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Electro-Optical Characterization and Enhanced Electroluminescence of Copper-Doped CdTe and ZnTe Quantum Dot for Nano-LED Applications

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Abstract

This study presents electro-optical characterization of self-assembled thin films composed of copper-doped CdTe and ZnTe quantum dots synthesized via a straightforward chemical route. High-resolution transmission electron microscopy (HRTEM) confirms that the CdTe:Cu and ZnTe:Cu quantum dots adopt a spherical structure with sizes below 15 nm and can be uniformly incorporated into thin films. Scanning electron microscopy (SEM) reveals surface morphology and roughness of these films. Optical absorption measurements show a blue-shifted sharp absorption edge at 426 nm for CdTe:Cu, corresponding to an increased band gap energy of 1.23 eV. For ZnTe:Cu quantum dots, a band gap increase of 1.91 eV is observed. Electroluminescence (EL) spectra of CdTe:Cu closely match their fluorescence spectra, exhibiting smooth and sharp emission peaks between 605 and 614 nm. Also, ZnTe:Cu quantum dots demonstrate intense green luminescence, attributed to effective Cu^{2+} ion incorporation, which enhances emission intensity in both nanocomposites. These findings highlight that copper doping significantly modifies the optical properties of CdTe and ZnTe quantum dots, producing enhanced luminescence suitable for applications in nano light-emitting devices (nano-LEDs). The ability to chemically prepare homogeneous films with controlled optical features offers promising opportunities in optoelectronic device fabrication.

Keywords: chemical route, copper doped, electroluminescence, quantum dots, nano-LEDs, CdTe, ZnTe.

INTRODUCTION

Among various semiconductor nanocomposites, II-VI group materials such as CdSe, CdTe, CdS, ZnS, and ZnSe have received extensive attention because they combine fundamental quantum size effects [1-24] with broad applicability. CdSe core with ZnS shell QDs, for example, are already commercially available, illustrating the practical potential of these materials. However, synthesis methods for II-VI nanocrystals [10-18] often involve expensive, complex processes, and achieving highly monodisperse quantum dots across varied chemical compositions remains a key challenge in materials science. Beyond CdTe, II-

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VI semiconductors such as ZnTe are important for various semiconductor devices including blue LEDs, laser diodes, solar cells, and microwave components. Nevertheless, ZnTe quantum dots are less explored, with only a few reports detailing their synthesis. Existing approaches include chemical replacement reactions yielding particles around 2.6 nm and colloidal core-shell ZnTe/ZnSe QDs smaller than 4 nm [10-20] . These promise potential in optoelectronics but require further development in synthesis efficiency and uniformity.

The advantage of inorganic semiconductor nanocomposites lies in their comparatively low material and processing costs relative to traditional semiconductor fabrication, enabling scalable production of large-area devices such as solar cells and nano-LED arrays. Developing cheap, non-toxic, and scalable synthesis methods aligns with the global push toward environmentally friendly nanotechnology manufacturing. This research contributes to that by demonstrating a new chemical approach to fabricate copper-doped II-VI quantum dots with enhanced luminescent and electroluminescent responses suitable for future optoelectronic and nano-LED applications [3-8] . The findings in copper-doped CdTe and the exploration of ZnTe quantum dots underscore the need for continued materials innovation to optimize particle size control, doping efficiency, emission stability, and device integration. These advancements will pave the way for the next generation of efficient, low-cost, quantum dot–based nano-LEDs with tunable color output and improved performance metrics[6-8].

The chemical synthesis route offers key advantages such as chemical stability and a slow agglomeration rate, making it a reliable method for preparing quantum dots (QDs) [1-10]. Structural analysis of copper-doped CdTe and ZnTe QDs was conducted using HRTEM and SEM, confirming their formation and morphology. Optical properties were studied through UV-Vis absorption and fluorescence spectroscopy, revealing distinct optical behaviors. Electroluminescence measurements showed sharp and intense luminescence peaks for both CdTe:Cu and ZnTe:Cu QDs. These results demonstrate that copper-doped CdTe and ZnTe quantum dots synthesized by this chemical method are promising candidates for application as nano light-emitting devices (nano-LEDs).

