

Luminescent Polymer Microcapsules Addressable by a Magnetic Field

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Received October 13, 2003. In Final Form: November 13, 2003

Ⓜ This paper contains enhanced objects available on the Internet at <http://pubs.acs.org/journals/langd5>.

The simultaneous encapsulation of both luminescent semiconductor and magnetic oxide nanoparticles in polymer microcapsules is demonstrated for the first time. Highly luminescent CdTe semiconductor nanocrystals serve as luminescent markers, while magnetic Fe₃O₄ nanoparticles allow external manipulation of the capsules by magnetic field. The method introduced is general enough to allow the fabrication of different types of multifunctional capsules in a similar way. The use of multifunctional water-compatible capsules introduced in this paper for the controlled release and directed drug delivery in biological systems is envisaged.

Introduction

A novel approach to fabricate nanoengineered core–shell capsules introduced recently¹ has the capacity to employ a great variety of substances as core materials and shell constituents. It is based on the combination of solvent-controlled precipitation^{2,3} and layer-by-layer adsorption^{4–6} of oppositely charged macromolecules on colloidal templates (cores) ranging in size from 50 nm to tens of micrometers, such as organic and inorganic colloid particles, protein aggregates, DNA in compact form, biological cells, and drugs. Various materials such as synthetic polyelectrolytes (PEs), natural polymers as polysaccharides, polypeptides and polynucleotides, lipids, and multivalent dyes can be used as layer constituents to fabricate the shells, thus engineering the required thickness, permeability, stability, biocompatibility, and affinity properties of the capsules. Some colloidal templates can be decomposed leaving behind defined hollow capsules which can be refilled with different substances, thus importing additional desirable properties to the composite system. Essentially, inorganic substances such as luminescent semiconductor^{7–9} or magnetic^{10,11} nanoparticles (NPs) can be successfully coated onto the polymer beads^{7,10} or incorporated into the capsules^{8,9,11} as well.

Because of the strong band gap luminescence tunable by size as a result of the quantum confinement effect, colloidal synthesized semiconductor NPs are currently of great interest as emitting materials for biolabeling applications.^{12–17} They are more stable toward photooxidation than organic dyes¹² and have nearly continuous excitation spectra above the threshold of absorption together with a strong, narrow, and symmetric emission band whose position depends on the particle size, allowing simultaneous excitation of many-color probes by a single narrow-band excitation source.¹⁷ Recent efforts in colloidal chemistry have provided powerful tools to synthesize nanoparticles of different materials in gram scale with variable and precisely controlled size, shape, composition, and surface properties.^{18,19} There are also a plenty of methods available in scientific literature which describe reliable syntheses of colloidal magnetic nanoparticles, like

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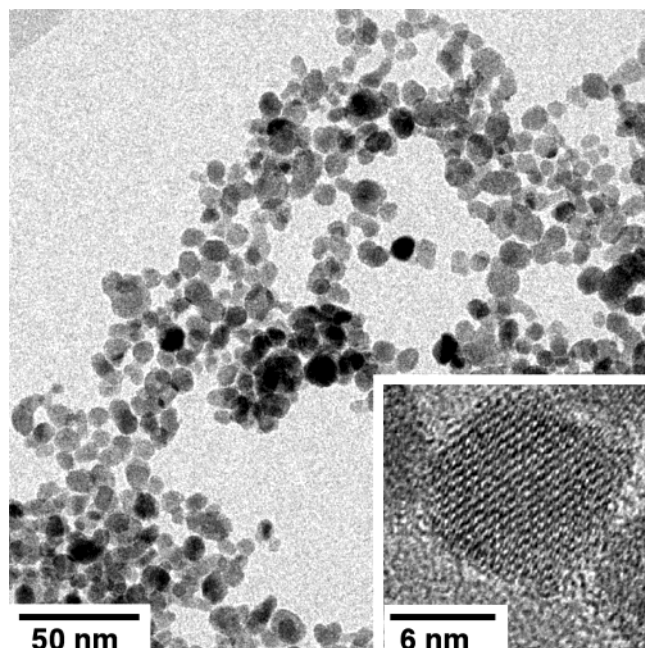


Figure 1. TEM image of Fe_3O_4 nanoparticles. Inset shows a HRTEM image of a representative single particle.

Fe_3O_4 produced directly in water²⁰ or CoPt_3 made in organic solvents.²¹

A general advantage of the encapsulation approach is the possibility to construct multifunctional capsules possessing several desirable properties in a single entity. In this paper, the simultaneous encapsulation of both luminescent semiconductor and magnetic oxide NPs is demonstrated for the first time. The desired functionalities provided by the above components are the following: (i) highly luminescent semiconductor NPs with narrow emission bands located at different wavelengths depending on the particle size¹² serve as luminescent markers while (ii) magnetic nanoparticles allow external manipulation

of the capsules by magnetic field. The method introduced is general enough to allow the fabrication of different types of multifunctional capsules in a similar way.

