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Controllable fabrication and characterization of biocompatible core-shell particles and hollow capsules as drug carrier

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Abstract

SiO_2@CdSe core-shell particles were fabricated by controllable deposition CdSe nanoparticles on silica colloidal spheres. Step-wise coating process was tracked by the TEM and XRD measurements. In addition, SiO_2@CdSe/polypyrrole(PPy) multi-composite particles were synthesized based on the as-prepared SiO_2@CdSe particles by cationic polymerization. The direct electrochemistry of myoglobin (Mb) could be performed by immobilizing Mb on the surface of SiO_2@CdSe particles. Immobilized with Mb, SiO_2@CdSe/PPy-Mb also displayed good bioelectrochemical activity. It confirmed the good biocompatible property of the materials with protein. CdSe hollow capsules were further obtained as the removal of the cores of SiO_2@CdSe spheres. Hollow and porous character of CdSe sub-meter size capsules made them becoming hopeful candidates as drug carriers. Doxorubicin, a typical an antineoplastic drug, was introduced into the capsules. A good sustained drug release behavior of the loading capsules was discovered via performing a release test in the PBS buffer (pH 7.4) solution at 310 k. Furthermore, SiO_2@CdSe/PPy could be converted to various smart hollow capsules via selectively removal of their relevant components.

Keywords: Core-shell particles; Hollow capsules; Bioactivity; Drug carrier

1. Introduction

Functionally core-shell nanospheres have attracted considerable attention in recent years owing to their current and potential applications as optoelectronic devices, electrochemical displays and sensors [1–5]. Apart from soft templates and in situ templates assistant [6], preparation of the core-shell structures usually involved coating hard templates [7]. Although various methods have been used, there is still a challenge in controllable coating of cores with variously functional shells. To date, polymer shell has often been directly coated via surface-initiate atom transfer radical polymerization method [8]. Most inorganic shells are formed either by directly deposition [9,10] or combination two pre-synthesized colloidal particles into core-shell assembly [11,12]. Meanwhile, microcapsule is another type of important material with wide applicability in encapsulation of drugs, enzymes, DNA, and other active macromolecules [13]. Based on the fabrication of these novel materials, it becomes more and more important to explore their probabilities in many application fields [14,15].

Chalcogenides particles are an important class of biological labeling owing to the light absorption and photoluminescence [16,17]. CdSe semiconductor quantum dots (QDs) can be covalently coupled to biomolecules so as to be used as fluorescent probes in biological detection [18]. And conductive polymers, with its electronic conductivity and ion exchange capacity [19], have also been intensively focused on due to the novel affinity with many organic and biological species [20,21]. For example, polypyrrole was confirmed to be a good binder in the planar electrochemical biosensors [22]. To get their core-

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shell and hollow particles with tailored structures and surface properties, many groups have put much effort on their fabrication. The great challenge is to realize fine coating via controllable polymerization and/or effective deposition.

Herein, we work at combination of semiconductor and conductive polymer into core-shell and hollow structures. The motivation of our work is to obtain more significantly functional core-shell or capsule nanocomposite particles for further application study. Firstly, SiO_2@CdSe and SiO_2@CdSe/polypyrrole (PPy) composite particles were synthesized. Based on the composite particles, novel capsules with different shell, such as CdSe, CdSe loaded PPy (CdSe/PPy), mesoporous PPy and PPy/CdSe hollow capsules with movable SiO_2 core (SiO_2@Air@PPy/CdSe) have been obtained. Both the electrochemical activity of core-shell particles with protein and the release behavior of CdSe capsules as drug carrier are discussed in detail.

2. Experimental

2.1. Materials and characterization

Tetraethoxysilane (TEOS), poly(*N*-vinylpyrrolidone) (PVP) (K30), sodium sulfite ($NaSO_3$), selenium (Se) powder, cadmium acetic $Cd(CH_3COO)_2{\cdot}2.5H_2O$, ammonia (32 wt.%) and ethanol were purchased from Shanghai Chemical Reagent Co. Horse heart myoglobin (Mb, MW 17800) was purchased from Sigma. Poly(diallyldimethylammonium) (PDDA) was from Aldrich. Doxorubicin (0411E2) was manufactured by Shenzhen Main Luck Pharmaceuticals Inc. All agents were used as obtained without further purification. Pyrrole was from Fluka chemie. After being distilled under decompression, the monomer was kept under 277 K. Phosphate buffer solutions (PBS, 0.1 M, containing 0.05 M KBr) at pH 7.0 were used as supporting electrolytes for electrochemical experiments. Phosphate buffer solutions (PBS) at pH 7.4 were used as solvent in drug-released measurement. All solutions were prepared with twice-distilled water.

Scanning electron microscopy (SEM) images were obtained on a JEOL JSM 840-A microscope. Transmission electron microscopy (TEM) studies were performed on a Hitachi H-800 microscope. The UV–vis spectra were registered by UV-2410 PC spectrophotometer. FTIR measurement was performed with a Vatar 360 FT-IR (Nicolet) spectrometer with a DTGS detector at 4 cm^{-1} resolution. X-ray photoelectron spectra (XPS) were obtained on a VGESCALABMKII X-ray photoelectron spectrometer, using non-monochromatized Mg Kα X-ray exciting radiation. XRD measurement was performed on the Philips X'pert X-ray diffractometer equipped with graphite monochromatized Cu Kα radiation (λ = 1.54178 Å). Electrochemical measurements were performed with CHI 621B electrochemical workstation (CH Instruments) using a basal plane pyrolytic graphite (PG, Advanced Ceramics, geometric area 0.16 cm^2) disk modified with films as the working electrode, a saturated calomel electrode (SCE) as the reference electrode, and a Pt flake as the counter electrode.