This research specifically focuses on a novel, simple chemical route for synthesizing copper-doped CdTe quantum dots. These doped nanostructures are investigated not only for their tunable optoelectronic properties but also for their enhanced electroluminescent characteristics, which are crucial for developing efficient nano-LED devices[5-9]. This study addresses the electroluminescence (EL) properties of transition metal–doped quantum dots (QDs), focusing on their application in solid-state nano light-emitting devices (nano-LEDs). Due to their reduced dimensionality, quantum dots exhibit a significant enhancement in the density of electronic states, which increases the probability of radiative recombination and thus light emission. These doped QDs promise cost-effective manufacturing routes for nano-LEDs, making them attractive for widespread technological use.

EXPERIMENTAL

A chemical synthesis method was employed to prepare CdTe quantum dots (QDs) [6-8]. The process began by mixing 1.25 g of tellurium powder with 50 ml of liquid paraffin, stirred continuously at 200°C for about 2 hours until a dark gray color formed, producing the tellurium precursor. In a separate beaker, 2 g of cadmium oxide, 10 ml of oleic acid, and 40 ml of liquid paraffin were stirred at 150°C for 1 hour until a light brown color appeared, creating the cadmium precursor. Five milliliters of the cadmium precursor were then quickly added to the tellurium precursor and stirred for 45 minutes at 200°C. Copper chloride was added afterward and stirred for 6 hours. The sample was left at room temperature for 10 hours before methanol was introduced to precipitate the CdTe QDs, followed by ethanol washing at 40°C to remove by-products prior to characterization.

Copper-doped ZnTe QDs were synthesized using a mixture of hydrazine hydrate, ethylene glycol, and deionized water in a 1:3:6 ratio. Then, 0.6 g zinc acetate and 0.638 g Tellurium powder were added and refluxed with stirring at 300°C. Copper chloride was added and stirred for 6 hours. The greenish-brown precipitate was collected, washed with anhydrous ethanol and hot distilled water multiple times, then vacuum-dried at 50°C for 6 hours. Samples with varying copper doping concentrations of 0%, 1%, 2%, and 3% were prepared, labeled as A, B, C, and D respectively.

The prepared quantum dot samples were characterized using various Tem, UV-Vis and SEM. UV-Visible absorption spectra were recorded using a Perkin Elmer Lambda-35 spectrophotometer. High-resolution transmission electron microscopy (HRTEM) was performed with a Jeol JEM-2100 at 200 kV to analyze particle shape, size distribution, and structure. CdTe:Cu and ZnTe:Cu samples were prepared on carbon-coated copper grids before imaging. Fluorescence spectra were measured at room temperature using a Perkin Elmer LS-45 spectrometer.

