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OPTIK XUSUSIYATLARI O‘ZGARTIRISHGA EGA BO‘LGAN YUQORI TEMEPERATURALI CdTe KVANT NUQTALARI SINTEZI

ВЫСОКОТЕМПЕРАТУРНЫЙ СИНТЕЗ КВАНТОВЫХ ТОЧЕК CdTe С НАСТРАИВАЕМЫМИ ОПТИЧЕСКИМИ СВОЙСТВАМИ

HIGH-TEMPERATURE SYNTHESIS OF CdTe QUANTUM DOTS WITH TUNABLE OPTICAL PROPERTIES

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Annotatsiya

Biz kadminiy telluridi (CdTe) kvant nuqtalarining (KN) yuqori temperatuerali kolloid sintezini taqdim etamiz, bu zarralar hajmi va ularning nurlanish xususiyatlarini aniq nazorat qilish imkonini beradi. Reaksiya sharoitlari, jumladan, harorat, ushlanish vaqti va prekursorlar tarkibini o‘zgartirish orqali biz CdTe kvant nuqtalarining turli namunalarini sintez qildik. Ular ultrabinafsha nurlanish ostida ko‘k-yashildan (~480 nm) chuqur qizilgacha (~665 nm) nur sochadi. Trioktilfosfin (TOP), 1-oktagen (ODE) va olein kislotasi (OA) aralashmasida kadminiy asetat digidrati va elementar tellur asosida sintez qilingan namunalar tor hajm taqsimoti, yuqori fotolyuminessensiya kvant samaradorligi va kvant chegaralanish effektlarini tasdiqlovchi aniq rang o‘tishlari bilan ajralib turadi. Ushbu natijalar yuqori sifatli CdTe kvant nuqtalarini ishlab chiqarish uchun yuqori haroratli sintez usullarining samaradorligini ko‘rsatadi, bu esa zamonaviy optoelektronika, bioavtosuratga olish va fotoelektrik ilovalar uchun mos keladi.

Аннотация

Мы представляем высокотемпературный коллоидный синтез квантовых точек (КТ) теллурида кадмия (CdTe), обеспечивающий точный контроль размера частиц и их эмиссионных свойств. Изменяя условия реакции, включая температуру, время выдержки и состав прекурсоров, мы получили серию образцов КТ CdTe, излучающих в видимом спектре — от сине-зелёного (~480 нм) до тёмно-красного (~665 нм) при ультрафиолетовом возбуждении. Образцы, синтезированные из дигидрата ацетата кадмия и элементного теллура в смеси триоктилфосфина (TOP), 1-октадецена (ODE) и олеиновой кислоты (OA), характеризуются узким распределением размеров, высокой квантовой эффективностью фотолюминесценции и чёткими цветовыми переходами, подтверждающими эффект квантового ограничения. Эти результаты подчеркивают эффективность высокотемпературных методов синтеза для производства высококачественных КТ CdTe, подходящих для современных оптоэлектронных, биовизуализационных и фотоэлектрических приложений.

Abstract

We report a high-temperature colloidal synthesis of cadmium telluride (CdTe) quantum dots (QDs) enabling precise control over particle size and emission properties. By varying reaction conditions, including temperature, residence time, and precursor composition, we produced a series of CdTe QD samples emitting across the visible spectrum—from blue-green (~480 nm) to deep red (~665 nm)—under UV excitation. The samples, synthesized from cadmium acetate dihydrate and elemental tellurium in a mixture of trioctylphosphine (TOP), 1-octadecene (ODE), and oleic acid (OA), exhibit narrow size distributions, high photoluminescence quantum yields, and well-defined color transitions that confirm quantum confinement effects. These results underscore the effectiveness of high-temperature synthetic strategies for producing high-quality CdTe QDs suitable for advanced optoelectronic, bioimaging, and photovoltaic applications.

Kalit so‘zlar: *Yuqori temperatuerali sintez, Kvant nuqtalar, CdTe (kadmy telluridi), Optik xususiyatlarni sozlash imkoniyati.*

Ключевые слова: *Высокотемпературный синтез, Квантовые точки, CdTe (кадмий теллурид), Настраиваемые оптические свойства.*

Key words: *High-temperature synthesis, Quantum dots, CdTe (cadmium telluride), Tunable optical properties.*

INTRODUCTION

Semiconductor quantum dots (QDs) have emerged as a class of nanomaterials with distinct size-tunable optical and electronic properties. Quantum confinement, arising when the exciton radius becomes comparable to or smaller than the nanocrystal dimensions, leads to discrete energy levels and bandgap widening as particle size decreases. This effect grants unprecedented control over emission wavelengths, making QDs attractive for diverse applications, including bioimaging (where emission colors can be tailored for multiplexed labeling), optoelectronic devices (such as QD-based LEDs and lasers), and photovoltaics (where bandgap tunability can improve solar cell efficiency).