Experimental Section

The capsules were templated on soluble melamine formaldehyde cores, 5.2 μm in diameter. The walls of the capsules consisted of two oppositely charged PEs: poly(styrene sulfonate) (PSS, $M_w \sim 70000$) and poly(allylamine hydrochloride) (PAH, $M_w \sim 50000$). The capsules with positively charged liquid interior comprised of PAH macromolecules (0.1 M of amino groups) have been prepared as described previously.⁸ CdTe NPs capped by thioglycolic acid were synthesized in aqueous solution according to the previously published procedure.²²

Fe_3O_4 magnetic NPs of average size of 8 nm and saturation polarization of 22 mT capped by citric acid and, thus, being negatively charged at slightly basic pH have been purchased from "Berlin Heart" as a magnetic fluid. Figure 1 shows representative transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) images of these NPs.

Results and Discussion

Figure 2 schematically shows the procedure used for the fabrication of the capsules and the encapsulation of NPs. The diameter of resulting capsules becomes slightly larger than that of the core templates,¹ being approximately 5.6 μm in our case. CdTe NPs (2–6 nm size range, dependent on the luminescence color desired) capped by thioglycolic acid and, thus, negatively charged at slightly basic pH were used as luminescent markers for the capsules. Figure 3 shows typical absorption and emission spectra of a size series of CdTe NPs, covering the spectral range from 500 to 800 nm. The full width at half-maximum for the photoluminescence band varies from 30 to 100 nm with increasing wavelength; the room-temperature quantum yield determined by comparison with Rhodamin 6G is in the range of 15–30%. The luminescence efficiency of CdTe NPs in physiological buffer solutions remained stable for 2 weeks, as earlier investigations have shown.⁹

The encapsulation of the NPs was achieved by soaking the capsules in aqueous 0.2 M NaCl solution containing

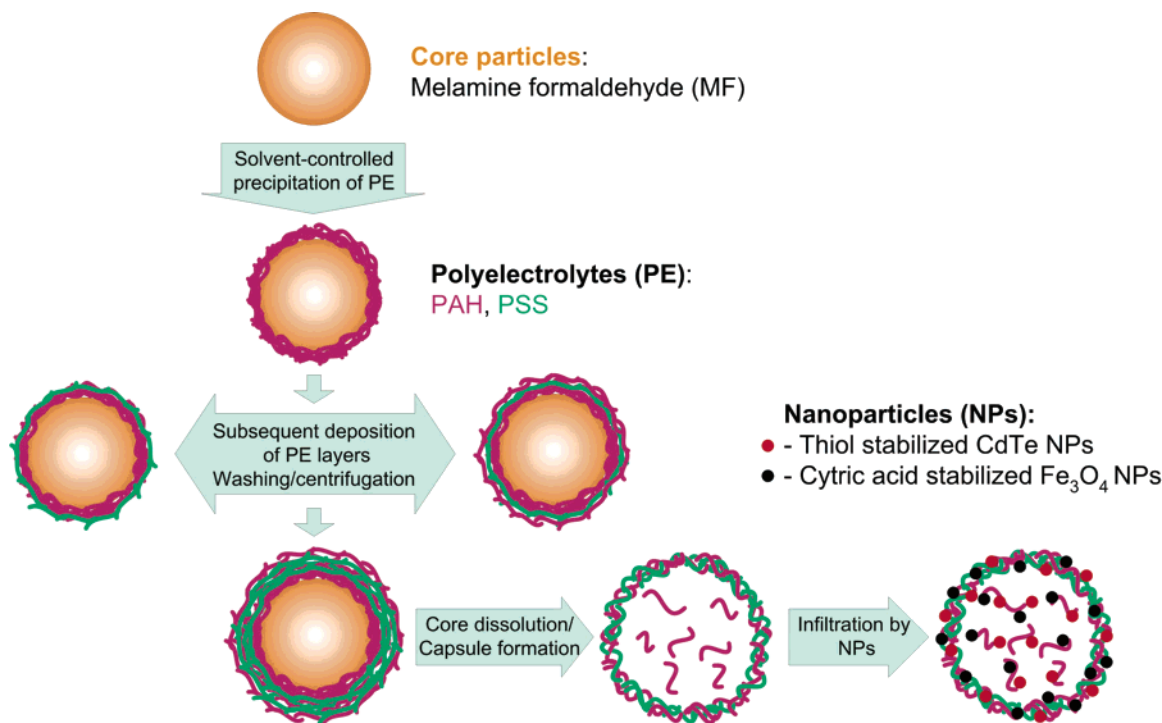


Figure 2. Schematics of fabrication of microcapsules and encapsulation of nanoparticles.

