



One-step Aqueous Synthesis of Zn-based Quantum Dots as Potential Generators of Reactive Oxygen Species

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Abstract

The actual incorporation of dopant species into the ZnS Quantum Dots (QDs) host lattice will induce structural defects evidenced by a red shift in the corresponding exciton. The doping should create new intermediate energetic levels between the valence and conduction bands of the ZnS and affect the electron-hole recombination. These trap states would favour the energy transfer processes involved with the generation of cytotoxic radicals, so-called Reactive Oxygen Species, opening the possibility to apply these nanomaterials in cancer research. Any synthesis approach should consider the direct formation of the QDs in biocompatible medium. Accordingly, the present work addresses the microwave-assisted aqueous synthesis of pure and doped ZnS QDs. As-synthesized quantum dots were fully characterized on a structural, morphological and optical viewpoint. UV-Vis analyzes evidenced the excitonic peaks at approximately 310 nm, 314 nm and 315 nm for ZnS, Cu-ZnS and Mn-ZnS, respectively, Cu/Zn and Mn/Zn molar ratio was 0.05%. This indicates the actual incorporation of the dopant species into the host lattice. In addition, the Photoluminescence spectrum of non-doped ZnS nanoparticles showed a high emission peak that was red shifted when Mn^{2+} or Cu^{2+} were added during the synthesis process. The main emission peak of non-doped ZnS, Cu-doped ZnS and Mn-doped ZnS were observed at 438 nm, 487 nm and 521 nm,

respectively. Forthcoming work will address the capacity of pure and Cu-, Mn-ZnS quantum dots to generate cytotoxic Reactive Oxygen Species for cancer treatment applications.

INTRODUCTION:

Semiconductors quantum dot (QDs) are fluorescent nanocrystals with a ranging diameter of 2 nm - 10 nm [1]. The optical properties of these nanoparticles rely upon the band gap energy values; if an energy equal or greater to the band gap energy is applied to a valence electron, it will be transferred to the conduction band and thus the electron hole pair is generated. The recombination of this electron will lead to a release of energy as fluorescence [2]. Due to intrinsic optical properties of QDs, which are dependent of their size, these nanoparticles have found many technological and bio-medical applications including production of LED's (light emitting diode), photo-degradation of organic compounds, bio-imaging, and as photosensitizer to generate cytotoxic reactive oxygen species (ROS) when activated with light [3–5]. This light-driven phenomenon promotes the medical applications of these QDs in the so-called Photodynamic Therapy (PDT). PDT is usually requires organic photo-sensitizers to generate ROS and the use of QDs as direct, water-soluble and stable photosensitizers opens new applications for these nanomaterials [6]. ROS can lead to cellular death by necrotic or apoptotic pathways. Postovit et al. presented the ROS as an innovative way to target cancer diseases. Thus, reactive oxygen species stimulate cell proliferation and induce genetic instability [4, 7]. Samia et al. found that the generation of SO species depends on the presence of molecular oxygen in the capping agent on the QD surface; they also found that carrier trapping and non- radiative carrier recombination could decrease the production of singlet oxygen [8]. The factors that govern the nanotoxicity and generation of ROS by QDs include the particle size, shape, bonded surface species, the type of surface coating, the presence of impurities at trace concentrations, degree of aggregation, among others [3]. Microwave assisted synthesis has been proved to be a simple and rapid route [9]. This synthesis method produces highly stable nanoparticles with outstanding optical properties, directly in aqueous phase [10]. Based on the above considerations, the present work was focused on the development of a microwave-assisted protocol to synthesize water dispersible doped and non-doped ZnS QDs. Also, CdS was produced using the same protocol for comparison purposes.

EXPERIMENTAL METHODS

A Zinc chloride (99.999% trace metals basis), solution was mixed with an aqueous solution in a microwave digestion vessel in presence of 3-mercaptopropionic acid (MPA, $\geq 99.0\%$) at pH 12.0. The pH was later adjusted to a value of 7.0 and finally placed in the microwave reactor system. The concentration of Zn^{+2} ions in starting solutions was 100 mM. All reagents were supplied by SIGMA-ALDRICH. The microwave power was set at 1000W and the synthesis temperature at 160°C, with a reaction time of 10 minutes. Once the reaction was completed, the solution was cooled to room temperature. The formed nanocrystals were precipitated with 2-propanol, centrifuged and resuspended in deionized water. For the synthesis of the dopant variants of ZnS Quantum dots, the Zinc chloride solution was contacted with either a manganese (II) chloride tetrahydrate (99.99% trace metals basis) or a copper (II) chloride dehydrate ($\geq 99.95\%$ trace metals basis) in an aqueous solution in a microwave digestion vessel in presence of MPA at pH 12.0; Cu/Zn and Mn/Zn ratios were 0.05% each. CdS QDs were synthesized by using a cadmium (II) sulfate 8/3 hydrate (ACS, $\geq 99.0\%$) in presence of thioglycolic acid (TGA, ACS, $\geq 98\%$) under temperature of 160°C for 10 minutes. CdS

