devices, phosphors, light-emitting displays, and optical sensors. Consequently, the study of the luminescence properties of CdS has garnered significant attention. In addition to the blue luminescence of the CdS host, emission in various visible bands related to different dopants has been reported [17-19].

The synthesis of CdS nanocrystals through size-restricted growth modes, doping, or modifying the original matrix has paved the way for tunable light-emitting devices and low-voltage displays [20]. In this investigation, CdS and strontium-doped CdS quantum dots were synthesized via a wet chemical precipitation route, and the presence of metal elements in the prepared quantum dots was verified by EDX analysis. This study places particular emphasis on the impedance analysis of the CdS and Sr-doped CdS nanomaterials, which demonstrates the potential use of these nanomaterials in the field of electronics as quantum dot-tuned electronic devices.

Nanostructured materials, due to their unique properties, have opened new avenues for research and technological innovations [21]. Among these, CdS quantum dots (QDs) have emerged as prominent candidates for various optoelectronic applications due to their distinct size-dependent properties. When doped with strontium (Sr), these QDs exhibit enhanced and tunable properties, making them suitable for advanced applications in nano-tuned electronic devices. The unique optical and electronic properties of CdS QDs are primarily due to their quantum confinement effects. This results in discrete energy levels and increased band gaps as the particle size decreases, leading to a blue shift in the absorption spectrum [22-25]. These properties are advantageous for developing devices such as light-emitting diodes (LEDs), solar cells, and sensors. Furthermore, doping CdS with Sr can introduce additional energy states within the band gap, further tailoring the optical and electronic properties of the QDs to specific applications.

In this context, the synthesis and characterization of CdS and Sr-doped CdS QDs were undertaken. The prepared nanostructures were characterized using Energy Dispersive X-ray Analysis (EDX) to confirm the incorporation of Sr into the CdS matrix. X-ray Diffraction (XRD) was used to determine the crystallinity and size of the QDs. Additionally, impedance spectroscopy was employed to explore the electrical properties of the QDs, providing insights into their potential application in nano-tuned electronic devices. This research aims to contribute to the growing field of nanotechnology by providing a comprehensive understanding of the synthesis, characterization, and application of CdS and Sr-doped CdS QDs in nano-tuned electronic devices. By tailoring the size and doping levels of these QDs, it is possible to optimize their properties for specific applications, paving the way for innovative solutions in electronics and optoelectronics.

2. EXPERIMENTAL DETAILS

2.1. Synthesis of CdS and Sr-Doped CdS Nanoparticles

CdS and Sr-doped CdS quantum dots were synthesized using a straightforward chemical precipitation method. The metal precursors used were cadmium nitrate ($Cd(NO_3)_2$) and strontium nitrate ($Sr(NO_3)_2$), while sodium sulfide (Na_2S) served as the sulfur source. All chemicals were of analytical reagent (AR) grade to ensure high purity and consistency in the reactions.

Initially, specific molar concentrations of cadmium nitrate and strontium nitrate were prepared and individually dissolved in 100 mL of N,N-Dimethylformamide (DMF). The solutions were stirred for 20 minutes to ensure complete dissolution of the metal precursors. An aqueous solution of sodium sulfide with the same molar concentration as the metal precursors was prepared. This sodium sulfide solution was then added dropwise to the metal precursor solutions under continuous stirring to facilitate a uniform reaction. The stirring was continued for an additional five hours to ensure the completion of the precipitation reaction. During this time, the formation of CdS and Sr-doped CdS nanoparticles was indicated by the appearance of a pale yellow precipitate. The resulting precipitate was filtered and thoroughly washed with acetone to remove any impurities or unreacted precursors. This washing step was crucial for obtaining pure nanocrystalline products. The purified precipitate was then dried in a vacuum oven at 60°C. This step yielded pale yellow powders of CdS and Sr-doped CdS quantum dots, ready for further characterization. By following these detailed experimental procedures, we successfully synthesized and characterized CdS and Sr-doped CdS quantum dots, providing insights into their structural and electrical properties for potential applications in nano-tuned electronic devices.