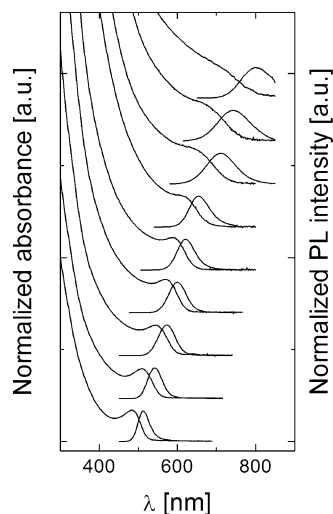


Figure 3. Absorption and emission spectra ($\lambda_{\text{ex}} = 400$ nm) of CdTe nanocrystals as synthesized in water.

$\sim 5 \times 10^{-6}$ M (particle concentration) CdTe NPs and $\sim 3 \times 10^{-7}$ M Fe_3O_4 (particle concentration) NPs for 1 h at pH

7.4–7.8, followed by their separation through centrifugation and redispersion in pure water. The concentration of magnetic NPs in solution used for encapsulation was chosen to be more than the order of magnitude lower than that of CdTe NPs in order to reduce the undesirable reabsorption of emitted light in the loaded capsules. As a result, at the chosen relation of concentrations the luminescence intensity of CdTe NPs reduced only by $\sim 20\%$ in the presence of magnetic NPs. The capsule walls are homogeneously porous on the size scale of ~ 10 nm and thus permeable for NPs smaller than 10 nm in diameter.^{1,23} Once penetrated, the negatively charged NPs remain captured in the capsule interior and on the capsule walls because of the electrostatic interaction between the acidic groups of the NP stabilizers and the amino groups of the PAH molecules. No leakage of NP into the surrounding solution was detected by precipitation of the capsules through centrifugation and taking the absorption and luminescence spectra of the remaining supernatant. The filling of the capsules with both types of NPs appeared sufficiently uniform with more preferential accumulation of NPs in the walls, as was proven by confocal microscopy and transmission electron microscopy measurements.

