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Solution Synthesis, Optical Properties, and Bioimaging Applications of Silicon Nanocrystals

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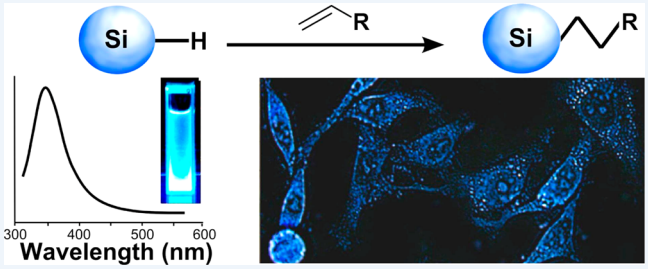
CONSPECTUS: Understanding and unlocking the potential of semiconductor nanocrystals (NCs) is important for future applications ranging from biomedical imaging contrast agents to the next generation of solar cells and LEDs. Silicon NCs (Si NCs) have key advantages compared with other semiconductor NCs due to silicon's high natural abundance, low toxicity and strong biocompatibility, and unique size, and surface dependent optical properties. In this Account, we review and discuss the synthesis, surface modification, purification, optical properties, and applications of Si NCs.



The synthetic methods used to make Si NCs have improved considerably in the last 5−10 years; highly monodisperse Si NCs can now be produced on the near gram scale. Scaled-up syntheses have allowed scientists to drive further toward the commercial utilization of Si NCs. The synthesis of doped Si NCs, through addition of a simple elemental precursor to a reaction mixture or by the production of a single source precursor, has shown great promise. Doped Si NCs have demonstrated unique or enhanced properties compared with pure Si NCs, for example, magnetism due to the presence of magnetic metals like Fe and Mn. Surface reactions have reached a new level of sophistication where organic (epoxidation and diol formation) and click (thiol based) chemical reactions can be carried out on attached surface molecules. This has led to a wide range of biocompatible functional groups as well as a degree of emission tuneability.

The purification of Si NCs has been improved through the use of size separation columns and size selective precipitation. These purification approaches have yielded highly monodisperse and pure Si NCs previously unachieved. This has allowed scientists to study the size and surface dependent properties and toxicity and enabled the use of Si NCs in biomedical applications.

The optical properties of Si NCs are complex. Using a combination of characterization techniques, researchers have explored the relation between the optical properties and the size, surface functionalization, and preparation method. This work has led to a greater fundamental understanding of the unique optical properties of Si NCs. Si NCs are being studied for a wide range of important applications, including LEDS with tunable electroluminescence ranging from NIR to yellow, the encapsulation of Si NCs within micelles terminated with proteins to allow targeted *in vivo* imaging of cells, Si NC−polymer hybrid solar cells, and the use of Si NCs in battery anodes with high theoretical capacity and good charge retention.

INTRODUCTION

There is great interest in the unique size and surface dependent optical properties of semiconductor NCs.[1−4] Si NCs are attractive because of their unique optical properties, high natural abundance, low toxicity, and well developed surface chemistry.[5−8] Si NCs have a diverse range of applications, such as bioimaging agents, water splitting, battery anodes, and use in next generation photovoltaic devices.[5,9−12] In this Account, we provide an outline of the exciting recent progress in the synthesis, surface functionalization, optical properties, and potential applications of Si NCs.

SOLUTION SYNTHESIS OF SILICON NANOCRYSTALS

A range of methods have been successfully developed to produce Si NCs.[13−19] The synthesis of Si NCs can be challenging due to the sensitivity of both precursors and uncapped Si NCs with oxygen and moisture. So, syntheses must typically be carried out under inert conditions.[13,14]

A versatile method to produce Si NCs is the reduction of halide salts using hydride reducing agents in the presence of surfactants, because the size of the Si NCs can be controlled by changing the surfactants or the strength of the reducing agent.[20−23] Wilcoxon and co-workers produced Si NCs between 1 and 10 nm by reducing silicon tetrachloride ($SiCl_4$) with lithium aluminum hydride ($LiAlH_4$) in the presence of the surfactant tetraoctylammonium bromide (TOAB) (Scheme 1).[22] Caution needs to be taken because silane gas can be generated during this reaction.[24] We then adapted Wilcoxon's synthesis to create highly monodisperse (1.8 ± 0.2 nm) alkyl or (1.4 ± 0.3 nm) alkylamine capped Si (and Ge) NCs with unique optical properties (Figure 1a).[14,20,21,25] The use of reducing agents for controlling the

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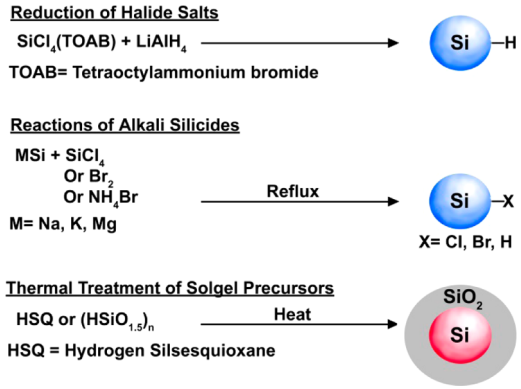
Scheme 1. Schematic Representation of Solution Synthetic Routes for Si NCs



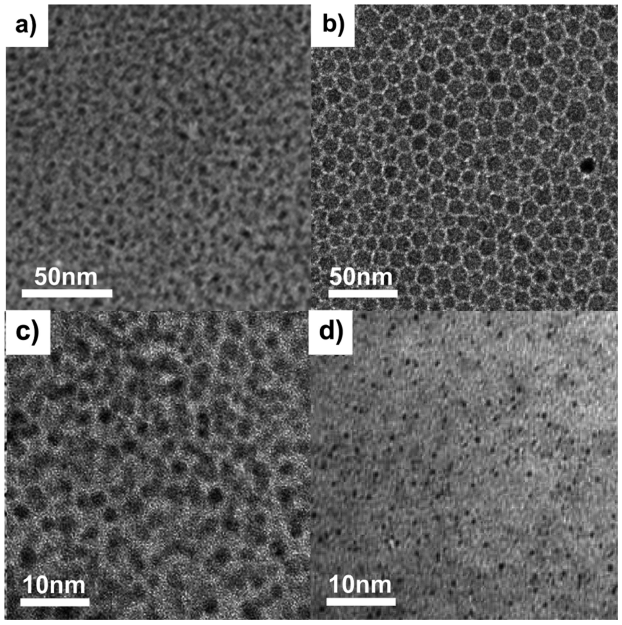


Figure 1. TEM images of Si NCs produced by (a) reduction of halide salts, (b) thermal treatment of HSQ, (c) microwave assisted reduction of APTMS, and (d) electrochemical etching. Panel a adapted with permission from ref 36. Copyright 2013 American Chemical Society. Panel b adapted with permission from ref 31. Copyright 2011 American Chemical Society. Panel c adapted with permission from ref 18. Copyright 2013 American Chemical Society. Panel d adapted with permission from ref 35. Copyright 2007 American Chemical Society.