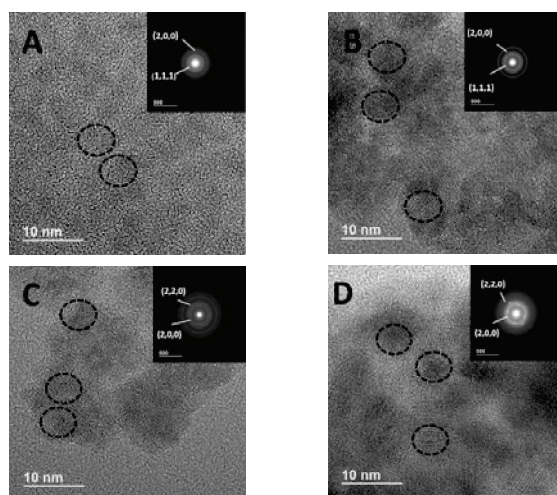
was considered based on earlier works where its capability to generate ROS was verified [11].

Samples were morphologically characterized by a high-resolution TEM (HRTEM) study which was performed on a JEM-ARM200F operated at 200 kV. The optical properties of synthesized quantum dots were evaluated by absorption and fluorescence spectroscopy using a Jasco V-630 Spectrophotometer and a Shimadzu RF-6000 Spectrofluorometer equipped with a 150-xenon lamp, respectively. Fourier Transform Infrared (FT-IR) Spectroscopy analysis between 500 and 4000 s⁻¹ was carried out in a Shimadzu IRAffinity-1S spectrophotometer.

RESULTS AND DISCUSSION

Structural and Chemical Characterization

High Resolution Transmission Electron Microscopy (HRTEM) and Electron Diffraction (ED) analyses of the nanoparticles demonstrated the formation of nanometric crystalline particles. These images evidence crystallinity even at such a small scale with an average size between 5-6nm. The crystallographic planes in the corresponding EDs confirmed the development of the host blende structure of ZnS. The Miller indexes correspond to an FCC crystalline structure [3, 4].



Figures 1A, 1B, 1C and 1D represent high resolution TEM for ZnS, Cu-ZnS, Mn-ZnS and CdS Quantum dots respectively. ED analyses are shown as inset in the HRTEM images.

The presence of functional groups related to 3-mercaptopropionic acid onto the Zn-based QDs surface was confirmed by Fourier Transmission Infrared Spectroscopy. As shown in Figure 2, the sample shows a strong band at 3379 cm⁻¹ that can be assigned to an alcohol functional group, in 3-MPA. Deprotonation of the thiol in the synthesis protocol creates a resonance structure in the carboxylic terminal of the molecules which

explains strong bands at 1535 cm^{-1} and 1396 cm^{-1} . The presence of MPA functional groups onto the Cu- and Mn-doped ZnS QDs were also verified (data not shown).

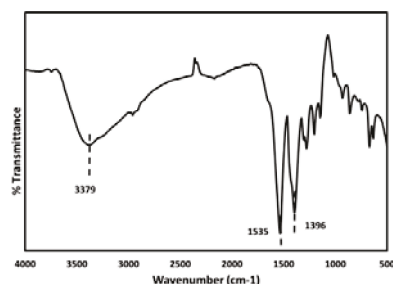


Figure 2: Fourier Transform Infrared spectroscopy for non-doped ZnS Quantum Dot.

The average chemical composition of synthesized QDs was determined using Energy Dispersion X-Ray (EDX) spectroscopy. Results, shown in Figure 3, evidenced the predominance of Zn and S, and minor amounts of the dopants.