2.2. Preparation and characterization of SiO_2@CdSe core-shell particles and CdSe hollow capsules

2.2.1. Preparation of silica spheres

Through the route illustrated in Fig. 1, monodispersed silica spheres were firstly synthesized via Stöber's method [23]. Briefly, 8 ml of aqueous ammonia (32 wt.%) was added into a solution containing 146 ml of ethanol and 3 ml of deionized water. Seven millilitres of TEOS was dropped into the above-prepared mixture at 298 K under vigorous stirring. The reaction

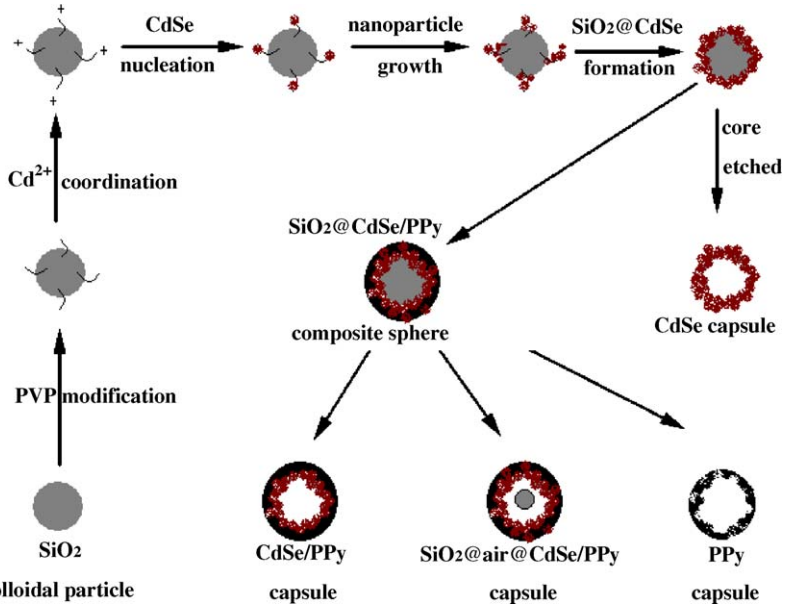

Fig. 1. Schematic diagram of the procedure for synthesizing core-shell particles and capsules.

mixture was kept stirring for 8 h to yield uniform silica particles.

2.2.2. Modifying SiO_2 core by PVP

0.2 g SiO_2 spheres were dispersed in 20 mL aqueous ethanol (1:1, v/v) solution containing 0.5 g PVP via ultrasound. The suspension was allowed to stand for 1 day to insure the surface of the silica spheres being sufficiently adsorbed by PVP molecules. Unabsorbed PVP molecules were removed by three centrifugation/dispersion cycles.

2.2.3. In-site deposition of CdSe nanoparticles on the SiO_2 core

Sodium sulfite ($NaSO_3$) aqueous solution and selenium (Se) powder were refluxing at 353 K for 12 h to prepared $NaSeSO_3$ [24]. Silica spheres modified by PVP were re-dispersed in aqueous ethanol (9:1, v/v) solution containing 0.2 M $Cd(CH_3COO)_2$ via ultrasound. The suspension was allowed to stand for 1 day to insure the Cd^{2+} ions could be coordinated with the modifying PVP. Redundant Cd^{2+} ions were removed by three centrifugation/dispersion cycles. The precipitation was re-dispersed in 20 mL deionized water for peptization. Then 20 mL freshly prepared $NaSeSO_3$ aqueous solution was added into 20 mL the above sol. Finally, 20 mL $Cd(CH_3COO)_2$ solution was slowly dropped under vigorously stirring. The reaction was carried out at 313 K for 10 h. The product was collected by centrifugation, washed by deionized water and ethanol twice then dried under vacuum.

2.2.4. CdSe hollow capsules

CdSe-silica core-shell particles were converted to CdSe hollow capsules after being soaked in 1 M NaOH aqueous solution under slightly ultrasonic then washed by distilled water and ethanol. The product was dried under vacuum at room temperature.

2.3. Novel core-shell particles and capsules based on the SiO_2@CdSe spheres

SiO_2@CdSe/polypyrrole composite spheres have been fabricated using the as-prepared SiO_2@CdSe particles as second template. Furthermore, PPy capsules, PPy/CdSe capsules and PPy/CdSe capsules with movable silica cores could be obtained by selectively eliminating method.

2.3.1. SiO_2@CdSe/polypyrrole composite spheres

As-prepared 0.1 g SiO_2@CdSe spheres were dispersed in 100 mL ethanol containing 1 g PVP by ultrasound. The suspension was allowed to stand for 1 day then un-adsorbed PVP was removed by several centrifugation/dispersion cycles at 3000 rpm. The sediment was re-dispersed in 100 mL distilled water. After 0.03 g $FeCl_3 \cdot 6H_2O$ was added under vigorous stirring, 60 μL pyrrole monomer was injected into the solution. The polymerization was performed under stirring at 298 K for 12 h. After washing several times with distilled water and ethanol, the SiO_2@CdSe/PPy composite particles were dried under vacuum at 323 K.

2.3.2. PPy/CdSe capsule with movable SiO_2 core

SiO_2@CdSe/PPy composite particles were converted to capsules after being soaked in 0.01 M NaOH aqueous solutions under slightly ultrasonic in controllable time.

2.3.3. PPy/CdSe hollow capsule

SiO_2@CdSe/PPy composite particles were converted to CdSe loaded PPy capsules after being soaked in 1 M NaOH aqueous solutions then washed by distilled water and ethanol.

2.3.4. Mesoporous PPy capsule

SiO_2@CdSe/PPy composite particles were converted to mesoporous PPy hollow capsules by soaking in 1 M NaOH and 1 M HCl aqueous solution successively under slightly ultrasonic then washed by distilled water and ethanol.