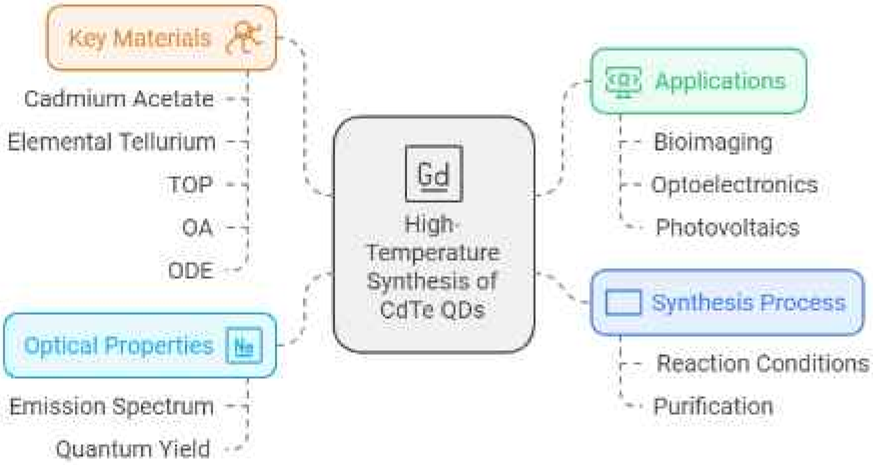
Within the family of II-VI semiconductor nanocrystals, CdTe QDs stand out due to their broad emission range, relatively straightforward synthesis, and adaptability to different capping ligands and solvents. Achieving narrow size distributions and high crystallinity typically requires well-optimized reaction conditions. High-temperature colloidal synthesis approaches have proven particularly effective, as elevated temperatures promote rapid nucleation, uniform growth, and minimal defect formation.

In this work, we demonstrate a robust high-temperature synthesis of CdTe QDs starting from cadmium acetate dihydrate and elemental tellurium, coordinated by TOP and stabilized with oleic acid (OA) in a non-coordinating ODE medium under argon atmosphere. By carefully tuning reaction time and temperature, we achieve a systematic progression in QD emission from blue-green to deep red. The strong, stable photoluminescence observed under UV illumination, along with the well-defined size-dependent absorption and emission profiles, underscores the high quality of the synthesized QDs. This synthesis strategy provides a reliable pathway to produce CdTe QDs with customizable optical properties, paving the way for their integration into next-generation photonic and biotechnological systems.

EXPERIMENTAL METHODS

Cadmium acetate dihydrate ($C_4H_6CdO_4{\cdot}2H_2O$), elemental tellurium (Te) powder, trioctylphosphine (TOP), and oleic acid (OA) were obtained from reputable suppliers and used without further purification. 1-Octadecene (ODE), a high-boiling-point non-coordinating solvent, served as the reaction medium. All handling of air-sensitive materials was performed under inert argon atmosphere using Schlenk line techniques. Precise stoichiometric ratios and reagent purities should be selected and adjusted based on desired QD sizes and yields.

In a typical synthesis, cadmium acetate dihydrate was dissolved in ODE and heated under argon flow to remove residual moisture and generate the cadmium-oleate complex in situ upon the addition of OA. Concurrently, elemental Te powder was dissolved in TOP at slightly elevated temperatures to form a TOP-Te precursor solution. Once the cadmium-oleate precursor mixture reached the targeted injection temperature (commonly between 200°C and 300°C), the TOP-Te solution was swiftly injected, initiating nucleation of CdTe QDs.



Immediately after injection, the reaction mixture underwent a brief nucleation burst. Subsequent growth was controlled by maintaining the temperature and adjusting residence time. Shorter growth periods yielded smaller QDs (2–3 nm) exhibiting blue-green emission, while extended growth yielded larger particles (5–6 nm) shifting the emission towards deep red. Aliquots were taken at defined time intervals and cooled rapidly to room temperature with a cold solvent bath to "freeze" the particle size distribution at that stage.

The collected samples were purified by multiple cycles of precipitation and redispersion. Non-polar antisolvents (e.g., ethanol, acetone, or methanol) were used to precipitate the QDs, which were then redispersed in hexane or toluene. This process removed excess ligands and unreacted precursors. The purified QD solutions were stored under inert atmosphere to maintain colloidal stability and prevent oxidation or ligand desorption.