RESULTS AND DISCUSSION

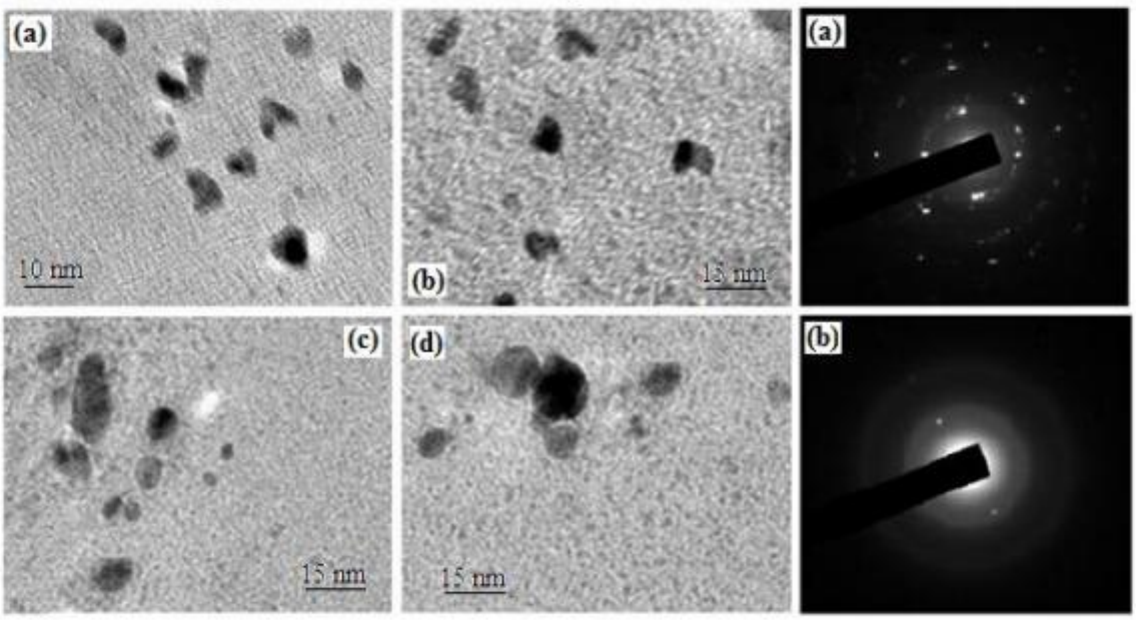

Fig. 1 High-resolution TEM images, SAED patterns of CdTe:Cu QDs

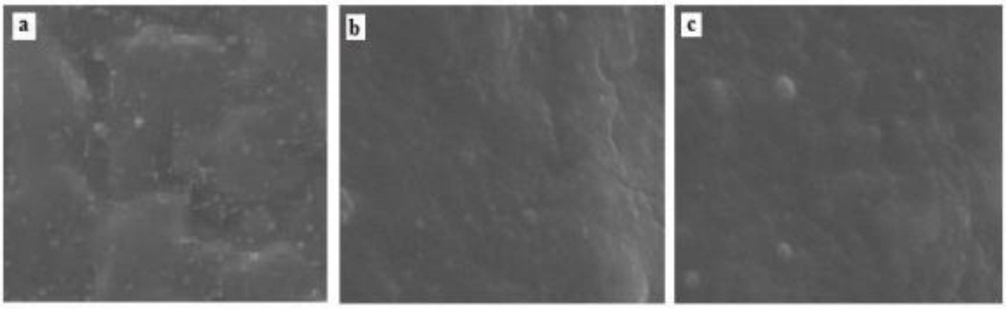

Fig. 2 SEM images CdTe & CdTe:Cu QDs.