2.4. RFIR and electrochemical measurement of core-shell spheres

Electrochemical measurements were performed with CHI 621B electrochemical workstation (CH Instruments) using a basal plane pyrolytic graphite (PG, Advanced Ceramics, geometric area 0.16 cm^2) disk modified with films as the working electrode, a saturated calomel electrode (SCE) as the reference electrode, and a Pt flake as the counter electrode. Buffers were purged with highly purified nitrogen for at least 10 min prior to a series of electrochemical experiments. For the bioelectrochemical studies of SiO_2@CdSe core-shell particles, the PG electrode was first immersed into PDDA solution (3 mg ml^{-1}, containing 0.5 M NaCl) for 20 min to adsorb positively charged PDDA as a precursor layer. The electrode was then alternately immersed for 20 min in SiO_2@CdSe water dispersion and Mb solution (1 mg ml^{-1} at pH 5.0) with intermediate water washing and nitrogen stream drying, forming an SiO_2@CdSe /Mb film. This film electrode was then placed in PBS (pH 7.0) for cycle voltammetrical experiment.

Sample films for reflectance absorption infrared (RAIR) spectroscopy were prepared by depositing film onto Al disks with an Au disk as the reference.

2.5. Typical drug storage experiment of CdSe hollow capsules

0.1 g CdSe capsules product was dispersed in 50 mg/10 ml doxorubicin methanol solution. The suspension was been under ultrasonic about 20 min and stirred for 24 h in the close vessel. Then the drug loaded CdSe capsules were separated and compacted into a disk by a pressure of 4 MPa. This 0.05 g disk was immersed into 10 ml PBS buffer (pH 7.4) at 310 K. The release medium (1.0 mL) solution was removed for analysis at given time intervals and replaced with the same volume of fresh preheated PBS. Each 1.0 mL extracted medium solution was diluted to 5.0 mL with PBS and analyzed by UV–vis spectroscopy in the range of 190–350 nm wavelengths.

3. Results and discussion

3.1. Formation of the qualified SiO_2@CdSe core shell particles

3.1.1. PVP modification

Pre-modification of silica with PVP macromolecules was necessary to generate suitable surface for directly deposition of CdSe particles on the surface of SiO_2 cores. Being dispersed in about PVP aqueous ethanol (1:1, v/v) solution via ultrasound, the SiO_2 spheres were effectively encompassed by PVP molecules that displayed in Fig. 2. It indicated that there was proper affinity between them. Although most of PVP macromolecules would be removed by later washing step, XPS measurement showed that about 0.9 mg m^{-2} content of PVP could be stably attached on the surface of the SiO_2 (compare the C and N % contents of the PVP-coated silica to that of PVP alone) (Fig. 3). Without the PVP modified, silica spheres could not be effectively coated by CdSe polycrystalline in the present preparation condition. Being an effective steric agent, PVP could promote a strong interaction between the core and shell owing to its specific character of structure and partially amphiphilic property [25].

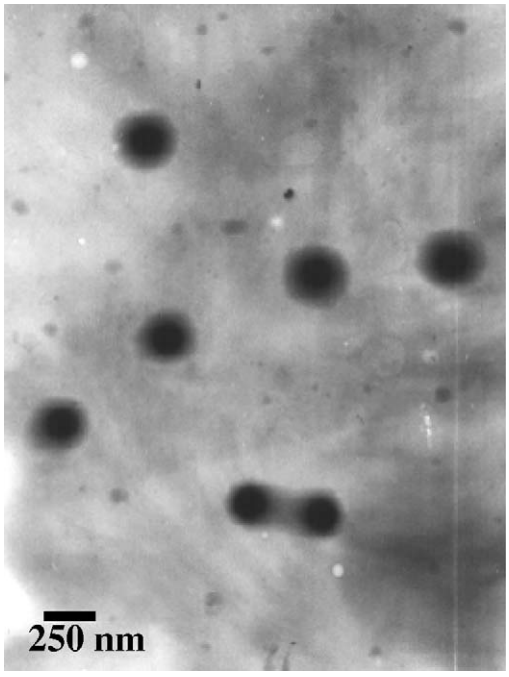

Fig. 2. TEM micrograph of SiO_2 spheres encompassed by PVP macromolecules.

3.1.2. Cd^{2+} coordination

It was necessary to introduce proper amount of Cd^{2+} ions on the PVP modifying SiO_2 cores before further in-site nucleation of the CdSe nanoparticles. It has been known that PVP and metal cations could form unstable complexes [26]. Similar type of Ag–O coordination, between pyrrolidone ring of PVP and the surface of metal, has been used in the fabrication of Ag nanowires [27]. Although TEM image showed the surface of silica spheres was smooth after the Cd^{2+} coordination, the polar part of PVP molecular around the SiO_2 cores might make CdSe quantum dots joined with specific chemical linkers and formation [28]. It has been found that the intensity of 330 nm absorption peak for PVP modifying silica core decreased when Cd^{2+} ions was introduced on them in the UV–vis spectrum (not shown). The decreasing intensity of the absorption peak may be due to