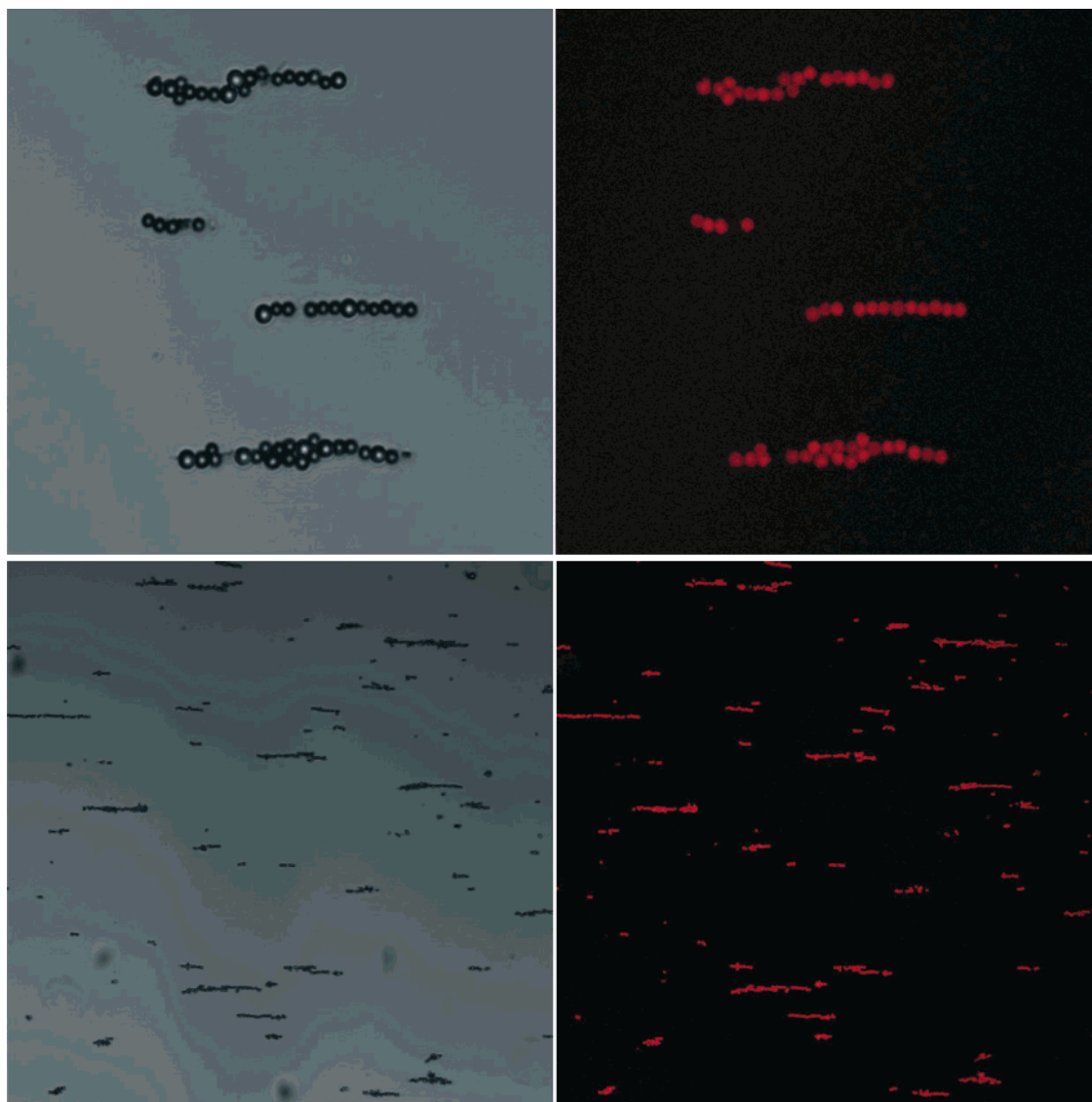


Figure 4. Microcapsules simultaneously loaded with luminescent semiconductor and magnetic oxide nanoparticles are aligned in magnetic field. The images were obtained with a confocal laser scanning microscope TCS Leica operating in transmission (left column) and in a luminescence (right column, excitation wavelength 476 nm) modes, respectively. Capsule diameter is $5.6 \mu\text{m}$ in all cases.

The main motivation for the simultaneous encapsulation of luminescent and magnetic NPs in the polymer capsules was the possibility to create by this means multifunctional objects addressable by a magnetic field and detectable by their luminescence. Figure 4 shows images of NP-loaded capsules obtained with a confocal laser scanning microscope TCS Leica in the transmission (left column) and in the luminescence (right column, excitation wavelength 476 nm) modes, respectively. A magnetic field from a samarium–cobalt magnet (IBS Magnet, Berlin) was applied for 20 min to a diluted aqueous solution of the NP-loaded capsules placed between two microscope cover slips. The capsules are aligned in parallel stripes in the magnetic field and remained ordered on the cover slip surface after removing the magnet. The stripes appear red under excitation by light because of the luminescence of the encapsulated CdTe NPs (4 nm size in this case). Such one-dimensional microarrays (luminescent microwires) can be easily created for example between two microelectrodes, thus allowing electrical contact to the capsule constituents. The movement of NP-loaded capsules toward a permanent magnet approaching their colloidal solution can be easily seen with a naked eye.

Ⓜ A video clip showing microcapsule movement in AVI format is available.

Conclusions

The simultaneous encapsulation of both luminescent semiconductor and magnetic oxide nanoparticles in polymer microcapsules is demonstrated for the first time.

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Highly luminescent CdTe semiconductor nanocrystals serve as luminescent markers, while magnetic Fe₃O₄ nanoparticles allow external manipulation of the capsules by magnetic field. The method introduced is general enough to allow the fabrication of different types of multifunctional capsules in a similar way. We envisage the use of multifunctional water-compatible capsules introduced in this paper for the controlled release and directed drug delivery in biological systems, as the interior of the capsules can be used for the encapsulation of drugs or enzymes.^{24,25} Luminescent semiconductor NPs, including IR-emitting ones⁹ can serve as luminescent markers for monitoring, imaging, and identification of different types of capsules in tissue, while the loading of capsules with magnetic NPs provides a possibility to direct them by applying an external magnetic field. This may be especially desirable for monitoring of such capsules as drug delivery systems to target them on specific parts of tissue/organs, where the capsules are to be preferentially taken up. A unique advantage of capsules in comparison to other systems is that they can be simultaneously loaded/functionalized with the above components, allowing combination of their properties in a single object.

Acknowledgment. Financial support was provided by the Sofia Kovalevskaya Program of the German Ministry of Science and by the EU Project "FUNLIGHT". We thank Andreas Kornowski (University of Hamburg) for his help with TEM. Professor Dr. H. Weller, Dr. A. Eychmüller, and Dr. D. V. Talapin (University of Hamburg) and Professor Dr. H. Möhwald (MPI of Colloids and Interfaces) are greatly acknowledged for stimulating discussions.

LA035914O

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