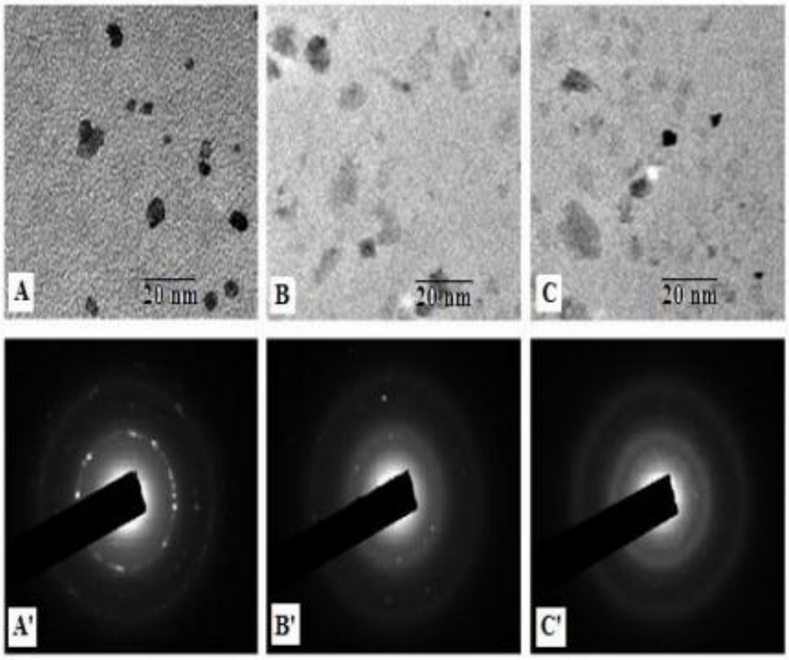

Fig. 3 High-resolution TEM images, SAED patterns of ZnTe:Cu QDs

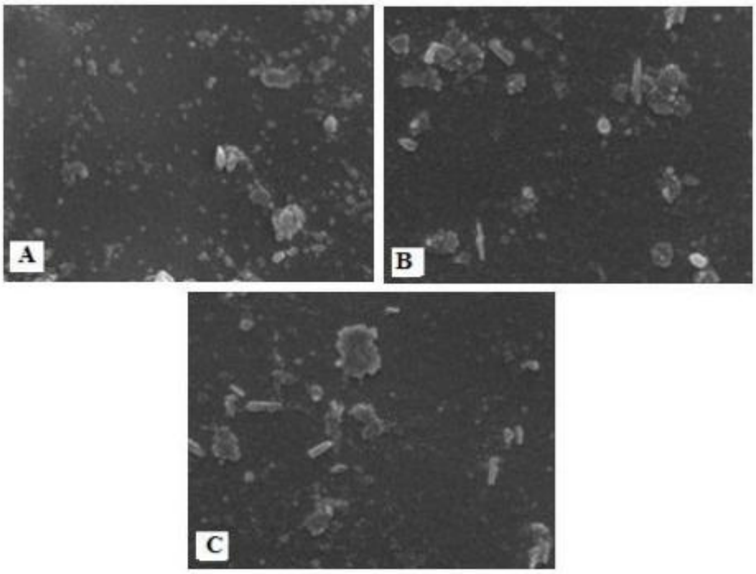

Fig. 4 SEM images ZnTe & ZnTe:Cu QDs.

High Resolution Transmission electron microscopy (TEM) in fig. 1 and scanning electron microscopy (SEM) in fig. 2 were used to study the morphology of CdTe:Cu and ZnTe:Cu quantum dots (QDs). For CdTe:Cu, TEM images reveal particle sizes ranging from 3 to 14 nm. Selected area electron diffraction (SAED) patterns show clear diffraction rings corresponding to lattice planes <111>, <220>, and <311> confirming good crystallinity [1-8]. High-resolution TEM images demonstrate well-separated, crystalline nanoparticles. SEM images indicate that CdTe:Cu QDs have rough surfaces.

Similarly, ZnTe:Cu QDs exhibit particle sizes between 2 and 14 nm as observed by TEM. SAED patterns display diffraction rings indexed to lattice planes <100>, <111>, and <200>, also indicating strong crystalline nature. High-resolution TEM confirms the formation of distinct, crystalline ZnTe:Cu nanoparticles. SEM analysis similarly shows rough surface morphology for ZnTe:Cu QDs [4-10]. These results highlight the well-defined size and crystallinity of both types of doped quantum dots.

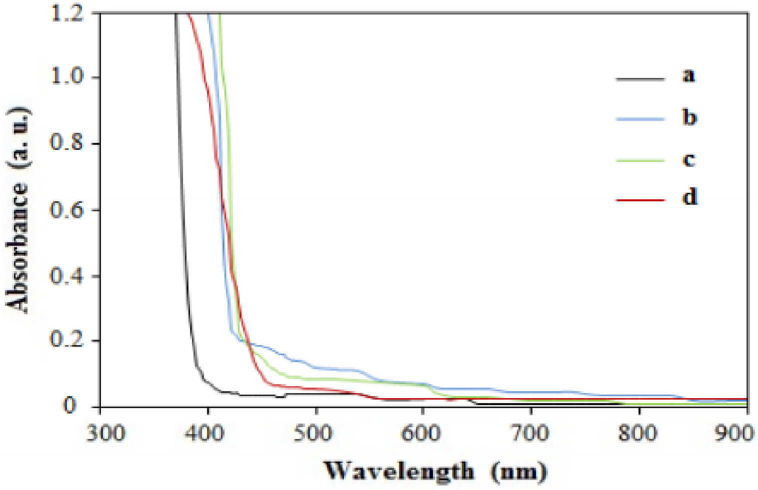

Fig. 5 Optical absorption spectra of CdTe:Cu QDs.