size of Si and Ge NCs was then investigated using four hydride reducing agents of varying strengths: sodium borohydride ($NaBH_4$), lithium borohydride ($LiBH_4$), superhydride ($LiBH(Et)_3$), and $LiAlH_4$.[26,27] The average particle size ranged from 2.5 ± 1.0 nm ($NaBH_4$) to 1.6 ± 0.4 nm ($LiAlH_4$).[26] It was found that with a stronger reducing agent, smaller and more monodisperse NCs were formed due to faster and more controlled nucleation and growth.[26] This work showed the broad ability of hydride reducing agents in controlling Si NC size.[26]

Zulihof and co-workers showed the scalability of the halide salt reduction method to produce alkyl capped Si NCs on a near-gram scale (0.85 g).[23] Importantly, the scale-up was achieved without sacrificing key factors, such as monodispersity (1.57 ± 0.21 nm) and optical properties.[23]

The reaction of alkali silicides (MSi, M = Na, K, or Mg) with $SiCl_4$ or ammonium bromide (NH_4Br) has been highly successful at producing Si NCs.[13,28,29] Kauzlarich and co-workers refluxed Mg_2Si with $SiCl_4$ in glyme/diglyme for 36−48 h to produce chlorine terminated Si NCs with sizes dependent on reflux time (2−5 nm) (Scheme 1).[13] Alkali silicides have also been used to produce doped Si NCs.[28,29] Mn and Fe doped Si NCs were produced by the reaction of M_xNaSi_{1-x} (M = Fe or Mn, x = 0.05, 0.1, 0.15) with NH_4Br. By controlling the ratio of M/NaSi, the amount of dopant present in the Si NCs could be controlled.[28,29]

Veinot and co-workers used the thermal treatment of hydrogen silsesquioxane (HSQ) in a reducing atmosphere to produce Si NCs embedded within a SiO_2 matrix (Scheme 1).[15,30] After acid etching (HF/EtOH), liberated NCs had an average size of 3.41 ± 1.41 nm.[15] NC size could be controlled by changing the processing temperature and etching time, as shown by X-ray diffraction.[15] Korgel and co-workers modified the thermal treatment of HSQ, producing Si NCs with a greater size range (3−90 nm) (Figure 1b).[31] Control of particle size was achieved by variation in the processing temperature and use of a single heating step.[31] Thermal processing of sol−gel precursors has been recently shown as a versatile route to produce other Si nanomaterials, such as SiC and SiN.[32]

Holmes et al. produced alkyl passivated Si NCs by the thermal decomposition of diphenylsilane in a hexane/octanol mixture under supercritical conditions.[16] NC size could be tuned from 1.5−4.0 nm depending on the Si/octanol molar ratio.[16] He and co-workers produced carboxyl terminated Si NCs through the microwave induced breakdown of Si nanowires (Si NWs) in the presence of glutaric acid.[33] Si NCs were monodisperse with particles having an average size of 3.11 ± 0.65 nm.[33] The same group developed a microwave based synthesis of Si NCs utilizing readily available precursors/reagents.[18] 3-Aminopropyltrimethoxysilane (APTMS) was reduced by trisodium citrate under microwave irradiation to produce alkylamine passivated Si NCs with an average size of 2.2 ± 1.7 nm (Figure 1c).[18]

HF assisted etching of wafers is one of the most common methods to make Si NCs.[34] One issue associated with electrochemical etching is the difficulty to control the size of produced Si NCs. Kang et al. developed an electrochemical synthesis to produce Si NCs with well controlled sizes (1−4 nm) (Figure 1d).[35] The key to this synthesis was the use of a unique electrolytic catalyst, produced by mixing H_2O_2 with a polyoxometalate anion, which, in combination with control over current density, allowed fine control over particle size.[35]

■ SURFACE MODIFICATION

Capping reactions, used to bind molecules onto the surface of Si NCs, are vital to protect them from air and moisture and also control solubility. Silicon has a high affinity for oxygen, as shown by the strength of the Si−O bond (809 kJ/mol). Upon exposure to air, Si NCs are immediately passivated with a complex oxide layer (SiO_x).[36] Oxide layers are known to modify the optical properties of the Si core.[36] Surface modification reactions are used to retain control over the optical properties and NC solubility.[13,14,31,37]

Hydrosilylation is a popular surface reaction that creates a strongly covalent and stable Si−C bond (451 kJ/mol).[14,31,37] Hydrosilylation involves the reaction between an alkene and a hydride terminated silicon surface, producing a Si−C bond.

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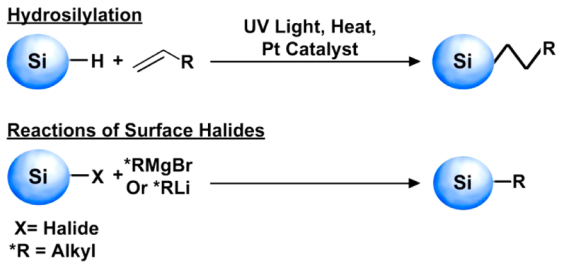
The reaction is usually initiated by heat, UV-light or white light, or a Pt catalyst (Scheme 2).[14,31,37]

Scheme 2. Si−C Bond Formation by Hydrosilylation or Reaction with the Si−X Bond (X = halide)



Ruckenstein and co-workers carried out UV-assisted hydrosilylation with poly(acrylic acid) (PAAc), producing carboxyl terminated Si NCs that were dispersible in water.[37] XPS, NMR, and FTIR confirmed the successful surface modification.[37]

