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One-Pot Microwave Synthesis of Water-Dispersible, Ultraphoto- and pH-Stable, and Highly Fluorescent Silicon Quantum Dots

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Supporting Information

ABSTRACT: Fluorescent silicon quantum dots (SiQDs) are facilely prepared via one-pot microwave-assisted synthesis. The as-prepared SiQDs feature excellent aqueous dispersibility, robust photo- and pH-stability, strong fluorescence, and favorable biocompatibility. Experiments show the SiQDs are superbly suitable for long-term immunofluorescent cellular imaging. Our results provide a new and invaluable methodology for large-scale synthesis of high-quality SiQDs, which are promising for various optoelectronic and biological applications.

There is a great current interest in the development of silicon functional nanomaterials for myriad applications owing to their attractive merits including excellent optical/electronic/mechanical properties, surface tailorability, compatibility with silicon technologies, etc.[1] Typically, fluorescent silicon quantum dots (SiQDs), as representative zero-dimensional silicon nanostructures, are highly promising for biological and biomedical applications, due to favorable biocompatibility and low toxicity.[2] In the past several years, exciting progress in the development of SiQDs-based fluorescent biological probes has been achieved. Specifically, hydrophilic molecule (e.g., acrylic acid or allylamine)-capped, polymer-coated, or micelle-encapsulated SiQDs have been prepared for biological imaging.[3]

SiQDs studied to date are hydrophobic (Si−H bonds covering the surface of SiQDs) and require additional surface modification (e.g., molecules capping, polymer coating, and micelle encapsulation) to render them hydrophilic.[3] In addition to relatively complicated procedures, such post-treatments may produce adverse effects on the physical/chemical properties of the SiQDs. For examples, the acrylic acid- or allylamine-capped SiQDs suffer from poor pH stability, although they are stable under normal conditions; e.g., fluorescence of the modified SiQDs is severely quenched with changing pH values, leading to difficulty for conjugation of SiQDs with antibody.[3a−d] While the polymer-coated or micelle-encapsulated SiQDs preserve robust pH stability, their sizes are significantly increased to tens of nanometers (50−150 nm),[3c−f] which is deleterious to bioapplications (nanoparticles with hydrodynamic diameters <10 nm are more favorable for *in vivo* and *in vitro* applications.[4]). Moreover, optical properties of the modified SiQDs are prone to deteriorate (e.g., photoluminescent quantum yield (PLQY) of SiQDs decreased from ∼17% to <10% after encapsulation).[3c,f] Consequently, despite those advances, further efforts are still needed to develop strategies for facile synthesis of high-quality SiQDs for broad applications.

In this Communication, we present a new microwave-assisted method for one-pot synthesis of water-dispersible SiQDs using silicon nanowires (SiNWs) and glutaric acid as precursors. Microwave dielectric heating is utilized in the synthesis because of its unique advantages such as rapid temperature elevation, homogeneous heating and high reaction selectivity.[5] Remarkably, SiQDs featuring excellent aqueous dispersibility, robust photo- and pH-stability, strong fluorescence (∼15%), and favorable sizes (∼4 nm) are facilely and rapidly prepared in short reaction times (e.g., 15 min). (See Supporting Information for experimental details and mechanism discussion.) We further demonstrate that the resultant SiQDs are promising biological probes for long-term and real-time immunofluorescent cellular imaging.

Figure 1 displays the transmission electron microscopy (TEM) image, high-resolution TEM (HRTEM) image, size distributions, and dynamic-light-scattering (DLS) histogram of the as-prepared SiQDs. As shown in Figure 1a, the resultant SiQDs appear as spherical particles with good monodispersity. Moreover, the well-resolved lattice planes of ∼0.16 nm spacing in the HRTEM image (Figure 1b) demonstrate the excellent crystalline structures of the as-prepared SiQDs. (See enlarged images in Figures S2 and S3.) The size distribution in Figure 1c, calculated by measuring more than 300 particles, shows the SiQDs have an average size of 3.11 ± 0.65 nm. The corresponding DLS result provides further demonstration of the small sizes of the resultant SiQDs (hydrodynamic diameter ∼4.22 nm, Figure 1d), which offer great advantages for bioimaging, such as high sensitivity, specific labels, minimal toxicity, etc.[4] The different diameters measured by TEM and DLS are due to different surface states of the samples under the tested conditions. Specifically, the aqueous SiQDs samples are directly measured by DLS, while water in the SiQDs samples must be strictly removed for TEM characterization, leading to relative larger hydrodynamic diameter than that measured by TEM.[4a,e,6]