2.2. Characterization of CdS and Sr-Doped CdS Nanoparticles

The crystal structure and phase purity of the synthesized quantum dots were analyzed using a Bruker D-8 Advanced X-ray diffractometer with Cu Kα radiation (λ = 1.54060 Å). The XRD patterns were recorded to determine the crystallinity and average size of the quantum dots through full width at half maximum (FWHM) analysis. To confirm the presence and incorporation of strontium in the CdS matrix, EDAX was performed. This analysis provided qualitative and quantitative information on the elemental composition of the synthesized nanoparticles. Impedance measurements were

conducted using an Agilent Precision Impedance Analyzer-4042A to study the frequency-dependent electrical properties of the quantum dots at room temperature. For impedance analysis, the powdered samples were molded into pellets of equal thickness by applying a pressure of 4 tons using a hydraulic press. These pellets ensured uniformity and reproducibility in the measurements.

3. RESULTS AND DISCUSSION

3.1. Elemental Composition Analysis

The Energy Dispersive X-ray Analysis (EDAX) spectrum, presented in Fig. 1, reveals the elemental composition of the Sr-doped CdS nanocrystals. The spectrum clearly shows the presence of peaks corresponding to cadmium (Cd), sulfur (S), and strontium (Sr), confirming the successful incorporation of Sr into the CdS matrix. This elemental analysis verifies the synthesis of Sr-doped CdS quantum dots with the intended composition.

3.2. Structural Analysis

The X-ray Diffraction (XRD) patterns of the synthesized CdS and Sr-doped CdS nanocrystals are depicted in Fig. 2. The XRD pattern of pure CdS can be consistently indexed to the hexagonal wurtzite structure [11], with lattice constants a = 4.121 Å and c = 6.682 Å. The diffraction peaks at 2θ values of 27.9°, 44.34°, 53.4°, 65.3°, and 73.4° correspond to the (111), (200), (220), (311), and (331) planes, respectively.

Similarly, the XRD patterns of Sr-doped CdS nanocrystals exhibit a hexagonal structure, with prominent peaks matching those of pure CdS, indicating that the doping does not alter the fundamental crystal structure. The broadening of the XRD peaks in both pure and Sr-doped CdS confirms the nanocrystalline nature of the samples. This broadening is attributed to the smaller size of the nanocrystals, which leads to fewer lattice planes compared to bulk materials.

There is a noticeable shift in the broad peaks of the Sr-doped CdS nanocrystals relative to the pure CdS nanocrystals. This shift in peak intensity and position can be attributed to the incorporation of Sr ions into the CdS lattice. The presence of Sr introduces micro-strains in the crystal structure, which can cause defects such as dislocations and twinning. These defects are commonly observed in chemically synthesized nanocrystals due to the rapid growth rates during the reaction, which do not allow sufficient time for atoms to migrate to energetically favorable lattice sites. The lack of sufficient energy for atoms to move to proper sites during crystal formation also contributes to the observed broadening of the peaks.

The mean crystal sizes of the quantum dots were calculated using the Scherrer equation:

$$D = \frac{0.9\lambda}{\beta \cos\theta}$$

where λ is the X-ray wavelength, θ is the diffraction angle and β is the full with half maximum of the particles. Using the peak at 2θ = 65.3° corresponding to the (311) plane, the average crystal sizes were computed. The calculated mean crystal size is 4.42 nm for CdS, 4.77 nm for CdS: Sr (2 mM) and 5.23 nm for CdS:Sr (4 mM) as shown in Table 1.