Our group applied Pt catalyzed hydrosilylation using H_2PtCl_6 to produce alkyl or alkylamine capped Si or Ge NCs that had long-term optical and chemical stability months after synthesis[20,21,25] NCs could be dispersed in either hydrophobic or hydrophilic solvents depending on the alkene used (1-heptene or allylamine, respectively).[20,21] FTIR confirmed successful surface modification.[20,21]

Rather than attach individual molecules with desired functional groups to the Si NCs, we created a flexible platform for the functionalization of Si NCs.[38] The carbon double bond of the -ene group on the surface molecules, extending from the Si NCs, can be reacted to produce a diverse range of oxygen containing functional groups; for example, -ene terminated Si NCs could be converted to an epoxide using m-CPBA.[38] Due to the high reactivity of epoxides, this could be further reacted to form diol surface functionalized Si NCs.[38] Throughout the reactions, FTIR and NMR were used to confirm the functionalities present at the surface.[38]

Cheng et al. used thiol−ene click chemistry to modify the surface of alkene passivated Si NCs.[39] By changing the terminal group on the alkanethiol from polar groups like COOH, SO_3^-, and NH_2 to the nonpolar CH_3, the Si NCs could be stable in a range of solvents, ranging from water to hexane.[39]

The Si−X bond (X = halide) is another reactive surface group that can be further functionalized to produce alkyl or alkoxy terminated Si NCs.[13] Kauzlarich and co-workers reacted chlorine terminated Si NCs with Grignard or alkyllithium reagents to produce alkyl capped Si NCs that were dispersible in nonpolar solvents, such as hexane (Scheme 2).[13]

Erogbogbo et al. demonstrated that alkyl capped Si NCs could be encapsulated within phospholipid micelles terminated with polyethylene glycol (PEGs) groups.[40,41] The modifiable nature of the terminal PEG phospholipid groups allowed a range of important biomolecules to be attached, including functionalization with peptides.[40,41] Ozin and co-workers encapsulated alkyl capped Si NCs within solid lipid nanoparticles (SLN) (made from a combination of stearic acid and polyoxyethylene) terminated by hydroxylated PEG groups.[42]

PURIFICATION

Purification of Si NCs is vital for applications such as bioimaging, where unreacted material or side products can cause cytotoxicity.[26] Initial toxicity studies highlighted that organic surfactant and lithium or chloride ion impurities could cause cytotoxicity. These findings motivated us to develop the use of size exclusion chromatography as a purification tool for Si NCs.[26] We showed quantitatively, through the use of ^{1}H NMR, that size selective chromatography can yield highly pure, monodisperse Si NCs with low toxicity (Figure 2a,b).[26]

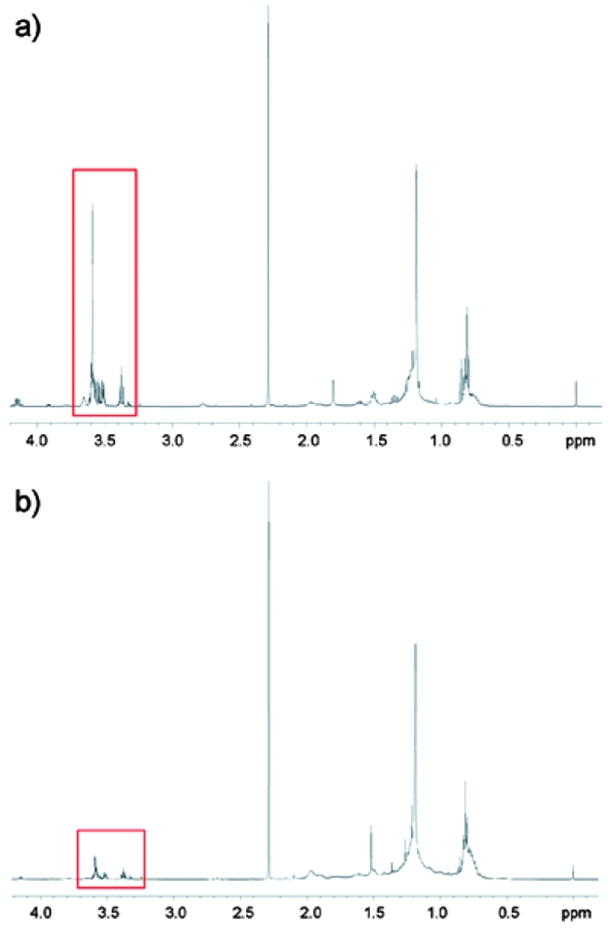


Figure 2. ^{1}H NMR of Si NCs (a) as synthesized and (b) after size exclusion chromatography. The peaks in the red boxes are from surfactant molecules. The decrease in intensity of these peaks from spectrum a to b indicates the loss of surfactant. Shiohara et al., ref 26, reproduced by permission of the Royal Society of Chemistry.

Size selectivity is important in the fabrication of LEDs to ensure color tunability.[11,43] Density gradient ultracentrifugation (DGU) has been used by the Ozin and Kortshagen groups to allow the size separation of as-produced polydisperse Si NCs, resulting in monodisperse Si NC samples.[44,45] Electron microscopy was used in both cases to prove that a high level of monodispersity was achieved.[44,45] Starting from a polydisperse sample of Si NCs, Mastronardi et al. used size selective precipitation with a centrifuge to produce a range of monodisperse clusters. Separation was achieved by varying the amount of antisolvent used and the number of centrifuge cycles.[43]

Size separation has also been achieved through the use of column chromatography.[22,46,47] Through the use of silica gel chromatography and high performance liquid chromatography, the Ruckenstein and Wilcoxon groups separated polydisperse samples of Si NCs into fractions of monodisperse Si NCs.[22,47]

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In both cases, photoluminescence spectroscopy was used to show that monodispersity was achieved.[22,47]

OPTICAL PROPERTIES

The optical properties of Si NCs can be complex; with many groups reporting emissions from Si NCs ranging from the UV to NIR.[13−15,17−19,33]