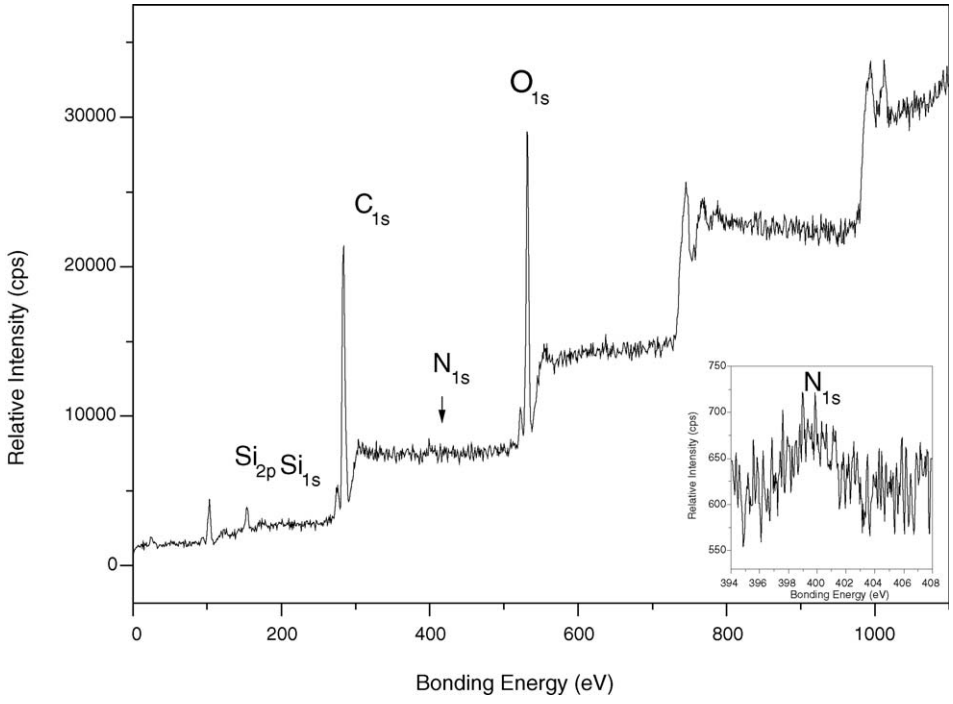

Fig. 3. XPS spectrum of PVP modifying SiO_2 spheres.

Table 1
SiO_2–CdSe composite sphere samples prepared from different Cd^{2+} ions concentrations

Sample	Cd^{2+} concentration (M)	CdSe particle size (nm)	State of CdSe particles in samples
1	0.01	5	Separated dots
2	0.05	8	Separated dots
3	0.10	10	Separated dots
4	0.20	12	Continuously shell

the coordination between Cd^{2+} ions and the modifying PVP on silica core.

3.1.3. Controllable deposition

The size of CdSe nanoparticles and step-wise constructing to CdSe shell could be controlled via adjusting the concentration of precursor solutions in reasonable range. To obtain well-dispersed coated composite particles, it was essential to adjust the concentration of starting materials. The experiment results showed that under identical conditions, the formation of core-shell structure strongly depended on the exposed surface areas relative to the shell materials. Only separated CdSe nanoparticles would be dispersed on the SiO_2 surface if the concentration of Cd^{2+} ions was too small. In contrast, if the amount of silica cores was too small and the concentration of Cd^{2+} ions was too high, mixture of coated particles and CdSe nanoparticles were obtained. The results were displayed in Table 1.

Fig. 4 a–d showed SiO_2–CdSe composite spheres prepared from 0.01, 0.05, 0.10, and 0.20 M concentrations of Cd^{2+} ions, respectively. The powder XRD patterns of those products were given in Fig. 5. The diffraction peaks in the patterns could be indexed to the pure cube phase of CdSe (JCPDS No. 19–191). Average crystallite sizes estimated from the XRD line broadening of (2 2 0) peak according the Scherrer equation were about 5 nm (corresponding to Fig. 4a), 8 nm (corresponding to Fig. 4b), 10 nm (corresponding to Fig. 4c) and 12 nm (corresponding to Fig. 4d). However, the particle sizes in TEM images (Fig. 4c, d) were larger than the crystallite sizes, indicating that the CdSe particles were polycrystalline. It showed that increasing the concentration of Cd^{2+} ions not only had the effect on crystallite size but also resulted in an increase in crystallinity of shell. Continuously shell structure formed from the 0.2 M Cd^{2+} precursor solutions. Typical TEM image of SiO_2@CdSe core-shell structure was displayed in Fig. 6a. Compared to previous methods for SiO_2@CdSe core-shell particles, this route is a faster one step in-site deposition process without using silane-coupling agent.

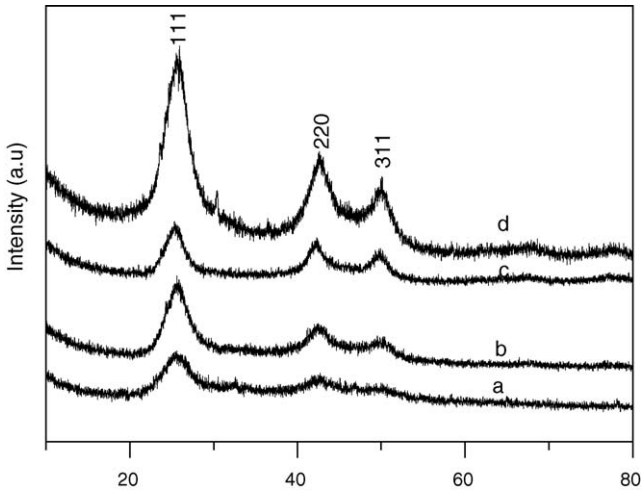

Fig. 5. X-ray diffraction patterns of SiO_2–CdSe composite samples 1–4 (a)–(d).

3.2. SiO_2@CdSe/PPy multi-composite core-shell particles

The as-prepared SiO_2@CdSe particles could save as second template to form multi-composite core-shell structure. It was found that modifying the surface of SiO_2@CdSe particles by PVP was still importantly to further effectively coating polypyrrole out-layer. The morphology of SiO_2@CdSe/PPy composite particles was displayed in Fig. 6. In TEM image