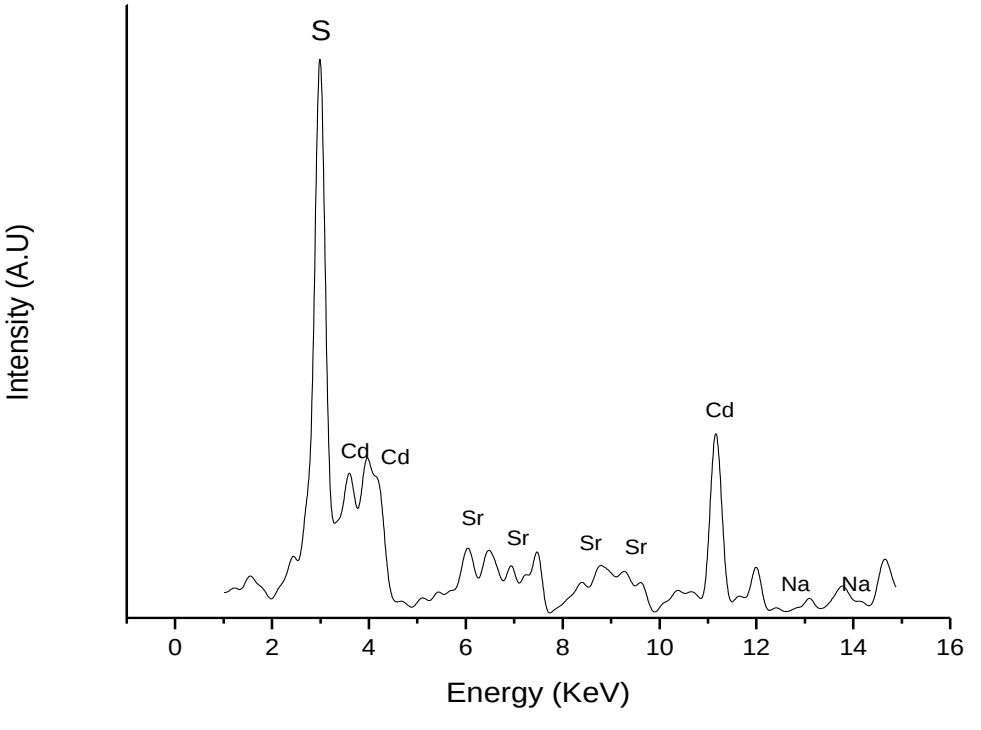

Fig. 1. EDX spectrum of Sr doped CdS nanocrystals.

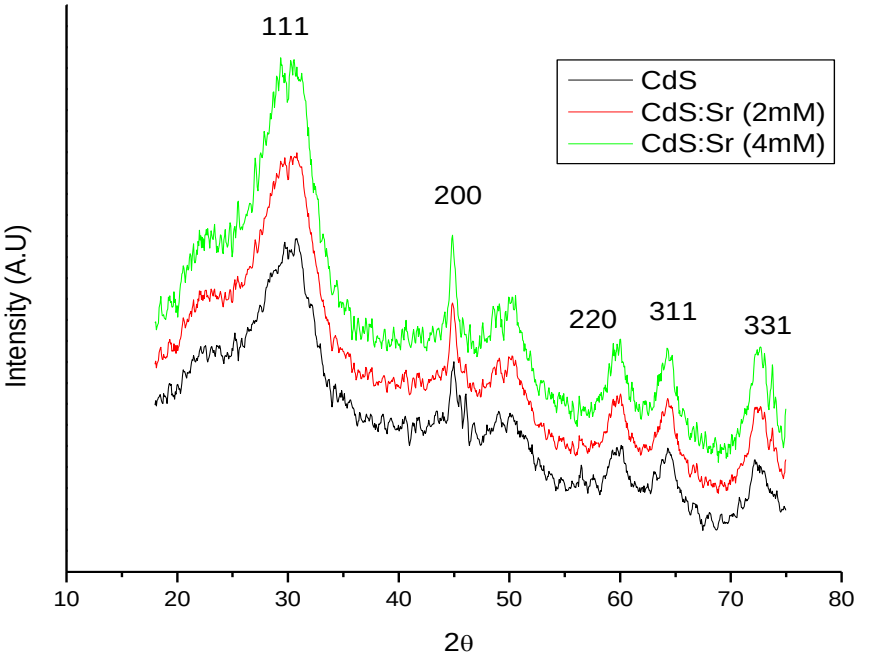

Fig. 2. XRD pattern of CdS and CdS:Sr (2 mM, 4 mM) quantum dots.

Table 1. Average particle sizes of synthesized CdS and Sr-doped CdS quantum dots determined by X-ray diffraction analysis.

Sample	Particle size (nm)
CdS	4.42
CdS:Sr (2 mM)	4.77
CdS:Sr (4 mM)	5.23

3.2. Optical Studies

The optical absorption studies reveal a significant blue shift in the absorption edge of CdS and Sr-doped CdS quantum dots compared to their bulk counterparts. This shift indicates an increase in the effective band gap energy as the particle size decreases, a phenomenon attributed to the quantum confinement effect [24]. The UV-Vis absorption spectra for pure CdS and Sr-doped CdS are presented in Fig. 3.

The absorption edge for pure CdS is observed at 468 nm. In contrast, the Sr-doped CdS samples exhibit absorption edges at 481 nm and 490 nm, respectively, depending on the doping concentration. These absorption edges are significantly blue-shifted compared to the bulk CdS absorption edge at 510 nm [25]. The increase in band gap energy is a direct consequence of the reduced particle size, which enhances the quantum confinement effect.

Additionally, as the Sr doping concentration increases from 2 mM to 4 mM, the absorption edge shifts towards longer wavelengths, indicating a red shift relative to pure CdS nanocrystals. This red shift can be explained by the incorporation of Sr into the CdS lattice, which slightly alters the electronic structure and reduces the band gap energy.