The emission observed and quantum yield are often dependent on the preparation method (Figure 3a−d).[18,21,31,48] Si NCs synthesized by low temperature solution methods (<160 °C) typically show UV-blue/green (390−500 nm) emission, with limited size tunability, moderate quantum yields (10−25%), and relatively fast emission decay times (1−10 ns).[13,14,18,33,39] Si NCs synthesized at higher temperatures typically show tunable emission (green to NIR), often with higher quantum yields (up to 70%) and slower emission decay times (microsecond).[15,17,31,48] The origins of the optical properties of Si NCs are best explained by surface effects (e.g., surface termination), defects, and size effects (through quantum confinement).[36,44,46,49,50]

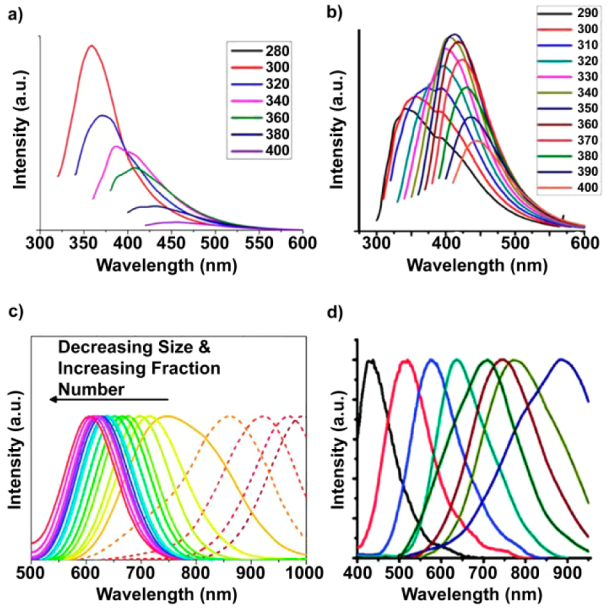

Figure 3. Emission spectra of Si NCs produced by low temperature, high temperature, and gas phase methods, emphasizing the difference in emissions between synthetic methods: (a) reduction of halide salts (low temperature); (b) reactions of alkali silicides (low temperature); (c) thermal treatment of sol−gels (high temperature); (d) laser pyrolysis of silane (gas phase). Panel a adapted with permission from ref 36. Copyright 2013 American Chemical Society. Panel b adapted with permission from ref 36. Copyright 2013 American Chemical Society. Panel c adapted with permission from ref 43. Copyright 2011 American Chemical Society. Panel d adapted with permission from ref 41. Copyright 2010 American Chemical Society.

Surface effects can alter the optical properties of Si NCs.[36,39,49,50] These include different surface terminations and the presence of surface oxide species and impurities.[36,49,50] We demonstrated that the optical properties of Si NCs are dependent on the polarity of surface terminations.[20,38] Four different terminations, alkene, diol, epoxy, and amine, all showed differences in absorption and emission spectra. Polar groups (diol, epoxy, and amine) demonstrated a 100 nm red-shift in emission relative to the nonpolar group (alkene).[38] This large shift in the emission was attributed to different radiative recombination channels available to polar and nonpolar capped Si NCs.[38] Dohnlová et al. studied the effect of surface termination on the optical properties of Si NCs.[49] Changing from an alkyl to an oxide terminated Si NC caused a large red-shift in the emission and an increase in the emission lifetime from nanosecond to microsecond.[49]

In collaboration with the Veinot and Kauzlarich groups, we studied the effect of impurity defects on the optical properties of Si NCs.[36] Using X-ray photoelectron spectroscopy, it was found that nitrogen/oxygen impurities present in Si NCs can give rise to the observed optical properties.[36] By treating hydride terminated Si NCs with nitrogen or oxygen containing surface molecules, commonly used in low temperature Si NC synthesis, the observed emission changed from red to blue.[36] The observed emission shift was accompanied by a change in the emission lifetime from microsecond to nanosecond.[36] TEM analysis showed no change in the NC size postmodification.[36]

Quantum confinement effects can also control optical properties of Si NCs.[17,31,43,46] These include size dependent absorption, emission, and emission lifetimes when a NC is smaller than the Bohr exciton radius (4.5 nm for Si NCs).[31,43] The effects of quantum confinement, such as size dependent emission, absorption, and emission lifetime, have been explored by several groups.[17,44,46] Ozin and co-workers studied the optical properties of size separated Si NCs.[43] Smaller Si NCs showed a blue-shift in the emission spectrum and a decreased emission lifetime, consistent with the quantum confinement model.[43] The blue-shift in emission was also well correlated with the size of the NCs, determined by TEM measurements.[43] Korgel and co-workers studied the optical properties of Si NCs with sizes between 3 and 12 nm, finding good agreement with the quantum confinement model.[31] The emission had a distinct blue-shift from 1060 nm for 12 nm Si NCs to 550 nm for 2.7 nm Si NCs, with quantum yield increasing as the size decreased.[31]

BIOLOGICAL APPLICATIONS AND TOXICITY

Bioimaging applications require materials with good biocompatibility, low toxicity, and stable emission. Organic dyes are currently used as bioimaging agents. However, organic dyes can suffer from photobleaching, rendering them unsuitable for long-term imaging experiments.[51] Si NCs have potential as future biological markers due to their low toxicity, optical properties, and photostability.[5,18,26,40,41]

Several *in vitro* and *in vivo* studies have proven the low toxicity of Si NCs.[52−55] The main factors affecting the toxicity of Si NCs are surface groups and size.[38,52,55,56]

In terms of *in vitro* toxicity, our group studied the effect of the surface functionality on lung and skin cell viability.[38] It was found that highly reactive surface groups, like epoxides, were twice as toxic to lung epithelial cells compared with amine or diol surface groups due to the epoxide's ability to cause oxidative stress within the cell.[38] Zuilhof and co-workers studied the surface and size dependent toxicity of Si NCs.[55] Surface groups with a positive charge within biological systems (amine) were found to be more toxic than groups that are neutral (azide, hydroxyl) or negatively charged (carboxylic acid) due to positively charged surface groups (amine) damaging mitochondrial membranes.[55] Smaller NCs (1.6 nm) were more toxic than larger NCs (3.9 nm) due to an increased surface area per unit volume.[55] Coating amine terminated Si NCs with biocompatible agents, like dextran, has been shown