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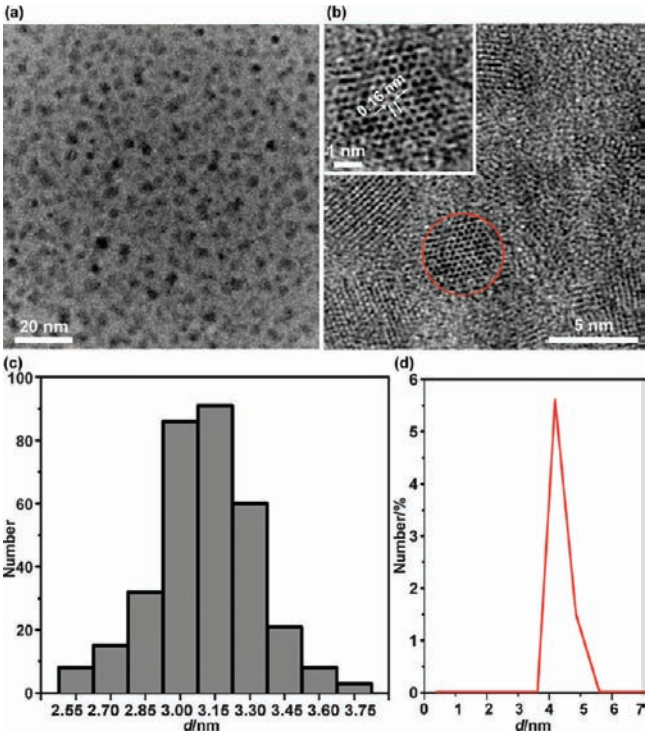

Figure 1. TEM and HRTEM images (a,b), size distribution (c), and representative DLS histogram (d) of the as-prepared SiQDs. Inset in (b) presents the HRTEM image of a single SiQD.

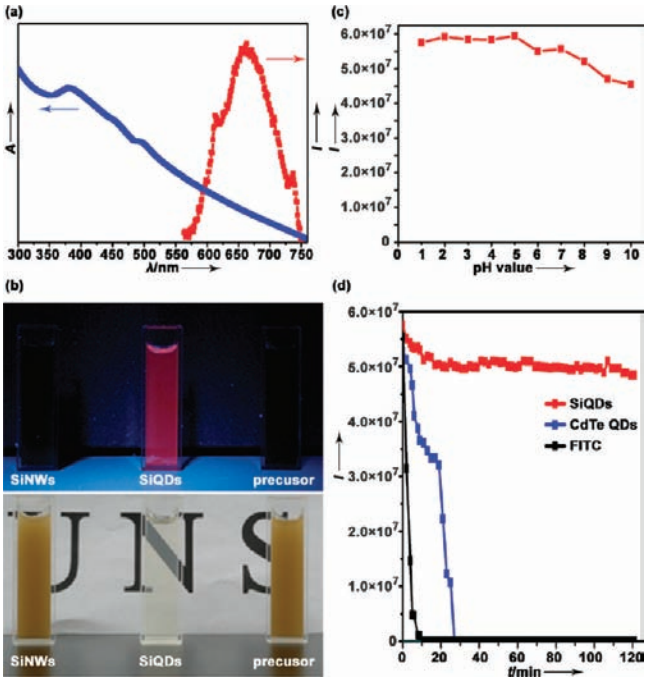

Figure 2. (a) Absorption and photoluminescence (UV-PL) spectra of the as-prepared SiQDs. (b) Photographs of aqueous solutions dispersed with the free-standing SiNWs (left), as-prepared SiQDs (middle), and reaction precursors (right) under 365 nm irradiation (up) or ambient light (bottom). (c) Temporal evolution of fluorescence of the SiQDs under various pH values. (d) Photostability comparison of FITC, CdTe QDs, and as-prepared SiQDs. All samples are continuously irradiated by a 450 W xenon lamp.