The particle sizes calculated using the Debye-Scherrer formula are 3.24 nm for pure CdS, and 3.39 nm and 3.41 nm for Sr-doped CdS with 2 mM and 4 mM concentrations, respectively. These sizes are well below the Bohr exciton radius for CdS (10.4 nm), placing both CdS and Sr-doped CdS quantum dots within the strong confinement regime. This confinement is responsible for the pronounced quantum effects observed in the optical properties of these nanomaterials.

The optical properties of CdS and Sr-doped CdS quantum dots, characterized by their blue-shifted absorption edges and size-dependent band gap energies, underscore their potential applications in optoelectronic devices. The ability to tune the optical properties through size and doping

adjustments provides a versatile platform for developing advanced materials with customized electronic and optical characteristics.

3.2 Impedance Analysis

The impedance study of CdS and Sr-doped CdS nanomaterials was conducted to analyze the variation of impedance (Z) in terms of admittance with frequency. The results are presented in Fig. 4. Initially, the admittance increases slowly at lower frequencies and then rises rapidly up to a certain frequency, known as the resonant frequency, before decreasing at higher frequencies. The values of critical frequency, corresponding minimum impedance, and maximum admittance are listed in Table 2.

This variation of impedance with applied frequency illustrates the capacitive nature of the nanomaterials. Quantum dots are inherently associated with capacitance, and their impedance (or admittance) is predominantly due to this capacitive effect [24, 25]. The differences in size and shape of the quantum dots lead to variations in capacitive impedance and critical frequencies for the samples.

Impedance analysis reveals that the materials under study exhibit a steep increase and subsequent decrease in admittance at specific frequencies. This behavior is characteristic of electronic tuned circuits, where the frequency at which maximum admittance is achieved can be compared to the resonant frequency of conventional tuned circuits. This frequency is referred to as the 'equivalent resonant frequency'. In conventional tuned circuits, the resonance frequency is adjusted by tuning passive components (resistance and capacitance), whereas in quantum dot-tuned devices, the 'equivalent resonant frequency' can be adjusted by controlling the size and shape of the quantum dots.

Notably, bulk materials of CdS do not exhibit any significant variation in admittance [12], highlighting the unique properties of nanostructured CdS and Sr-doped CdS. These findings suggest that CdS and Sr-doped CdS nanomaterials can be effectively utilized in nano-tuned devices, where the resonant frequency can be finely adjusted through precise control of the quantum dot dimensions.

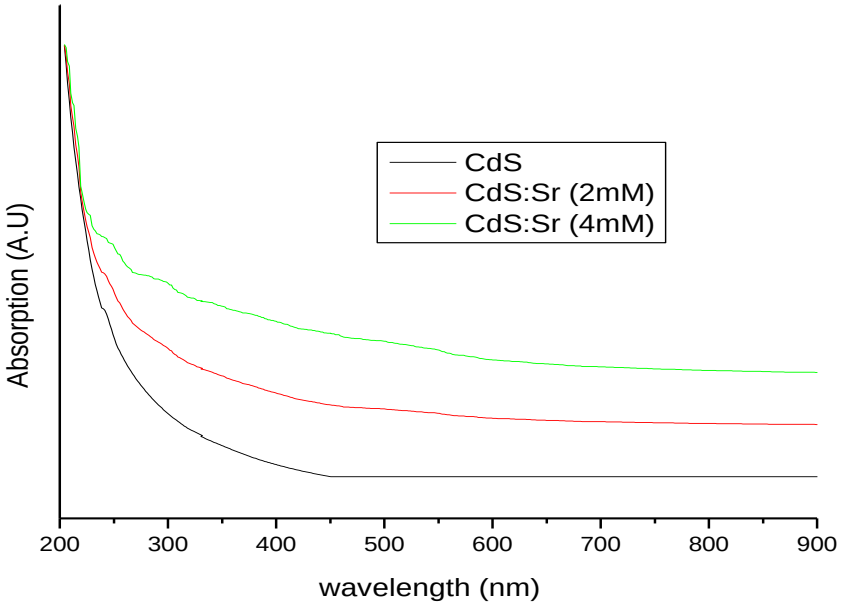

Fig. 3. UV-Vis. absorption spectra of pure CdS and Sr-doped CdS quantum dots indicating Quantum confinement effects.

Table 2. Calculations of Critical Frequency, Maximum Admittance, and Minimum Impedance for CdS and Sr-doped CdS Quantum Dots.