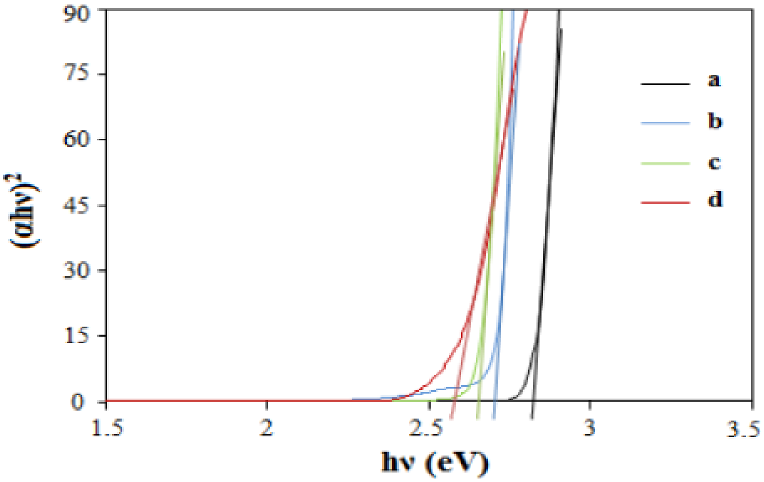

Fig. 6 Band gap energy of CdTe:Cu QDs.

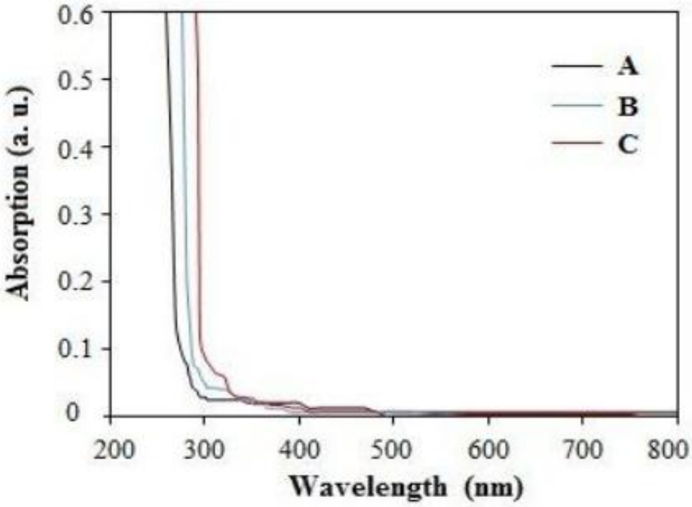

Fig. 7 Optical absorption spectra of ZnTe:Cu QDs.

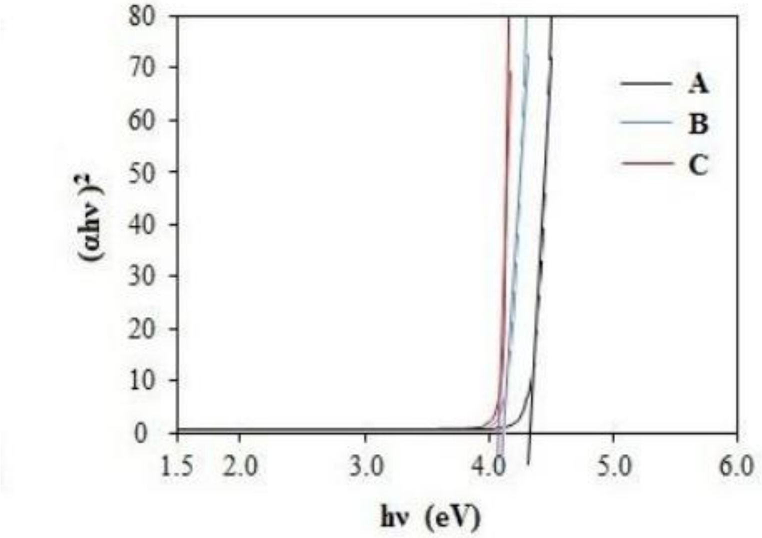

Fig. 8 Band gap energy of ZnTe:Cu QDs.

