A simple strategy for quantum dot assisted selective detection of cadmium ions†

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Here we report a simple strategy for selective detection of cadmium ions by manipulating the electron transfer pathways of surface-engineered quantum dots.

Cadmium is considered as a widespread health hazardous global pollutant. The levels of cadmium have increased dramatically in many areas due to human activity.[1] Cadmium level has been increased as a result of mining, smelting, fossil fuel combustion and industrial use. In addition, phosphate fertilizers and waste water sludge,[2] which are often used as soil amendment are also cause of large scale cadmium contamination. These sources lead to cadmium contamination in food, which could lead to dietary cadmium exposure.[3] Biological effects of chronic cadmium exposure include renal dysfunction, calcium metabolism disorders and an increased incidence of certain forms of cancer,[2] possibly due to direct inhibition of DNA mismatch repair by cadmium.[4] With time and regular exposure cadmium is accumulated in tissues which could be alarming over time. Thus, the sensitive and selective detection of cadmium in primary sources could prevent human exposure to cadmium.

Current techniques for cadmium screening are labor intensive and expensive.[2,5] Therefore, developing simple but efficient detection techniques will have high impact. In this direction, chemosensors are attractive and could be introduced for selective detection of metal ions.[6] There are a few reports on optical based detection of cadmium ions using organic based fluorescent dyes.[7] However, these dye molecules usually suffer from severe limitations such as low signal intensities and photobleaching. Furthermore, most of them tend to exhibit a narrow excitation followed by a broad emission band with red tailing.[8]

Recently, research on the quantum dots (Qdots) have been subject of considerable interest[9] due to their widespread applications ranging from electronics to solar cells to quantum computing to biological markers. The luminescence of Qdots is extremely sensitive to their surface states. The surface interaction between certain analytes and Qdots will influence the efficiency of the electron–hole recombination process. So far luminescence based transduction has been the primary approach for developing Qdot based optical sensors.[10] Qdot based sensor have been reported for the optical sensing of small molecules (*e.g.* benzylamine,[11] benzyl alcohol[12]) and ions (*e.g.* bivalent Mn,[13] Co,[13] Ni,[13] Zn,[13] Cu,[14] Ag,[15] and cyanide[16] ions). These Qdot based sensors have disadvantages such as non-specific binding with metal ions and the sensing mechanism is based on quenching of luminescence intensity. However, the use of Qdots for the selective detection of heavy metal ions is minimally investigated.

In this study, we demonstrate for the first time a Qdot based probe for selective detection of cadmium ions. Unlike the previous approaches for detection of metal ions by fluorescence quenching mechanism, here we have demonstrated a fluorescence enhancement based detection probe. In particular, we have used dopant based core–shell CdS:Mn/ZnS Qdots.

The CdS:Mn/ZnS Qdots were synthesized by a water-in-oil (W/O) microemulsion method following a published protocol.[17] The Qdots (size ~3–4 nm) are highly monodispersed with an emission maxima at 592 nm. The response of the Qdots in terms of its emission intensity to various metal ion environments was studied. It was observed that the Qdots either do not respond to certain ions (Li^+, Na^+, K^+, Ca^{2+}, Zn^{2+}, Cd^{2+}) or suffer a luminescence quenching in presence of various transition and heavy metal ions (Cu^{2+}, Mn^{2+}, Co^{2+}, Ni^{2+}, Fe^{2+}, Hg^{2+}, Pb^{2+}) (see ESI†). Due to this non-selective behavior of the Qdots it is difficult to apply them directly for metal ion detection. Surface modification of the Qdots by attaching a certain metal-specific ligand could be an attractive approach to overcome this non-specific response of the Qdots to various metal ions. Based on this idea, we have developed a novel nano-probe (ligand conjugated quantum dots, QDL) consisting of CdS:Mn/ZnS Qdot as core and a Cd^{2+} selective ligand[7] (1,10-diaza-18-crown-6, **L1**) as shell for the selective detection of Cd^{2+}. Our goal is to combine highly sensitive, bright and photostable Qdots with Cd^{2+} selective **L1** to develop a robust detection probe. Although other ligands[18] were also reported earlier as Cd^{2+} capturing agents but they lack specific selectivity for Cd^{2+} over other related transition metal ions.

This probe features excellent selectivity for Cd^{2+} over competing analytes. Scheme 1 outlines the synthesis of QDL.