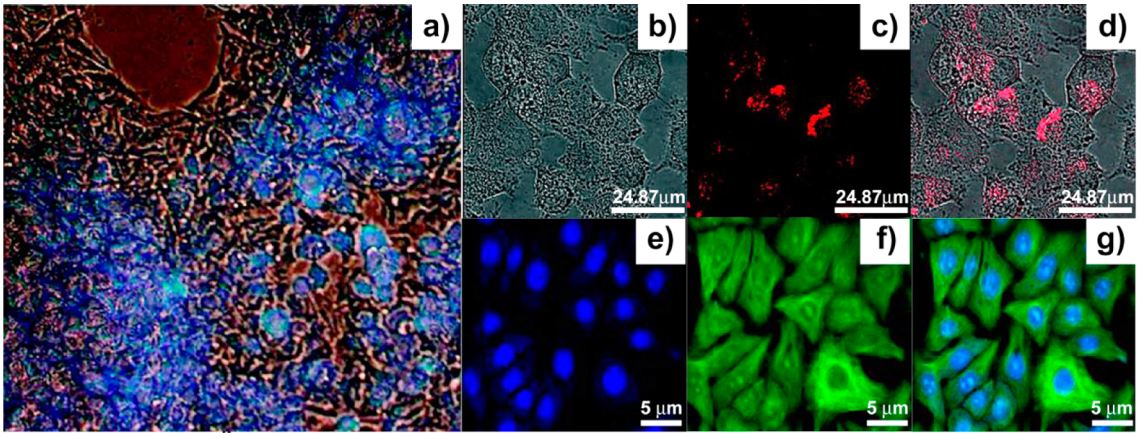

Figure 4. (a) Fluorescent image of HeLa cells using blue emitting Si NCs; (b) transmitted image of pancreatic cancer cells; (c) fluorescent image of pancreatic cancer cells with red emitting micelle encapsulated Si NCs; (d) overlay image of panels b and c; (e) fluorescent image of the nuclei of HeLa cells by blue emitting Si NCs; (f) fluorescent image of the microtubules of HeLa cells by the dye FTIC; (h) overlay image of panels e and f. Panel a adapted with permission from ref 38. Copyright 2009 American Chemical Society. Panels b–d adapted with permission from ref 40. Copyright 2008 American Chemical Society. Panels e–g adapted with permission from ref 18. Copyright 2013 American Chemical Society.

to lower toxicity. This emphasizes the importance of using surface functionalities with benign biological activity.[55]

In vivo toxicity studies by Swihart and co-workers, carried out on two animal lines (mice and monkeys), showed that a large dose of Si NCs (200 mg/kg) had no adverse effects in terms of blood chemistry, behavior, and weight.[52] However, pathology work did show a difference between mouse and monkey models, with mice showing adverse effects in the liver.[52] To understand the excretion pathway of Si NCs, Tu et al. carried out *in vivo* positron emission tomogorpahy (PET) studies on mice. These showed that Si NCs are largely removed via renal filtration within minutes to hours after injection, with a small population residing within the liver for up to several weeks.[53]

The suitability of the optical properties of Si NCs for bioimaging has been studied by several groups with a particular focus on stability.[18,21,26,33,41,57]

In 2004, Ruckenstein and co-workers reported the first account of bioimaging using red emitting Si NCs to image CHO cells.[37] Red emitting Si NCs had strong luminescence after 24 h of UV exposure. In comparison, a series of organic dyes lost emission after 20 min.[37] With the Yamamoto group, we illustrated the first use of blue emission for the imaging of HeLa cells.[21] Blue emitting Si NCs had strong luminescence after 60 min of UV exposure. In comparison, an organic dye had a significant decrease in luminescence over the same time period.[21] Further studies, showed longer term photostability of blue emitting Si NCs (Figure 4a).[26] Confocal studies showed that blue emitting Si NCs still had fluorescence in MCF-7 cells after a 24 h incubation period, making them suitable candidates for longer term imaging.[26]

Swihart, Prasad, and co-workers showed that red emitting Si NCs encapsulated within PEG phospholipid micelles could be used to image panc-1-cells (Figure 4b,c,d).[40] Luminescence from micelle encapsulated Si NCs had good temperature and pH stability, with luminescence still visible after 2 months of storage.[40] Prasad and co-workers showed that micelle encapsulated Si NCs conjugated to a protein, with emission ranging from red to NIR, could be used for *in vivo* multicolor imaging of mice limbs, with two different emissions (red and green) clearly visible.[41] The emission from micelle encapsulated Si NCs had good stability in terms of pH and temperature.[41]

He and co-workers developed a class of red and blue emitting Si NCs conjugated to proteins that allowed immunofluorescent cell imaging of HeLa cells (Figure 4e–g).[18,33,57] Red and blue Si NC conjugates had good photo- and pH-stability.[18,33,57] Under continuous UV light, red and blue Si NC conjugates had emission for up to 180 and 60 min, respectively, without loss in emission.[18,57]

FUTURE PERSPECTIVES, POTENTIAL CHALLENGES, AND CONCLUSIONS

The low toxicity of Si NCs, combined with silicon's natural abundance, make them highly attractive materials for a wide range of future applications, from optoelectronic devices to medical imaging. However, for the full potential of Si NCs to be unlocked, there are still many interesting and exciting challenges that need to be overcome. Synthetic protocols need further improvements in terms of scale-up, possibly by using flow rather than batch processes. Additionally, many methodologies use hazardous and toxic starting materials. Most syntheses require post-synthetic treatments to not only produce highly monodisperse NCs but also remove byproducts. Purification techniques, such as size selective column chromatography, must be utilized in order to produce highly pure monodisperse samples, but these can dramatically decrease overall yield and need refinement.

Doped and bimetallic Si NCs have great scope, with additional elements adding further optical, electronic, or magnetic properties to the NCs. Si can form alloys with a range of elements, for example Fe, Ge, or Sn. Therefore, there is a real opportunity to develop NCs with random or ordered alloy or core–shell structures. These materials can have unique or enhanced chemical or physical properties relative to their single metal systems.

A full understanding of the origins and tuneability of the optical properties of Si NCs is still needed to integrate both theoretical and experimental understandings.

Applications of Si NCs, such as *in vivo* cell imaging, LEDs, and battery anodes are attractive with excellent future prospects. In terms of bioimaging agents, further developments are needed for Si NCs, including increasing quantum yields for orange and red emission and development for multifunctional

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therapies, including drug delivery. With so much work still to do in the field of Si NCs, the future is very bright.