Figure 5 presents a comparison of the optical absorption spectra for CdTe and CdTe:Cu quantum dots (QDs) with varying copper doping concentrations measured at room temperature. All samples exhibit blue-shifted absorption edges compared to the bulk material, attributed to quantum confinement effects. The absorption edges for samples a, b, c, and d appear at 397 nm, 426 nm, 434 nm, and 453 nm, respectively [6]. The sharp absorption peaks indicate a near-monodisperse size distribution. Using the Tauc model, band gap energies were calculated as 2.82 eV, 2.65 eV, 2.62 eV and 2.52 eV respectively, compared to 1.44 eV for bulk CdTe. The band gap decreases with increased copper doping. Applying the effective mass approximation (EMA), particle sizes were estimated as 6.6 nm to 7.4 nm, increasing slightly with doping (fig.6).

Similarly, ZnTe and ZnTe:Cu QDs were analyzed under the same criteria (fig.7 & 8). Absorption edges were observed at 283 nm, 298 nm, and 301 nm for samples A, B, and C, respectively, all blue-shifted from the bulk ZnTe value of 2.23 eV due to quantum confinement. Band gaps were calculated as 4.39 eV, 4.15 eV, and 4.14 eV, indicating an increase of approximately 1.91 eV compared to bulk. EMA-based size estimates ranged from 11.72 nm to 12.5 nm, slightly increasing with copper doping [8]. These results confirm that copper doping influences both the optical properties and sizes of CdTe and ZnTe quantum dots.

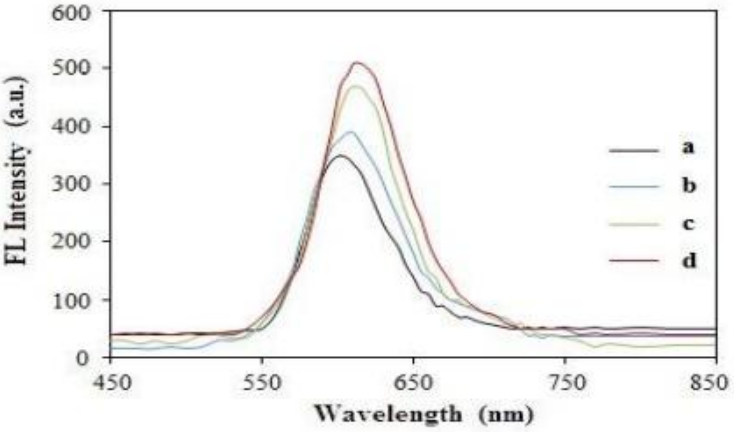

Fig. 9 Fluorescence spectra of CdTe:Cu QDs.

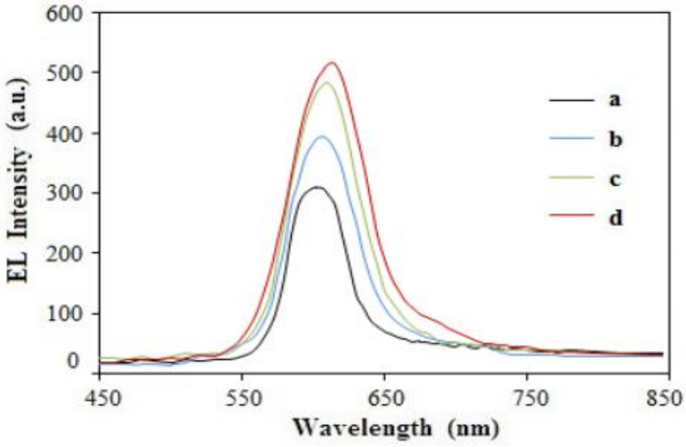

Fig.10 Electroluminescence spectra of CdTe:Cu QDs.