Figure 2a presents the normalized UV-PL spectra of the resultant SiQDs, indicating that the SiQDs possess good optical properties with clearly resolved absorption peak and symmetrical PL peak (maximum emission wavelength at ~660 nm). Significantly, in contrast to severely turbid solution dispersed with free-standing SiNWs or reaction precursors (SiNWs mixed with glutaric acid), the aqueous solution of SiQDs is highly transparent in ambient light (Figure 2b). It clearly shows that the as-prepared SiQDs feature excellent aqueous dispersibility, which is attributed to the large amount of surface-covered glutaric acid with hydrophilic carboxylic groups. (See FTIR in Figure S5.)[3d,e,5b−5d] The distinct red luminescence under UV irradiation further demonstrates the strong fluorescence of the as-prepared SiQDs (Figure 2b). Moreover, the SiQDs possess robust pH stability and preserve stable fluorescence under wide-ranging pH values. Particularly, the PL intensity only decreases slightly, by ~15%, in acidic-to-basic environments spanning a pH range of 1−10 (Figure 3c). We attribute this robust pH stability to the glutaric acid, which provides dicarboxylic ligands and a protective shell around the QDs.[3c−e] Furthermore, the SiQDs show superior photostability compared to FITC dye and CdTe QDs (recognized as photostable fluorescent labels[2]). Figure 3d shows the fluorescence of FITC is quickly quenched in 3-min UV irradiation due to severe photobleaching. Comparatively, the CdTe QDs are more photostable, retaining >50% of the original PL intensity after 20-min UV irradiation. Nevertheless, the fluorescence of CdTe QDs becomes undetectable in ~25 min due to surface deterioration under intense UV irradiation (Figure 3c).[5b−d,7] In striking contrast, the fluorescence intensity of SiQDs decreases only slightly, preserving ~90% of the initial intensity under 120-min UV irradiation (Figure 3b). We attribute such remarkable photostability to the protection from the ligands shell and the unique PL properties of SiQDs,[8] similar to those in the reported acrylic acid/allylamine-capped and polymer-coated SiQDs.[3a−e] In addition to the high photo- and pH-stability, the as-prepared SiQDs are noncytotoxic due to favorable biocompatibility of bulk silicon.[2c,3] No obvious decrease of cell viability is observed when cells are cultured with the SiQDs (see Figure S6).

The water-dispersible, highly photo- and pH-stable, strongly luminescent, and biocompatible SiQDs are further explored as biological fluorescent probes. For targeted immunological labeling of Hela cells (one typical kind of cervical cancer cells), the SiQDs are first conjugated with a goat anti-mouse antibody via traditional EDC/NHS cross-linking reaction; i.e., the carboxylic acid groups of ligands on the surface of SiQDs readily react with the amino groups of antibody by using EDC and NHS as zero-length cross-linkers.[9] Based on highly specific antibody−antigen immunoreactions, the resultant SiQDs bioconjugates are specifically targeted to the microtubules of Hela cells, which are beforehand incubated with a microtubules-specific anti-tubulin antibody.[3d,5c,5d] Figure 3a shows the photoluminescence of the SiQDs-labeled cellular microtubules is intense and clearly spectrally resolved. More significantly, the SiQDs are particularly suitable for long-term and real-time cellular imaging due to their ultrahigh photostability. In our experiment, the SiQDs-labeled microtubules yielded stable fluorescent signals during 120-min continuous observation (Figure 3b), in good accord with the above discussion on the excellent photostability of SiQDs. Moreover, the SiQDs maintained distinctive red fluorescence throughout 240-min irradiation in our experiment (see Figure S7). In contrast, for the control groups using the CdTe QDs or FITC