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Notes

The authors declare no competing financial interest.

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Benjamin F. P. McVey received his B.Sc. in chemistry from Victoria University of Wellington in 2011. Since 2013, he has been pursuing his Ph.D. under the supervision of Associate Professor Richard Tilley. His research is focused on the synthesis of group IV and CZTS nanoparticles.

Richard D. Tilley is part of the School of Chemical and Physical Sciences, Victoria University of Wellington (VUW), and MacDiarmid Institute of Advanced Materials and Nanotechnology, NZ. A native of the U.K., he graduated with a Masters of Chemistry from Oxford University, U.K. He earned his Ph.D. in the Department of Chemistry, University of Cambridge, U.K., after which he was a Postdoctoral Fellow for two years at the Toshiba Basic R&D center, Japan. His research is focused on the solution phase synthesis of nanoparticles and quantum dots for applications ranging from catalysis to biomedical imaging. He was recently awarded the Easterfield Medal by the RSC and NZIC.

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REFERENCES

(1) Kim, J. Y.; Voznyy, O.; Zhitomirsky, D.; Sargent, E. H. 25th Anniversary Article: Colloidal Quantum Dot Materials and Devices: A Quarter-Century of Advances. *Adv. Mater.* **2013**, *25*, 4986−5010.

(2) Warner, J. H.; Tilley, R. D. Synthesis and Self-Assembly of Triangular and Hexagonal CdS Nanocrystals. *Adv. Mater.* **2005**, *17*, 2997−3001.

(3) Siah, W. R.; LaGrow, A. P.; Banholzer, M. J.; Tilley, R. D. CdSe Quantum Dot Growth on Magnetic Nickel Nanoparticles. *Cryst. Growth Des.* **2013**, *13*, 2486−2492.

(4) Xu, Y.; Al-Salim, N.; Bumby, C. W.; Tilley, R. D. Synthesis of SnS Quantum Dots. *J. Am. Chem. Soc.* **2009**, *131*, 15990−15991.

(5) Peng, F.; Su, Y.; Zhong, Y.; Fan, C.; Lee, S.-T.; He, Y. Silicon Nanomaterials Platform for Bioimaging, Biosensing, and Cancer Therapy. *Acc. Chem. Res.* **2014**, *47*, 612−623.

(6) Cheng, X.; Lowe, S. B.; Reece, P. J.; Gooding, J. J. Colloidal Silicon Quantum Dots: From Preparation to the Modification of Self-Assembled Monolayers (SAMs) for Bio-Applications. *Chem. Soc. Rev.* **2014**, *43*, 2680−2700.

(7) Dohnalová, K.; Gregorkiewicz, T.; Kůsová, K. Silicon Quantum Dots: Surface Matters. *J. Phys.: Condens. Matter* **2014**, *26*, No. 173201.

(8) He, Y.; Fan, C.; Lee, S.-T. Silicon Nanostructures for Bioapplications. *Nano Today* **2010**, *5*, 282−295.

(9) Deb-Choudhury, S.; Prabakar, S.; Krsinic, G.; Dyer, J. M.; Tilley, R. D. Silicon and Germanium Nanoparticles with Tailored Surface Chemistry as Novel Inorganic Fiber Brightening Agents. *J. Agric. Food Chem.* **2013**, *61*, 7188−7194.

(10) Wu, H.; Cui, Y. Designing Nanostructured Si Anodes for High Energy Lithium Ion Batteries. *Nano Today* **2012**, *7*, 414−429.

(11) Maier-Flaig, F.; Rinck, J.; Stephan, M.; Bocksrocker, T.; Bruns, M.; Kübel, C.; Powell, A. K.; Ozin, G. A.; Lemmer, U. Multicolor Silicon Light-Emitting Diodes (SiLEDs). *Nano Lett.* **2013**, *13*, 475−480.

(12) Liu, C.-Y.; Holman, Z. C.; Kortshagen, U. R. Hybrid Solar Cells from P3HT and Silicon Nanocrystals. *Nano Lett.* **2009**, *9*, 449−452.

(13) Yang, C.-S.; Bley, R. A.; Kauzlarich, S. M.; Lee, H. W. H.; Delgado, G. R. Synthesis of Alkyl-Terminated Silicon Nanoclusters by a Solution Route. *J. Am. Chem. Soc.* **1999**, *121*, 5191−5195.

(14) Tilley, R. D.; Yamamoto, K. The Microemulsion Synthesis of Hydrophobic and Hydrophilic Silicon Nanocrystals. *Adv. Mater.* **2006**, *18*, 2053−2056.

(15) Hessel, C. M.; Henderson, E. J.; Veinot, J. G. C. Hydrogen Silsesquioxane: A Molecular Precursor for Nanocrystalline Si−SiO_2 Composites and Freestanding Hydride-Surface-Terminated Silicon Nanoparticles. *Chem. Mater.* **2006**, *18*, 6139−6146.

(16) Holmes, J. D.; Ziegler, K. J.; Doty, R. C.; Pell, L. E.; Johnston, K. P.; Korgel, B. A. Highly Luminescent Silicon Nanocrystals with Discrete Optical Transitions. *J. Am. Chem. Soc.* **2001**, *123*, 3743−3748.

(17) Li, X.; He, Y.; Talukdar, S. S.; Swihart, M. T. Process for Preparing Macroscopic Quantities of Brightly Photoluminescent Silicon Nanoparticles with Emission Spanning the Visible Spectrum. *Langmuir* **2003**, *19*, 8490−8496.

(18) Zhong, Y.; Peng, F.; Bao, F.; Wang, S.; Ji, X.; Yang, L.; Su, Y.; Lee, S.-T.; He, Y. Large-Scale Aqueous Synthesis of Fluorescent and Biocompatible Silicon Nanoparticles and Their Use as Highly Photostable Biological Probes. *J. Am. Chem. Soc.* **2013**, *135*, 8350−8356.

(19) Mangolini, L.; Thimsen, E.; Kortshagen, U. High-Yield Plasma Synthesis of Luminescent Silicon Nanocrystals. *Nano Lett.* **2005**, *5*, 655−659.

(20) Tilley, R. D.; Warner, J. H.; Yamamoto, K.; Matsui, I.; Fujimori, H. Micro-Emulsion Synthesis of Monodisperse Surface Stabilized Silicon Nanocrystals. *Chem. Commun.* **2005**, 1833−1835.