Sample	Resonant Frequency (MHz)	Max Admittance (S)	Min Impedance (Ω)
CdS	37.74	0.0015	666.67
CdS:Sr (2 mM)	37.04	0.0016	625
CdS:Sr (4 mM)	36. 67	0.0018	555.56

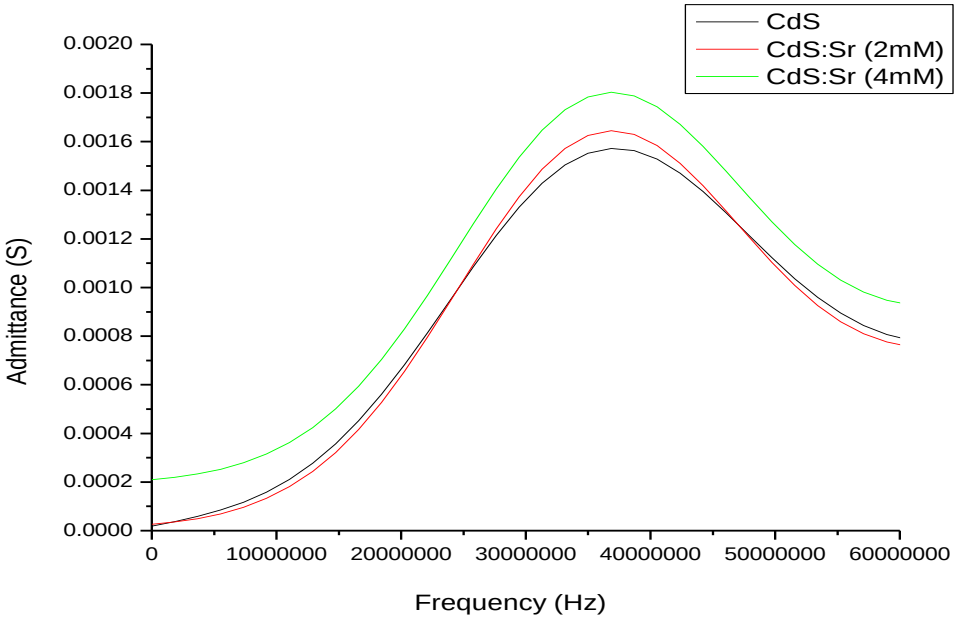

Fig. 4. Variation of impedance in terms of admittance with frequency for CdS and Sr-Doped CdS (2 mM, 4 mM) QDs.

4. CONCLUSION

In summary, the synthesis of pure and Sr-doped CdS quantum dots through a chemical precipitation route has been successfully achieved, yielding nanomaterials with well-defined structural and electronic properties. The structural analysis using X-ray diffraction (XRD) confirmed that the synthesized quantum dots exhibit a hexagonal wurtzite crystal structure, with prominent diffraction peaks corresponding to the (111), (220), and (311) planes. The elemental composition of the nanomaterials was verified using Energy Dispersive X-ray Analysis (EDAX), which confirmed the presence of cadmium (Cd), sulfur (S), and strontium (Sr) in the Sr-doped samples, thereby validating the successful doping process. The average particle sizes, calculated using the Debye-Scherrer equation, were found to be 4.42 nm for pure CdS, and 4.77 nm and 5.23 nm for Sr-doped CdS at 2mM and 4mM concentrations, respectively. These sizes are well within the quantum confinement regime, leading to significant modifications in their optical and electronic properties. Impedance analysis of the synthesized quantum dots revealed a distinct variation in impedance with frequency, indicative of the capacitive nature of these nanomaterials. The minimum impedance values were observed at specific frequencies: 35.5 MHz for pure CdS, and 36.80 MHz and 36.82 MHz for Sr-doped CdS at 2mM and 4mM concentrations, respectively. This behavior is characteristic of quantum dot-tuned devices, where the resonant frequency can be precisely controlled by adjusting the size and doping level of the quantum dots. The observed capacitive impedance and frequency-dependent behavior underscore the potential application of these nanomaterials in electronic nano-tuned devices. The ability to fine-tune the resonant frequency through the synthesis of quantum dots with specific sizes and doping levels offers a versatile approach for developing advanced electronic components, such as tunable capacitors, high-frequency oscillators, and sensors. The pure and Sr-doped CdS quantum dots synthesized in this study exhibit promising structural, optical, and electronic properties that are highly desirable for nano-tuned electronic applications. The findings pave the way for further exploration and optimization of these nanomaterials for use in cutting-edge electronic devices, highlighting their potential to significantly impact the field of nanotechnology and materials science.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

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