The ligand **L1** was attached directly to Qdot surface *via* zero-length covalent coupling. This was accomplished by using carbon disulfide (CS_2) as a linker. The CS_2 formed a stable carbodithioate ($–CS_2$) linkage[19] directly on to ZnS surface of Qdots as well as coupling with the secondary amine groups of **L1** (zero-length coupling). Due to bidentate nature of CS_2,

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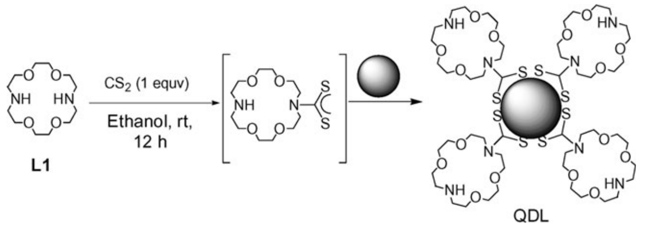
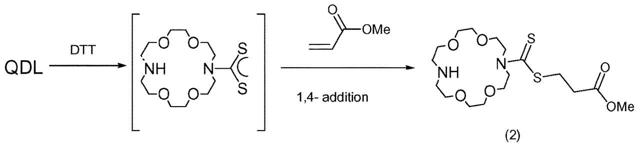
† Electronic supplementary information (ESI) available: Fig. S1: Fluorescence responses of Qdots to various metal ions. Characterization of **L1**, QDL and 1,4-addition product of DTT cleaved **L1**–CS_2 complex. See DOI: 10.1039/b803166e



Scheme 1 Synthesis of QDL.



Scheme 2 Detachment and isolation of the CS_2–**L1** intermediate from the Qdot surface.

improved stability of the probe is expected over any mercapto based monodentate ligands. In this coupling, it is expected to observe efficient electron transfer process from **L1** to Qdots.

The ligand attachment to the Qdot surface was carried out by using a simple experimental procedure. An ethanolic solution of CS_2 (0.09 mL, 1.098 mmol) was added dropwise to a solution of 1,10-diaza-18-crown-6 (**L1**) (288 mg, 1.098 mmol) in ethanol and sonicated for 5 min. 50 ml of the microemulsion containing Qdots[17] was added to the above mentioned CS_2–**L1** reaction mixture and stirred at room temperature for 24 h. The final product was washed several times in ethanol to remove unreacted CS_2 and **L1**. The attachment of **L1** to Qdots was confirmed by the spectroscopic (^{1}H NMR and IR) data (see ESI†). The ^{1}H NMR spectra were recorded on a Varian 500 MHz NMR instrument using DMSO-d_6 as solvent for all these products.

In order to test the stability of covalent coupling between the Qdots and **L1**, we have performed a competitive ligand exchange assay with thioglycolic acid. We did not observe any loss of **L1** from QDL as evident from the ^{1}H NMR study, even after 12 h reaction. This study indicated that the ligand attachment protocol is robust and the final product QDL is stable.

Photoluminescence (PL) studies revealed that the PL intensity of QDL was significantly quenched with respect to the Qdots (see ESI†). On the other hand the PL intensity of only CS_2 attached Qdots remained unaffected. The PL intensity of the Qdot also did not change in presence of the free ligand in solution. These studies showed that the attached ligand provided an alternative annihilation pathway to the excited electrons causing the luminescence quenching. A few recent studies[11,20–22] have demonstrated the electron transfer process between semiconductor Qdots and surface bound organic molecules such as *n*-butyl amine[11] and dopamine.[21] In most cases luminescence quenching of the semiconductor Qdots was observed due to blocking of the exciton (electron–hole pair) recombination process.[11,21,22] The luminescence quenching in QDL is indicative of photoinduced electron transfer from **L1** (electron rich secondary amines) to Qdots through carbodithioate (–CS_2) linkage.

To validate the electron transfer mechanism from the ligand to the Qdots *via* the carbodithioate (–CS_2) linkage, we have performed a ligand detachment experiment. This was carried out *via* dithiothreitol (DTT) assisted disulfide bond cleavage. The experimental procedure is depicted in Scheme 2.

DTT is a reagent commonly utilized to cleave the disulfide bond. So it was expected that upon DTT addition the PL intensity of the QDL will be restored to that of the Qdot intensity level. When DTT was added to the QDL, an initial minute increase of PL intensity was observed. This result was not significant enough to attribute the signal enhancement to the ligand detachment, indicating a possible reattachment of the ligand to the Qdot surface. Since the CS_2–**L1** intermediate was attached to the Qdot surface *via* carbodithioate (–CS_2) linkage under similar condition, it is likely that the CS_2–**L1** intermediate will be re-attached to the Qdot. To avoid this reattachment, we have added a trapping reagent, methyl acrylate to capture the detached CS_2–**L1** intermediate. This was accomplished *via* a 1,4-addition reaction between the CS_2–**L1** intermediate and methyl acrylate. The product (**2**) was confirmed by ^{1}H NMR study (see ESI†). Once methyl acrylate was added we observed a significant restoration of the PL intensity. This clearly showed that there was no structural or chemical change in the Qdots after QDL formation. The luminescence quenching of the QDL was indeed due to an electron transfer mechanism.

To test the feasibility of using QDL as Cd^{2+} detection probe, photoluminescence studies of the QDL were carried in different metal ion environments. The PL spectra of the QDL were measured in several steps by slowly increasing the metal ion concentration. Fig. 1 shows the response of the QDL to different concentrations of Cd^{2+}. The spectra shows significant increase in the luminescence of QDL.