(21) Warner, J. H.; Hoshino, A.; Yamamoto, K.; Tilley, R. D. Water-Soluble Photoluminescent Silicon Quantum Dots. *Angew. Chem., Int. Ed.* **2005**, *44*, 4550−4554.

(22) Wilcoxon, J. P.; Samara, G. A.; Provencio, P. N. Optical and Electronic Properties of Si Nanoclusters Synthesized in Inverse Micelles. *Phys. Rev. B* **1999**, *60*, 2704−2714.

(23) Rosso-Vasic, M.; Spruijt, E.; van Lagen, B.; Cola, L. D.; Zuilhof, H. Alkyl-Functionalized Oxide-Free Silicon Nanoparticles: Synthesis and Optical Properties. *Small* **2009**, *5*, 1835−1841.

(24) Wilcoxon, J. P.; Samara, G. A.; Provencio, P. N. Erratum: Optical and Electronic Properties of Si Nanoclusters Synthesized in Inverse Micelles [Phys. Rev. B **60**, 2704−2714 (1999)]. *Phys. Rev. B* **2007**, *76*, No. 199903.

(25) Warner, J. H.; Tilley, R. D. Synthesis of Water-Soluble Photoluminescent Germanium Nanocrystals. *Nanotechnology* **2006**, *17*, 3745−3749.

(26) Shiohara, A.; Prabakar, S.; Faramus, A.; Hsu, C.-Y.; Lai, P.-S.; Northcote, P. T.; Tilley, R. D. Sized Controlled Synthesis, Purification, and Cell Studies with Silicon Quantum Dots. *Nanoscale* **2011**, *3*, 3364−3370.

(27) Prabakar, S.; Shiohara, A.; Hanada, S.; Fujioka, K.; Yamamoto, K.; Tilley, R. D. Size Controlled Synthesis of Germanium Nanocrystals by Hydride Reducing Agents and Their Biological Applications. *Chem. Mater.* **2009**, *22*, 482−486.

(28) Singh, M. P.; Atkins, T. M.; Muthuswamy, E.; Kamali, S.; Tu, C.; Louie, A. Y.; Kauzlarich, S. M. Development of Iron-Doped Silicon Nanoparticles As Bimodal Imaging Agents. *ACS Nano* **2012**, *6*, 5596−5604.

(29) Tu, C.; Ma, X.; Pantazis, P.; Kauzlarich, S. M.; Louie, A. Y. Paramagnetic, Silicon Quantum Dots for Magnetic Resonance and Two-Photon Imaging of Macrophages. *J. Am. Chem. Soc.* **2010**, *132*, 2016−2023.

(30) Henderson, E. J.; Kelly, J. A.; Veinot, J. G. C. Influence of $HSiO_{1.5}$ Sol−Gel Polymer Structure and Composition on the Size and Luminescent Properties of Silicon Nanocrystals. *Chem. Mater.* **2009**, *21*, 5426−5434.

(31) Hessel, C. M.; Reid, D.; Panthani, M. G.; Rasch, M. R.; Goodfellow, B. W.; Wei, J.; Fujii, H.; Akhavan, V.; Korgel, B. A. Synthesis of Ligand-Stabilized Silicon Nanocrystals with Size-Depend-