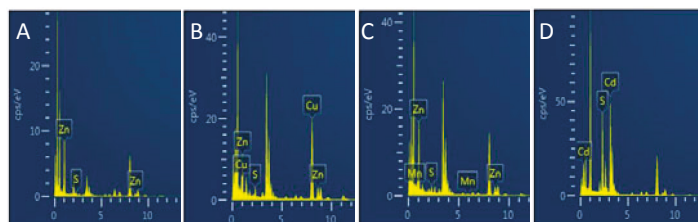


Figure 3: Energy Dispersive X-Ray Spectrum for ZnS (A), Cu-ZnS (B), Mn-ZnS (C) and CdS QDs (D), respectively. Unidentified peaks are attributed to materials pertaining to the holder in which the analysis was carried out.

Optical Properties

UV-Vis analyses, shown in Figure 4, evidenced the presence of shoulders centered approximately on 310 nm, 314 nm and 315 nm for ZnS, Cu-ZnS and Mn-ZnS, respectively, which corresponds to the excitonic peak in ZnS nanostructures [13, 14]. The band gap energy of ZnS was estimated, using Tauc's relationship, at 3.70 eV that suggests the quantum confinement effect (ZnS bulk, 3.6 eV) [6]. The presence of doping agents (i.e Cu^{2+} or Mn^{2+}) into the ZnS nanoparticles does not achieve a change in the band gap value. As we can see in Figure 4, doped variants samples evidenced similar absorption peaks to non-doped ZnS nanostructures, but different fluorescent peaks (Figure 5). The substitution of Zn^{2+} by Cu^{2+} or Mn^{2+} ions into the ZnS lattice site would explain the red-shift in the excitonic peak, as seen in Figure 5, where the main emission peaks are 438nm, 487nm and 521nm for ZnS, Mn-ZnS and Cu-ZnS quantum dots

respectively. By incorporating these ions into the crystal lattice of the QD, we should be creating intermediate energetic levels in the particle and subsequently tuning the main emission peak to a higher wavelength [12]. The incorporation of a doping agent i.e. copper or manganese into the quantum dots lattice should promote the energy transfer process from the triplet state- quantum dots to molecular oxygen and subsequent enhancement of singlet oxygen generation which is a type ROS. This characteristic suggests that more energy will be transfer from an excited triplet state of (Cu^{2+} or Mn^{2+})-doped quantum dots to the molecular oxygen in order to generate ROS in aqueous phase [3]. Thus, the addition of a doping agent like Cu^{2+} or Mn^{2+} into the lattice site could favor the generation of ROS after light excitation [15]. This later statement is supported by comparison with what has been found for CdS. CdS nanostructures showed an absorption peak centered around 441nm and a maximum emission peak at 470nm, which have been related to their capability to generate ROS [11], [16].

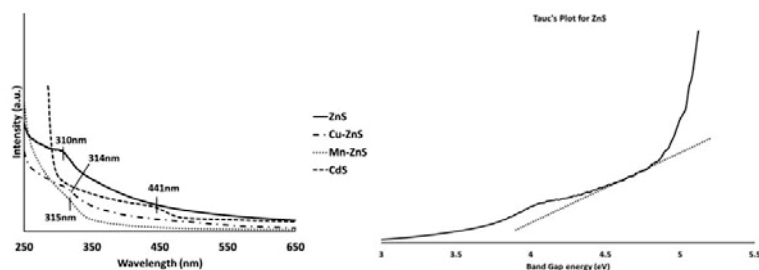


Figure 4: UV-vis absorption spectra for ZnS, Cu-ZnS, Mn-ZnS and CdS QDs (left) and Tauc's plot for ZnS (right).

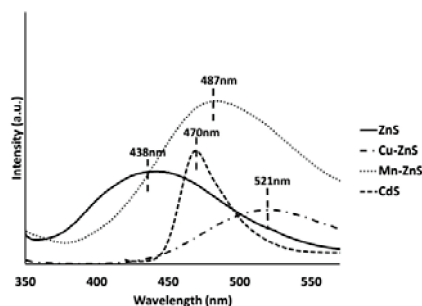


Figure 5: Photoluminescence spectra for ZnS, Cu-ZnS, Mn-ZnS and CdS QDs. The excitation wavelength for ZnS, Cu-ZnS, Mn-ZnS was 310nm and for CdS was 400nm.

CONCLUSIONS

Quantum dots were synthesized by a Microwave-assisted synthesis method in aqueous phase and characterized via UV-vis, FT-IR, PL, HRTEM, ED and EDX

techniques. Zn based QDs evidenced a significant red-shift of the exciton when doped with either Copper or Manganese species that indicate the capability of tuning the QDs optical properties by actual incorporation of dopant species into the ZnS host lattice. Future works include the assessment of the generation capacity of ZnS-based QDs to generate ROS and its subsequent effect on cancer cell viability.

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