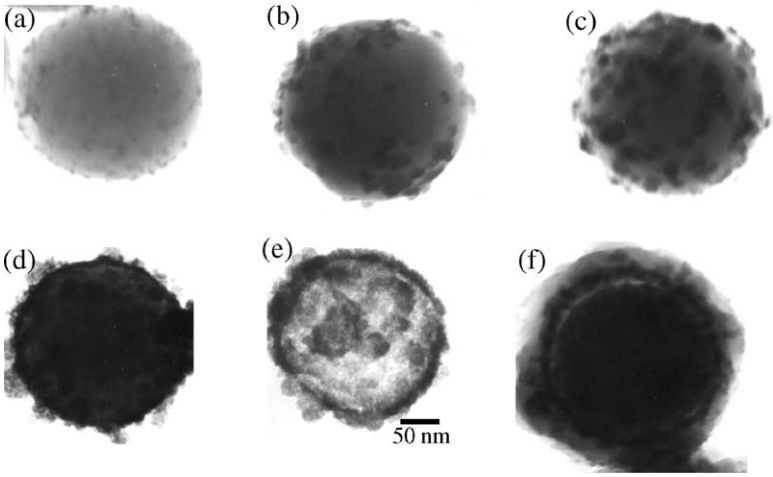

Fig. 4. TEM micrographs of spheres during the successive synthesis steps. A scale bar is 50 nm which corresponds to all photos. SiO_2–CdSe composite samples 1–4 (a)–(d), CdSe hollow capsule (e), SiO_2@CdSe /PPy composite sphere (f).

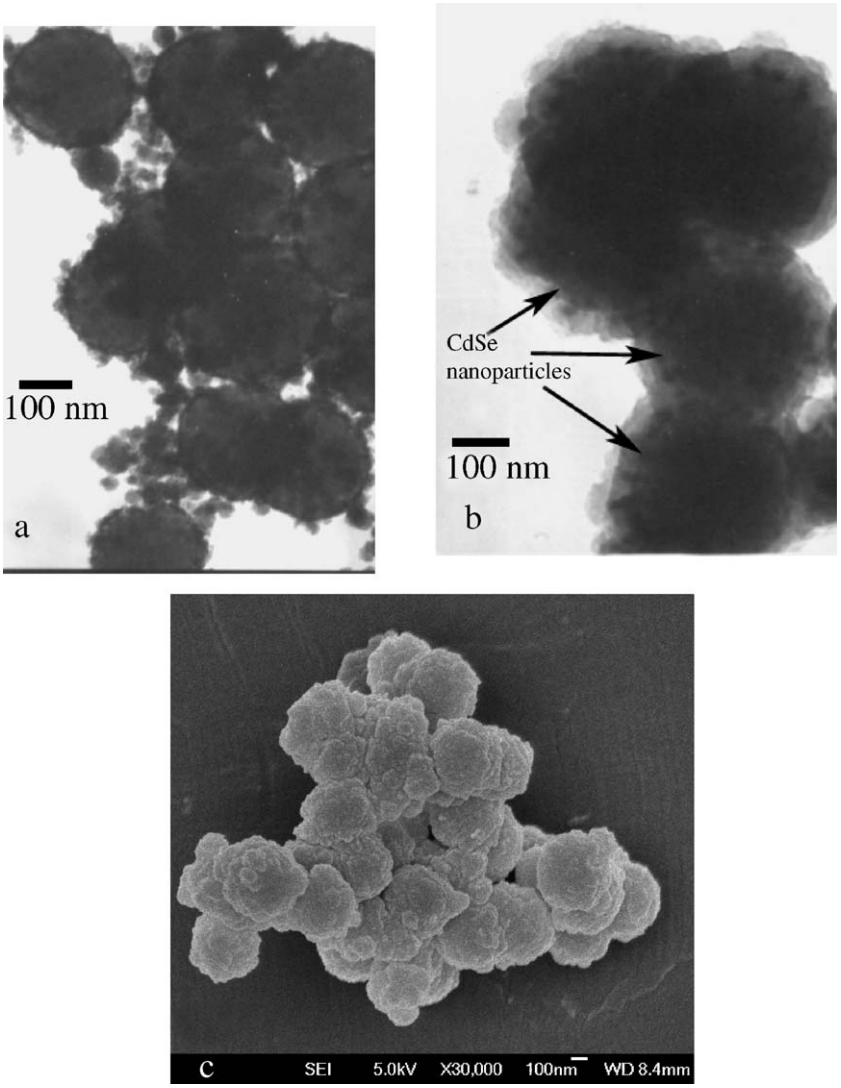

Fig. 6. TEM micrographs of SiO_2@CdSe core-shell particles (a), SiO_2@CdSe/PPy composite spheres (b) and SEM image of SiO_2@CdSe /PPy composite spheres (c).

(Fig. 6b), the mid-layer was consisted by CdSe nanoparticles. Meanwhile, it seemed that there were many CdSe nanoparticles dispersed inside the polypyrrole out-shell, indicating that the polymer layer could effectively envelop CdSe nanoparticles inside it even some CdSe nanoparticles once attached on the as-prepared SiO_2@CdSe particles unsmoothly. Fig. 6c is the SEM image of the SiO_2@CdSe/PPy spheres with smooth surface.

In one hand, being enwrapped by polymer layer, the chalcogenides particles would not easy escape from the composite particles in many application. On the other hand, conductive polymer is one of most important polymer that has been widely used for biomedical applications [29]. Grafted certain group, colloidal particles with PPy surface could make proteins retaining their biological activity [30]. Inorganic–organic hybrid materials usually have higher flexility and easy machining. Compared to SiO_2@CdSe particles, SiO_2@CdSe/PPy composite particles might be more stably during the further treating process, which would be beneficial for their immunoassays application.