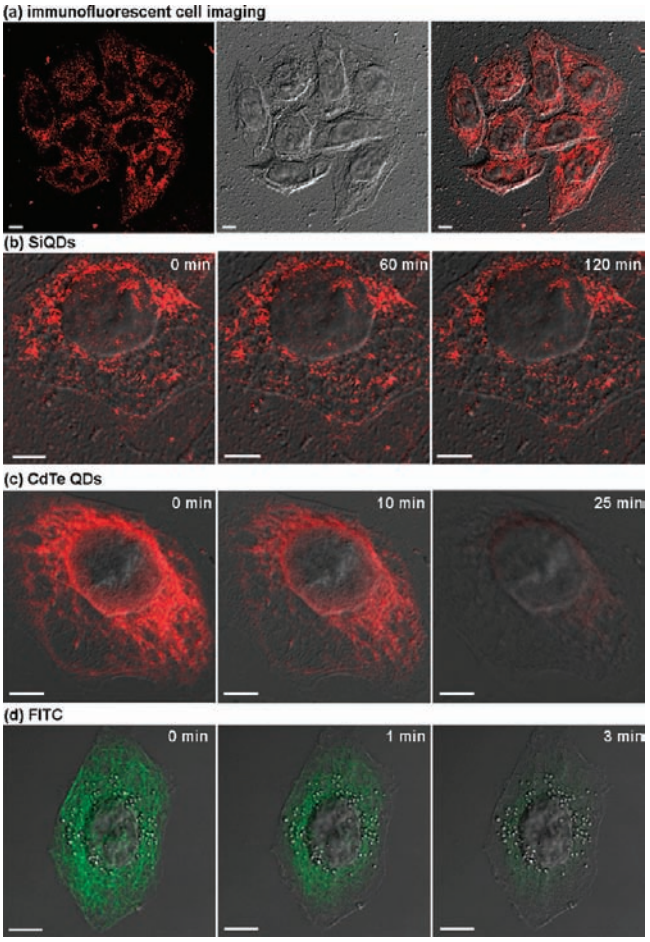

Figure 3. Photos of immunofluorescent cell imaging captured by laser-scanning confocal microscopy. (a) Left: microtubules of Hela cells are distinctively labeled by the SiQDs/protein bioconjugates. Middle: bright-field image. Right: superposition of fluorescence and transillumination images. (b−d) Stability comparison of fluorescence signals of Hela cells labeled by SiQDs (b), CdTe QDs (c), and FITC (d). Scale bar = 5 μm.

as fluorescent labels, the signals almost completely disappeared in short-time irradiation (Figure 3c,d). Specifically, the green fluorescence of FITC rapidly diminished in 3 min due to severe photobleaching (Figure 3d), and the CdTe QDs displayed bright and spatially resolved luminescence in the initial 10-min observation due to greater photostability than FITC, but the red signals were obviously depressed and nearly vanished after 25-min irradiation (Figure 3c).

In summary, we have developed a facile and rapid one-pot microwave-assisted synthesis of SiQDs. Significantly, the as-prepared SiQDs possess excellent aqueous dispersibility, ultra-high photo- and pH-stability, strong photoluminescence, and favorable biocompatibility. Such resultant SiQDs are particularly suitable for long-term and real-time immunofluorescent cellular imaging as promising biological fluorescent probes. The microwave methodology is readily scalable to large reaction volume,[10] e.g., 20 mL aqueous samples containing ~0.1 g of SiQDs are readily prepared via 15-min microwave reaction, providing sufficient SiQDs for diverse applications, and ~1 mL of SiQDs sample is adequate for immunofluorescent cellular imaging in our experiment. Consequently, the present microwave-assisted strategy provides a powerful approach to large-scale synthesis of high-quality SiQDs, which are promising for myriad SiQDs-based optoelectronic and biological applications, such as solar cells, biosensors, *in vitro* and *in vivo* imaging, etc.[1,2]

■ ASSOCIATED CONTENT

Supporting Information. Experimental methods, Figures S1−S11, and corresponding discussions. This information is available free of charge via the Internet at http://pubs.acs.org.

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