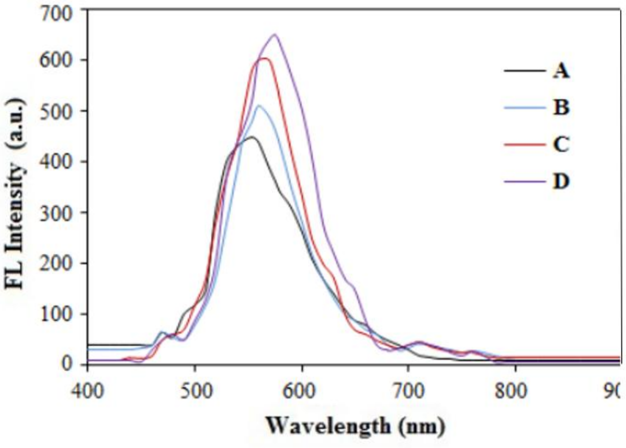

Fig.11 Fluorescence spectra of ZnTe:Cu QDs.

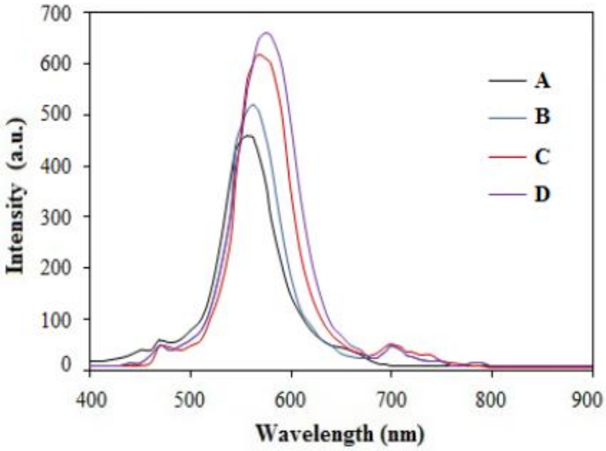

Fig.12 Electroluminescence spectra of ZnTe:Cu QDs.

Figure 9 shows the fluorescence spectra of all prepared CdTe and CdTe:Cu samples recorded at room temperature with an excitation wavelength of 350 nm. For CdTe:Cu quantum dots, luminescence peaks occur at 602 nm, 607 nm, 611 nm, and 614 nm for samples a, b, c, and d, respectively. Electroluminescence (EL) spectra (fig. 10) closely follow these fluorescence peaks within the same wavelength range [6-8]. Similarly, ZnTe:Cu samples display fluorescence peaks (fig. 11) at 554 nm, 562 nm, 569 nm, and 576 nm for samples A, B, C, and D. The EL spectra correspond closely with fluorescence, featuring green-region emission (fig. 12).

The luminescence is attributed to intermediate surface states of the quantum dots. As copper doping increases, peak intensity rises and tends to saturate at higher concentrations for CdTe and ZnTe QDs both. This enhancement is likely due to the involvement of Cu^{2+} ions. Moreover, the emission peaks shift slightly toward longer wavelengths and broaden with increased doping, possibly reflecting size growth of the QDs. Notably, EL peaks are narrower and sharper than fluorescence peaks, suggesting better-defined emission suitable for light-emitting devices in the green region. Narrow EL peaks in CdTe:Cu and ZnTe:Cu confirm their potential for green LEDs.

CONCLUSIONS

CdTe quantum dots doped with copper, sized under 15 nm, were synthesized using a simple chemical route. XRD analysis confirmed a cubic structure with no other crystalline phases. A blue shift in absorption edges due to quantum confinement increased the band gap by 1.08 eV compared to bulk material. Luminescence peaks appeared between 602 and 614 nm, attributed to intermediate surface states, shifting slightly to longer wavelengths with higher doping. Similarly, copper-doped ZnTe quantum dots under 15 nm showed cubic structure and blue-shifted absorption edges, increasing the band gap by 1.91 eV. Their luminescence peaked between 554 and 575 nm, also shifting with doping. These advances suggest potential for nano-LED development.

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