3.3. Electrostatic immobilization of myoglobin (Mb) onto core-shell particles

3.3.1. RFIR spectra

Modified by positively charged PDDA, SiO_2@CdSe particles could adsorb negatively charged Mb on their surface via electrostatic collaboration. Infrared absorption spectroscopy can provide information on the secondary structure of proteins immobilized on solid surfaces [31,32]. We used it to characterize [SiO_2@CdSe-Mb] and [SiO_2@CdSe/PPy-Mb] core-shell structures (Fig. 7b and c). The amide I band of protein at 1700–1600 cm^{-1} caused by C=O stretching vibrations of the peptide linkage and the amide II band at 1600–1500 cm^{-1}caused by a combination of N–H in-plane bending and C–N stretching of the peptide groups are usually used as the sensitive markers of protein conformational changes. Pure Mb film in Fig. 7c demonstrated the RAIR peak at 1652 cm^{-1} for the amide I band and the peak at 1558 cm^{-1} for the amide II band. The amide I and II bands of Mb in [SiO_2@CdSe-Mb] nanoclusters film (curve 7b) were

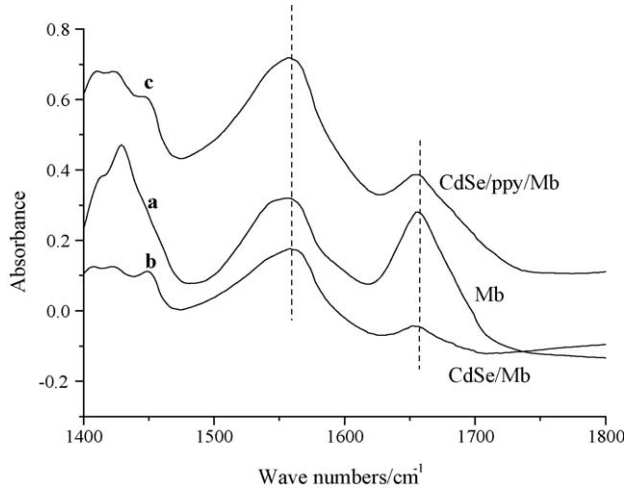

Fig. 7. RAIR spectra of Mb (a), SiO_2@CdSe–Mb (b) and SiO_2@CdSe/PPy–Mb (c) films.

located at 1652 cm^{-1} and 1555 cm^{-1} respectively, which are almost same as that in the pure Mb films. It indicates that Mb absorbed on the surface of SiO_2@CdSe particles essentially retains its native secondary structure. The result is in agreement with the RFIR measurement of [SiO_2@CdSe/PPy-Mb] sample (curve c).

3.3.2. Electrochemical studies

Fig. 8 is cycle voltammograms (CV) of the above two samples. It is known that there is no redox peaks at the bare PG electrode. And Mb biomolecule shows very slow electron transfer kinetics at a bare PG electrode [33]. There is no electrochemical response observed at this potential window when only SiO_2@CdSe particles has been absorbed on the surface of electrode (curve b). But when {SiO_2@CdSe /Mb) film has been absorbed on the surface of electrode, there is a pair of well-defined nearly reversible peaks at about −0.340 V, characteristic of Mb heme Fe^{III}/Fe^{II} redox couples (curve c). It indicates that SiO_2@CdSe can promote the electron transfer kinetics of Mb [34]. With QDs on the surface, the biomolecules may covalently couple onto SiO_2@CdSe core-shell colloidal particles [35]. The good biocompatible property of the material with protein makes it possible for SiO_2@CdSe as a potential candidate for fluorescent probes in biological detection biosensor [36].

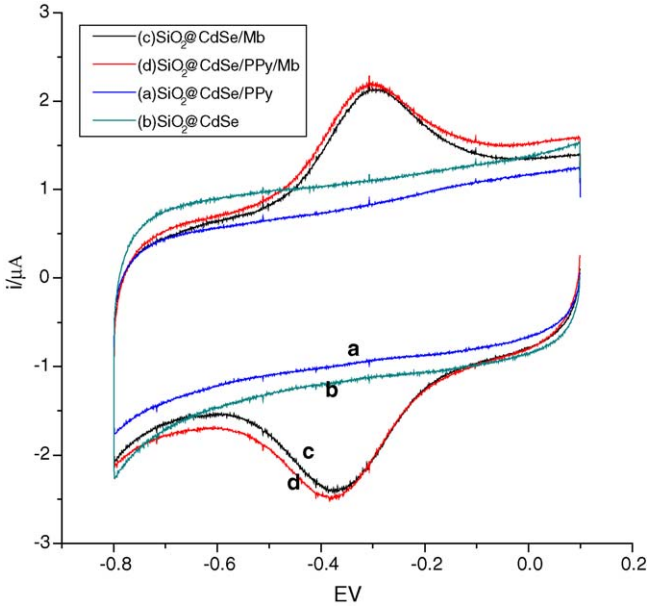

Fig. 8. Cycle voltammograms at scan rate 0.2 V s^{-1} in pH 7.0 buffer for SiO_2@CdSe monolayer film (a), SiO_2@CdSe–Mb film (b), SiO_2@CdSe/PPy monolayer film (c) and SiO_2@CdSe/PPy–Mb film (d).

There is also no electrochemical response can be observed at this potential window when only SiO_2@CdSe/PPy was absorbed on the surface of electrode (curve a). But when {SiO_2@CdSe/PPy /Mb} film has been absorbed on the surface of electrode, a pair of well-defined nearly reversible peaks appears (curve d). With the same peak potential, the peak current of {SiO_2@CdSe/PPy /Mb} film become bigger that that of {SiO_2@CdSe /Mb} film (comparing d and c, a and b). It indicates that, with the conductive polymer shell, multi composite SiO_2@CdSe/PPy may promote the electron transfer kinetics of Mb better.

3.4. Novel capsules

Hollow structures, especially hollow capsules, are the important structures in pharmaceutics and biochemistry for encapsulation and controlled release. Nontoxic and biocompatible materials are necessary on this area [37].

3.4.1. CdSe hollow capsules

When the silica cores were eroded by NaOH aqueous solution, SiO_2@CdSe composite particles could be transformed to CdSe hollow capsules. The product is displayed in Fig. 9. In the TEM image (Fig. 9a), the inset is its corresponding ED pattern. Their hollow microstructure could also be confirmed by some broken capsules in SEM image (Fig. 9b). It means that CdSe shell structure is permeable to the dilute basic little molecules for the dissolution of silica core and stability during this elimination process. As the CdSe shell is composed of nanocrystallines, its porous nature is characteristic, which is much important for drug carriers.