As mentioned earlier, Cd^{2+} by itself did not affect the fluorescence of the Qdots. These results indicated that in presence of the Cd^{2+} ions, the electron transfer between the Qdot and ligand was inhibited in QDL. This is due to the complex formation between Cd^{2+} and **L1**. Since the donor electrons of the amine group of the **L1** is now engaged in the complex formation with Cd^{2+}, the electron transfer from the **L1** to the Qdots is stopped. As a result, Qdot emission was restored. Fig. 1(b) shows the nature of PL peak intensity variation with respect to the increase of Cd^{2+} concentration.

The spectral nature indicated that once the **L1**–Cd complex formation is complete, the excess Cd^{2+} remained ineffective.

To test the selectivity of the QDL for Cd^{2+}, we have performed several experiments with other environmentally relevant metal ions. As expected, we observed high selectivity of QDL for Cd^{2+} over other metal ions. Fig. 2 depicts the fluorescence responses of QDL in the presence of different metal ions. We have not only observed excellent selectivity of QDL for Cd^{2+}, high sensitivity was noticed due to almost complete restoring of the QDL luminescence intensity to that of QD. It was observed that the response of the QDL to many other metal ions remained identical to that of Qdot. Only Zn^{2+} showed a small increase in the PL intensity of the QDL. In comparison to Cd^{2+}, Zn^{2+} showed a feeble (Fig. 2) restoration of QDL luminescence intensity upon addition of 2 mM of Zn^{2+}. This is due to lower affinity of Zn^{2+} for **L1** as also observed by others.[7] The emission intensity of QDL remained unaltered upon addition of 100 mM of Li^+, Na^+, K^+ and Ca^{2+}, indicating excellent selectivity over these alkali and alkaline earth cations (Fig. 2). Quenching of QDL

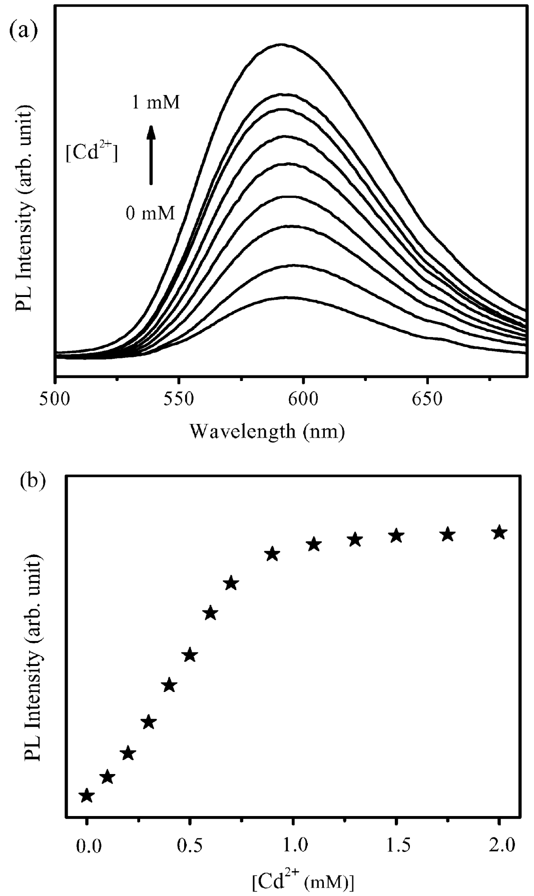


Fig. 1 (a) Effect of the external Cd^{2+} environment on the fluorescence properties of QDL (5 mg per ml solvent). (b) The nature of photoluminescence intensity variation of the QDL in response to various amounts (mM) of Cd^{2+} ions.

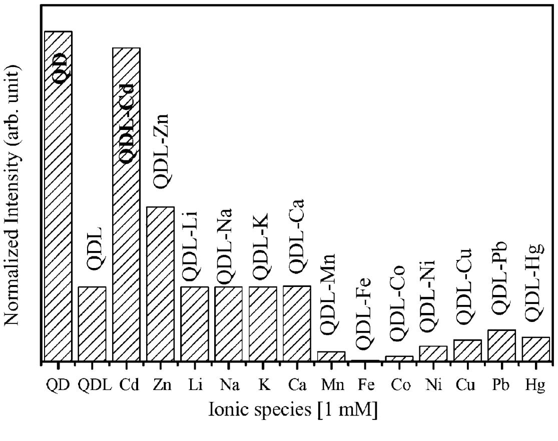


Fig. 2 Fluorescence responses of QDL to 1 mM of various metal ions.

luminescence intensity was observed when treated with transition metal ions (Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}) and heavy metal ions (Hg^{2+} and Pb^{2+}) (see Fig. 2). This clearly indicated that the **L1** did not form any complex with these transition and heavy metal ions. The quenching of luminescence intensity of the Qdots as well as QDL by transition and heavy metal ions was possibly due to exchange of metal ions with Qdots.[13,23]

In summary, we have demonstrated a novel strategy for the selective detection of Cd^{2+} by using Qdot probes. The basic idea is to modify the Qdot surface with the metal ion selective ligand *via* a zero length coupling chemistry. The detection is based on an electron transfer process between the Qdot and the ligand, and subsequent blocking of the electron transfer pathways upon exposure to Cd^{2+}. This strategy could be extended to optically detect other potentially harmful metal ions by Qdot probes.

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