ent Photoluminescence Spanning Visible to Near-Infrared Wavelengths. *Chem. Mater.* **2012**, *24*, 393−401.
(32) Kelly, J. A.; Henderson, E. J.; Veinot, J. G. C. Sol-Gel Precursors for Group 14 Nanocrystals. *Chem. Commun.* **2010**, *46*, 8704−8718.
(33) He, Y.; Zhong, Y.; Peng, F.; Wei, X.; Su, Y.; Lu, Y.; Su, S.; Gu, W.; Liao, L.; Lee, S.-T. One-Pot Microwave Synthesis of Water-Dispersible, Ultraphoto- and pH-Stable, and Highly Fluorescent Silicon Quantum Dots. *J. Am. Chem. Soc.* **2011**, *133*, 14192−14195.
(34) Heinrich, J. L.; Curtis, C. L.; Credo, G. M.; Sailor, M. J.; Kavanagh, K. L. Luminescent Colloidal Silicon Suspensions from Porous Silicon. *Science* **1992**, *255*, 66−68.
(35) Kang, Z.; Tsang, C. H. A.; Zhang, Z.; Zhang, M.; Wong, N.-b.; Zapien, J. A.; Shan, Y.; Lee, S.-T. A Polyoxometalate-Assisted Electrochemical Method for Silicon Nanostructures Preparation: From Quantum Dots to Nanowires. *J. Am. Chem. Soc.* **2007**, *129*, 5326−5327.
(36) Dasog, M.; Yang, Z.; Regli, S.; Atkins, T. M.; Faramus, A.; Singh, M. P.; Muthuswamy, E.; Kauzlarich, S. M.; Tilley, R. D.; Veinot, J. G. C. Chemical Insight into the Origin of Red and Blue Photoluminescence Arising from Freestanding Silicon Nanocrystals. *ACS Nano* **2013**, *7*, 2676−2685.
(37) Li, Z. F.; Ruckenstein, E. Water-Soluble Poly(acrylic acid) Grafted Luminescent Silicon Nanoparticles and Their Use as Fluorescent Biological Staining Labels. *Nano Lett.* **2004**, *4*, 1463−1467.
(38) Shiohara, A.; Hanada, S.; Prabakar, S.; Fujioka, K.; Lim, T. H.; Yamamoto, K.; Northcote, P. T.; Tilley, R. D. Chemical Reactions on Surface Molecules Attached to Silicon Quantum Dots. *J. Am. Chem. Soc.* **2010**, *132*, 248−253.
(39) Cheng, X.; Gondosiswanto, R.; Ciampi, S.; Reece, P. J.; Gooding, J. J. One-Pot Synthesis of Colloidal Silicon Quantum Dots and Surface Functionalization via Thiol-Ene Click Chemistry. *Chem. Commun.* **2012**, *48*, 11874−11876.
(40) Erogbogbo, F.; Yong, K.-T.; Roy, I.; Xu, G.; Prasad, P. N.; Swihart, M. T. Biocompatible Luminescent Silicon Quantum Dots for Imaging of Cancer Cells. *ACS Nano* **2008**, *2*, 873−878.
(41) Erogbogbo, F.; Yong, K.-T.; Roy, I.; Hu, R.; Law, W.-C.; Zhao, W.; Ding, H.; Wu, F.; Kumar, R.; Swihart, M. T.; Prasad, P. N. In Vivo Targeted Cancer Imaging, Sentinel Lymph Node Mapping and Multi-Channel Imaging with Biocompatible Silicon Nanocrystals. *ACS Nano* **2011**, *5*, 413−423.
(42) Henderson, E. J.; Shuhendler, A. J.; Prasad, P.; Baumann, V.; Maier-Flaig, F.; Faulkner, D. O.; Lemmer, U.; Wu, X. Y.; Ozin, G. A. Colloidally Stable Silicon Nanocrystals with Near-Infrared Photoluminescence for Biological Fluorescence Imaging. *Small* **2011**, *7*, 2507−2516.
(43) Mastronardi, M. L.; Maier-Flaig, F.; Faulkner, D.; Henderson, E. J.; Kübel, C.; Lemmer, U.; Ozin, G. A. Size-Dependent Absolute Quantum Yields for Size-Separated Colloidally-Stable Silicon Nanocrystals. *Nano Lett.* **2012**, *12*, 337−342.
(44) Miller, J. B.; Van Sickle, A. R.; Anthony, R. J.; Kroll, D. M.; Kortshagen, U. R.; Hobbie, E. K. Ensemble Brightening and Enhanced Quantum Yield in Size-Purified Silicon Nanocrystals. *ACS Nano* **2012**, *6*, 7389−7396.
(45) Mastronardi, M. L.; Hennrich, F.; Henderson, E. J.; Maier-Flaig, F.; Blum, C.; Reichenbach, J.; Lemmer, U.; Kübel, C.; Wang, D.; Kappes, M. M.; Ozin, G. A. Preparation of Monodisperse Silicon Nanocrystals Using Density Gradient Ultracentrifugation. *J. Am. Chem. Soc.* **2011**, *133*, 11928−11931.
(46) Wilson, W. L.; Szajowski, P. F.; Brus, L. E. Quantum Confinement in Size-Selected, Surface-Oxidized Silicon Nanocrystals. *Science* **1993**, *262*, 1242−1244.
(47) Hua, F.; Swihart, M. T.; Ruckenstein, E. Efficient Surface Grafting of Luminescent Silicon Quantum Dots by Photoinitiated Hydrosilylation. *Langmuir* **2005**, *21*, 6054−6062.
(48) Jurbergs, D.; Rogojina, E.; Mangolini, L.; Kortshagen, U. Silicon Nanocrystals with Ensemble Quantum Yields Exceeding 60%. *Appl. Phys. Lett.* **2006**, *88*, No. 233116.
(49) Dohnalová, K.; Poddubny, A. N.; Prokofiev, A. A.; de Boer, W. D. A. M.; Umesh, C. P.; Paulusse, J. M. J.; Zuilhof, H.; Gregorkiewicz, T. Surface Brightens Up Si Quantum Dots: Direct Bandgap-Like Size-Tunable Emission. *Light Sci. Appl.* **2013**, *2*, No. e47.
(50) Warner, J. H.; Rubinsztein-Dunlop, H.; Tilley, R. D. Surface Morphology Dependent Photoluminescence from Colloidal Silicon Nanocrystals. *J. Phys. Chem. B* **2005**, *109*, 19064−19067.
(51) Resch-Genger, U.; Grabolle, M.; Cavaliere-Jaricot, S.; Nitschke, R.; Nann, T. Quantum Dots Versus Organic Dyes as Fluorescent Labels. *Nat. Methods* **2008**, *5*, 763−775.
(52) Liu, J.; Erogbogbo, F.; Yong, K.-T.; Ye, L.; Liu, J.; Hu, R.; Chen, H.; Hu, Y.; Yang, Y.; Yang, J.; Roy, I.; Karker, N. A.; Swihart, M. T.; Prasad, P. N. Assessing Clinical Prospects of Silicon Quantum Dots: Studies in Mice and Monkeys. *ACS Nano* **2013**, *7*, 7303−7310.
(53) Tu, C.; Ma, X.; House, A.; Kauzlarich, S. M.; Louie, A. Y. PET Imaging and Biodistribution of Silicon Quantum Dots in Mice. *ACS Med. Chem. Lett.* **2011**, *2*, 285−288.
(54) Fujioka, K.; Hiruoka, M.; Sato, K.; Manabe, N.; Miyasaka, R.; Hanada, S.; Hoshino, A.; Tilley, R. D.; Manome, Y.; Hirakuri, K.; Yamamoto, K. Luminescent Passive-Oxidized Silicon Quantum Dots as Biological Staining Labels and Their Cytotoxicity Effects at High Concentration. *Nanotechnology* **2008**, *19*, No. 415102.
(55) Bhattacharjee, S.; Rietjens, I. M. C. M.; Singh, M. P.; Atkins, T. M.; Purkait, T. K.; Xu, Z.; Regli, S.; Shukaliak, A.; Clark, R. J.; Mitchell, B. S.; Alink, G. M.; Marcelis, A. T. M.; Fink, M. J.; Veinot, J. G. C.; Kauzlarich, S. M.; Zuilhof, H. Cytotoxicity of Surface-Functionalized Silicon and Germanium Nanoparticles: The Dominant Role of Surface Charges. *Nanoscale* **2013**, *5*, 4870−4883.
(56) Wang, Q.; Bao, Y.; Zhang, X.; Coxon, P. R.; Jayasooriya, U. A.; Chao, Y. Uptake and Toxicity Studies of Poly-Acrylic Acid Functionalized Silicon Nanoparticles in Cultured Mammalian Cells. *Adv. Healthcare Mater.* **2012**, *1*, 189−198.
(57) Zhong, Y.; Peng, F.; Wei, X.; Zhou, Y.; Wang, J.; Jiang, X.; Su, Y.; Su, S.; Lee, S.-T.; He, Y. Microwave-Assisted Synthesis of Biofunctional and Fluorescent Silicon Nanoparticles Using Proteins as Hydrophilic Ligands. *Angew. Chem., Int. Ed.* **2012**, *51*, 8485−8489.