3.4.2. Drug loading and releasing

To explore the probability of porous CdSe hollow capsules as drug carrier, doxorubicin, a typical anti-cancer drug, was introduced into this product. In FTIR spectra (Fig. 10c), three characteristic peaks of doxorubicin (at 891 cm^{-1}, 763 cm^{-1} and 690 cm^{-1}) (curve a) are observed in the loading capsules. It confirmed the existence of drug in the capsules. UV–vis spectra (Fig. 11) were employed to test the release behavior of doxorubicin loaded in CdSe capsules. PBS buffer (pH 7.4) was used as simulative body fluid. The test was taken at 310 K. After the release rate reached its maximum at 8 h (curve b), it decreased slowly with time within 1 week. It was found that a little amount of doxorubicin could still be tested even after 14 days, indicating the good sustained release drug behavior [38].

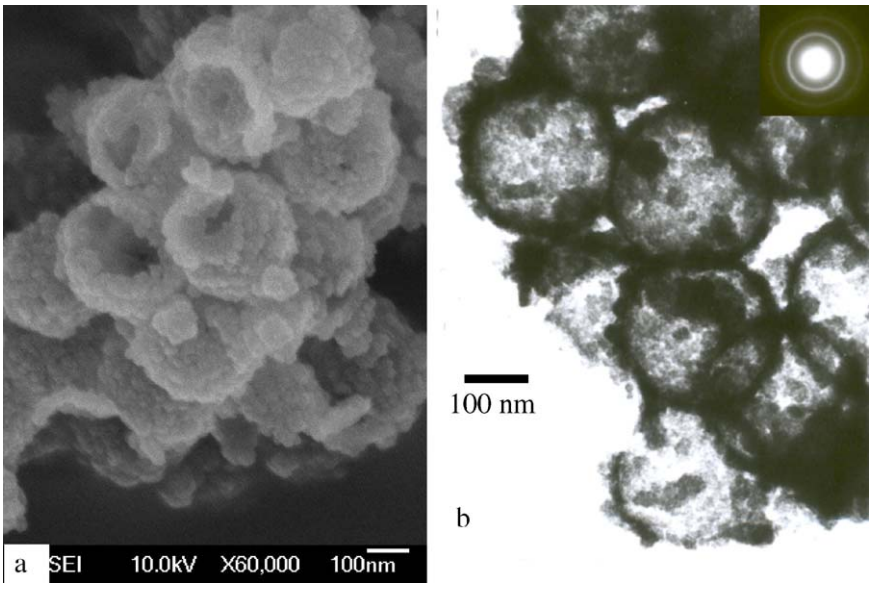

Fig. 9. SEM (a) and TEM (b) micrographs of CdSe hollow capsules.

3.4.3. PPy/CdSe capsules, movable-core SiO_2@Air@PPy/CdSe capsules and mesoporous PPy capsules

Recently, there is a trend to fabricate multifunctional nanospheres [39] and capsules [40] in order to satisfy multi-application in special fields. As the SiO_2 cores being removed, SiO_2@CdSe/PPy composite spheres could convert to CdSe loaded PPy (PPy/CdSe) hollow hybrid capsule. The typical TEM images were given in Fig. 12 (a and b). It was found that the shell was composed by two layers. The inter one was the CdSe continuous shell, while the outer one was PPy layer with CdSe nanoparticles dispersed inside it. It was known that polymeric shell could help to minimize selectivity and biocompatibility problems for biosensors through their ability to act as surface modifiers and as selective barriers of biosensors [41]. As combination of both QDs and conductive polymer shell, the hybrid capsules may have more significant character in further application study.

As the controllable removal of SiO_2 core from the multi-composite particles, SiO_2@CdSe/PPy spheres could convert to movable core SiO_2@Air@PPy/CdSe capsules. In Fig. 12(c and d), partly eroded silica cores were suspended inside PPy/CdSe composite shells. Different eroding time for composite particles may lead to different size of movable SiO_2 core. The type of nanostructure is one of interesting materials in recent years [42,43].

Sub-meter size hollow capsules with mesoporous shell have offered a wide range of applications in separation, sensors due to their high surface areas, well-defined pore structures [44]. Most study are involved of mesoporous silica [45]. Herein, in the outlay of SiO_2@CdSe/PPy spheres, CdSe nanoparticles were dispersed inside the PPy shell. Therefore, mesoporous polypyrrole hollow particles could be obtained if both SiO_2 and CdSe were eliminated from the composite particles. Their morphology was displayed in Fig. 12e. The

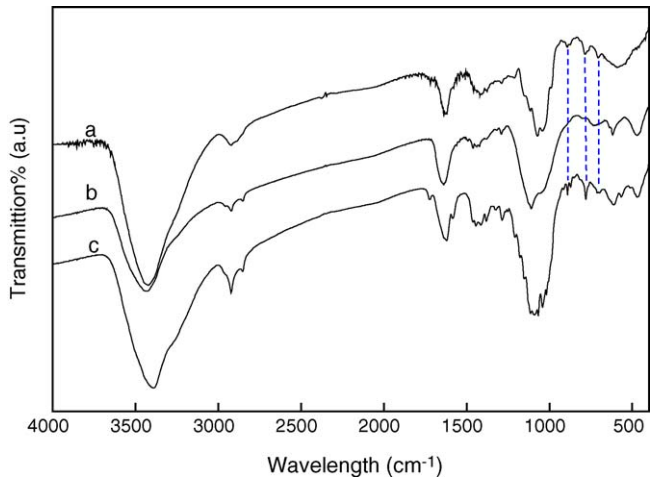

Fig. 10. FTIR spectra of doxorubicin (a), CdSe capsules (b) and CdSe capsules carrying doxorubicin (c).