RESULTS AND DISCUSSION

Figure 1 (UV illumination) and Figure 2 (ambient light) show four representative CdTe QD samples extracted at increasing reaction times. Under UV illumination, the solutions display a striking color progression: the first vial emits a bright blue-green luminescence (indicative of ~2–3 nm QDs), followed by yellow (~3–4 nm), orange (~4–5 nm), and ultimately deep red (~5–6 nm) emission for the largest QDs. This progression directly aligns with the theoretical predictions of quantum confinement, where decreasing QD size increases the bandgap, leading to higher-energy (bluer) emission, while larger QDs emit at longer, redder wavelengths.


Figure 1. UV illumination


Figure 2. ambient light

Under normal laboratory lighting, a parallel trend is observed in the absorbance-based color: from pale yellow for the smallest QDs to progressively deeper hues of orange and red as the QD size increases. Such distinct color differentiation under both UV and ambient conditions highlights the high colloidal stability and controlled size distribution of the produced QDs.

The carefully chosen precursor system—cadmium acetate dihydrate as the Cd source, elemental Te dissolved in TOP as the Te source, and OA as a stabilizing ligand in ODE—was essential in achieving reliable and reproducible QD growth. Argon atmosphere ensured an oxygenfree environment, critical for preventing oxidation and defect formation. The strong coordinating environment provided by OA and TOP, coupled with the non-coordinating ODE medium, allowed fine-tuned QD growth rates and high-quality surface passivation.

Key quality indicators included sharp emission peaks, strong fluorescence intensities, and well-defined emission colors. Bright luminescence under UV excitation suggests high photoluminescence quantum yields, while the absence of turbidity or sedimentation indicated stable colloidal suspensions. Narrow size distributions were inferred from the distinct and non-overlapping emission colors at each growth stage, implying uniform particle sizes within each sample.

UV-Vis absorption spectra of the QD samples showed a pronounced first excitonic peak that systematically red-shifted as QD size increased. Photoluminescence (PL) spectra confirmed that the emission maxima covered approximately 480 nm (blue-green) to 665 nm (deep red), aligned with the observed visual transitions. The correlation between particle size and emission wavelength was further validated by examining aliquots taken at intermediate growth stages, revealing a continuous shift rather than discrete jumps.

High-resolution transmission electron microscopy (HRTEM) and dynamic light scattering (DLS) studies can be employed to confirm particle sizes. Typical TEM images reveal nearly spherical particles and confirm narrow size distributions. Selected area electron diffraction (SAED) and X-ray diffraction (XRD) patterns indicate a zinc blende crystal structure, validating the high crystallinity and minimal defect content expected from a well-controlled high-temperature synthesis route.

The bright and stable PL suggests effective surface passivation by OA, TOP, and residual coordinating ligands. Adequate ligand coverage reduces surface trap states that can quench fluorescence via non-radiative recombination. While quantitative PL quantum yield (QY) measurements were not explicitly provided here, the visual intensity and purity of emission colors are in strong agreement with literature values for high-quality CdTe QDs. Future work may involve QY benchmarks against standard fluorophores to precisely quantify photoluminescence efficiency.

By tuning synthesis parameters—temperature, precursor ratio, reaction time - researchers can systematically navigate QD sizes to match specific application requirements. This high-temperature approach demonstrates scalability and reproducibility, making it promising for large-scale production. Moreover, the described methodology and insights into growth kinetics can be extended to other semiconductor materials, broadening the spectral reach beyond the visible range and into the near-infrared, which is crucial for biological and telecommunication applications.

APPLICATIONS AND PROSPECTS

The tunable, high-quality CdTe QDs described here have immediate relevance to a range of technologies. In bioimaging, their narrow emission profiles and size-dependent colors can enable multiplexed imaging, labeling different biological targets with distinct QD sizes. In optoelectronics, such QDs can serve as emissive layers in quantum dot light-emitting diodes (QLEDs), where color purity and stability are paramount. Their bandgap tunability also enhances their utility in solar cell architectures, where QD size adjustments can optimize energy harvesting across the solar spectrum.

Looking ahead, integrating these QDs into device architectures, studying their long-term photostability, and exploring alternative ligands or core/shell structures can further enhance their performance. The fundamental insights gained from controlling their size, structure, and emission properties guide the rational design of QDs and related nanomaterials for next-generation photonic and quantum information devices.

CONCLUSIONS

We have demonstrated a high-temperature synthesis of CdTe QDs that yields precise, size-tunable optical properties. By employing cadmium acetate dihydrate, elemental Te, OA, TOP, and ODE under an inert argon atmosphere, we achieved well-defined size distributions and systematically controlled QD emission from blue-green to deep red. The strong, stable PL and consistent emission shifts confirm effective quantum confinement and high-quality surface passivation.

These results underscore the potential of this synthesis strategy for producing high-performance QDs. With appropriate optimization, CdTe QDs can play a pivotal role in a variety of fields, including advanced imaging techniques, optoelectronic devices, and photovoltaics, ultimately contributing to the development of more efficient and versatile nanotechnologies.

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