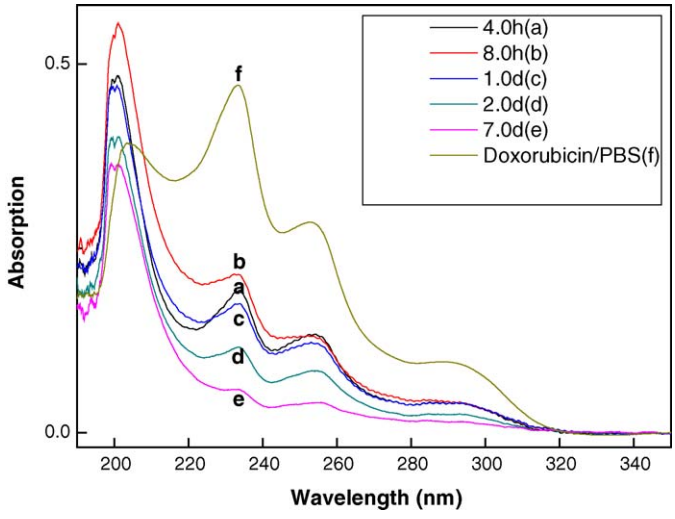

Fig. 11. Release behavior of CdSe hollow capsules as doxorubicin carrier.

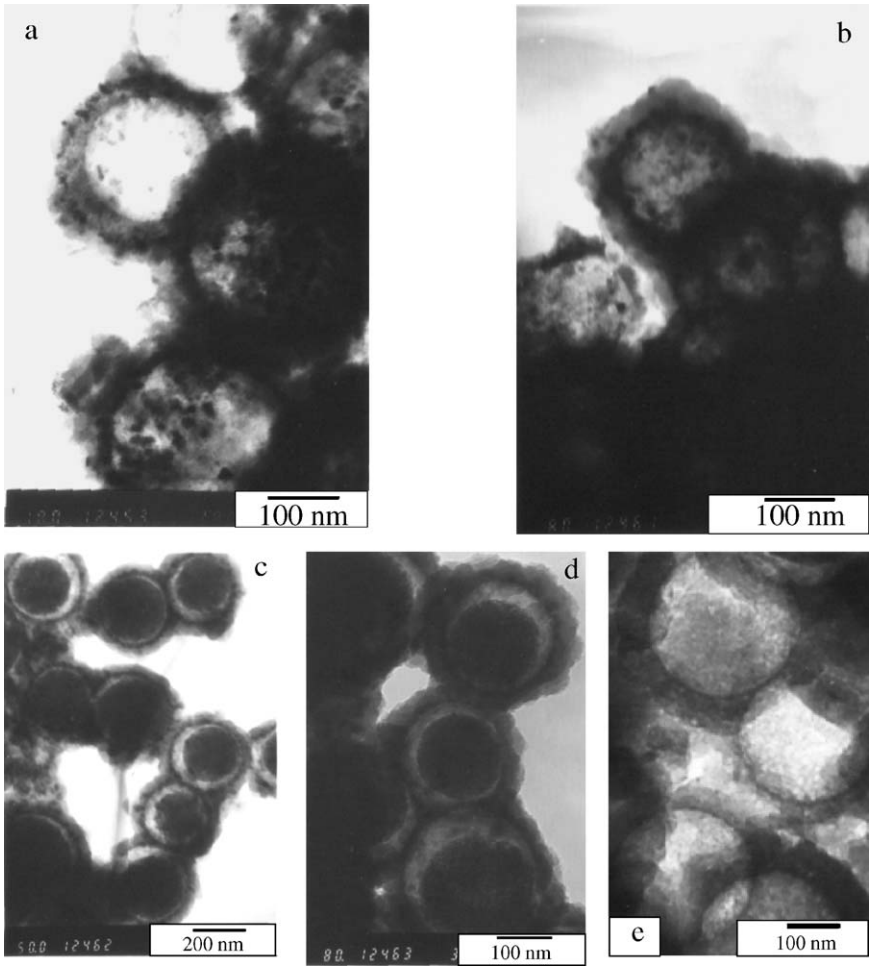

Fig. 12. TEM micrographs of CdSe/PPy (a, b), SiO_2@air@CdSe/PPy (c, d) and mesoporous polypyrrole (e) capsules.

mesoporous nature of shell may lead to higher penetrability and carrying capability that are important factors in further applications [46].

4. Summary

SiO_2–CdSe composite particles were fabricated by controllable deposition CdSe semiconductor quantum dots (QDs) on silica colloidal particles. The size of CdSe nanoparticles could be controlled between 5 and 12 nm via adjusting the concentration of precursor solution. SiO_2@CdSe core-shell spheres with the shell composed by CdSe nanocrystallines were formed from 0.2 M Cd^{2+} ions solution. With the surface of QDs, SiO_2@CdSe particles could promote the electron transfer of horse heart myoglobin (Mb) during the electrochemical measurement, indicating their potential application in biosensor for detection. Core-shell type of SiO_2@CdSe spheres could be transformed to CdSe hollow capsules as removal of the cores. After introducing doxorubicin into the capsules, FTIR spectra confirmed the existence of loading drug. It was found that the drug-loading CdSe capsules displayed the good sustained release behavior. It may be due to the hollow and porous character of the sub-meter size capsules. Additionally, further coating SiO_2@CdSe by conductive polypyrrole was also realized. Compared to SiO_2@CdSe spheres, the multi-composite particles make protein having better bioelectrochemical activity. Furthermore, selectively eliminating the component of SiO_2@CdSe/PPy resulted in some smart capsule structures, such as PPy/CdSe hybrid hollow capsules, PPy mesoporous hollow capsules and movable-core SiO_2@Air@PPy/CdSe capsules. Their possibilities for application are under investigation.

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