

Chapter 2

Silicon Nanostructures

Abstract Functional nanomaterials play fundamental roles in the development of nanotechnology, serving as novel and powerful tools for both basic studies and practical applications. Silicon nanomaterials are an important type of nanomaterials, exhibiting unique optical, electronic, or/and mechanical properties. The fast development of silicon nanomaterials with well-defined structures and required functionalities has vastly promoted the advancement of silicon nanotechnology. Silicon nanoparticles (SiNPs) and silicon nanowires (SiNWs) are well known as the most important zero- and one-dimensional silicon nanostructures. In the past three decades, scientists have made great strides in developing a great deal of fabrication techniques to prepare SiNPs and SiNWs. In particular, solution-phase reduction, electrochemical etching and microwave-assisted synthesis, etc., have been well developed for the production of SiNPs. On the other hand, several well-studied strategies (e.g., chemical vapor deposition (CVD), oxide-assisted growth (OAG), electroless etching, etc.) are highly efficacious for the synthesis of SiNWs. In this chapter, we give an introduction to these classic synthetic methods in a detailed way, and discuss the prospect of the design and fabrication of functional silicon nanostructures.

Keywords Silicon nanostructures • Nanotechnology • Synthetic methods • Surface modification • Silicon nanoparticles • Silicon nanowires • Silicon nanohybrids

Increasingly rapid advancement of nanotechnology has fueled a continual and urgent investigation for fabricating functional nanomaterials [1, 2]. Scientists have done elegant work on rational design of nanomaterials with well-defined structures [3–6]. To date, a variety of nanomaterials (e.g., silver/gold nanoparticles, magnetic nanoparticles, fluorescent semiconductor quantum dots, carbon nanodots/nanotubes, graphene, etc.) have been well established, greatly promoting the development of chemical, physical, and biological fields from basic research to practical applications.

Silicon material is the leading semiconductor material and dominates current industry. Silicon nanomaterials, known as one of the most important types of nanomaterials, feature a number of unique merits, such as excellent

electronic/mechanical/optical properties, huge surface-to-volume ratios, and facile surface modification [7–10]. More importantly, the renowned biocompatibility of silicon (e.g., silicon naturally exists in human as a common trace element) leads to the promising prospect of silicon nanomaterials-based applications, including solar cells, sensors, catalysis, bioimaging, etc. To meet the increasing requirement of these applications, silicon nanomaterials with controllable structures and required functionality remain in great demand.

This chapter mainly introduces representative strategies for preparation of the most important zero- and one-dimensional silicon nanostructures, i.e., silicon nanoparticles (SiNPs) and silicon nanowires (SiNWs). Typically, several dominant synthetic methods for the preparation and surface modification of SiNPs are illustrated in Sect. 2.1. In Sect. 2.2, we introduce the classic strategies for synthesis of SiNWs, and further discuss the pros and cons of these methods. We then give a brief introduction to silicon-based nanohybrids in Sect. 2.3, and finally make a summary of this chapter in Sect. 2.4.

2.1 Fluorescent Silicon Nanoparticles

Bulk silicon with an indirect band gap basically features poor optical properties [11]. However, when the size of silicon particles is reduced to nanoscale (generally less than 5 nm), the overlap of the electron and hole wave functions is distinctly increased, leading to dramatic enhancement of recombination rates of electrons and holes. As a result, such small-sized SiNPs exhibit relatively strong fluorescence, showing the prospect of long-awaited optical applications [12, 13]. Therefore, intense studies have been intrigued to develop fluorescent SiNPs and their optics-relative applications since the first observation of porous silicon-based fluorescence [14, 15].

In recent two decades, many synthetic strategies (e.g., solution-phase reduction [16, 17], microemulsion [18, 19], sonochemical synthesis [20], mechanochemical synthesis [21], laser ablation [22], plasma-assisted aerosol precipitation [23–25], electrochemical etching [26–30], and microwave-assisted synthesis [31–34], etc.) have been developed for the preparation of SiNPs. For the solution-phase reduction synthesis proposed by Kauzlarich and coworkers, silicon halides (e.g., SiCl_4) are reduced in organic solution (e.g., ethylene glycol dimethyl ether) to produce silicon nanocrystalline under mild conditions [16]. Moreover, surface of the prepared SiNPs is readily modified, offering possibility to modify the SiNPs to meet various requirements [16]. Plasma-assisted aerosol precipitation is considered as another established method for production of SiNPs with high efficiency and yield [23–25]. In this synthetic strategy, luminescent SiNPs between 2 and 8 nm can be rapidly synthesized via a single-step non-thermal plasma process [24]. In 2009, Lee and coworkers developed a polyoxometalate (POMs)-assisted electrochemical etching method for synthesizing multi-color luminescent SiNPs [27]. In this system, graphite and silicon wafer serve as anode and cathode in an electrochemical

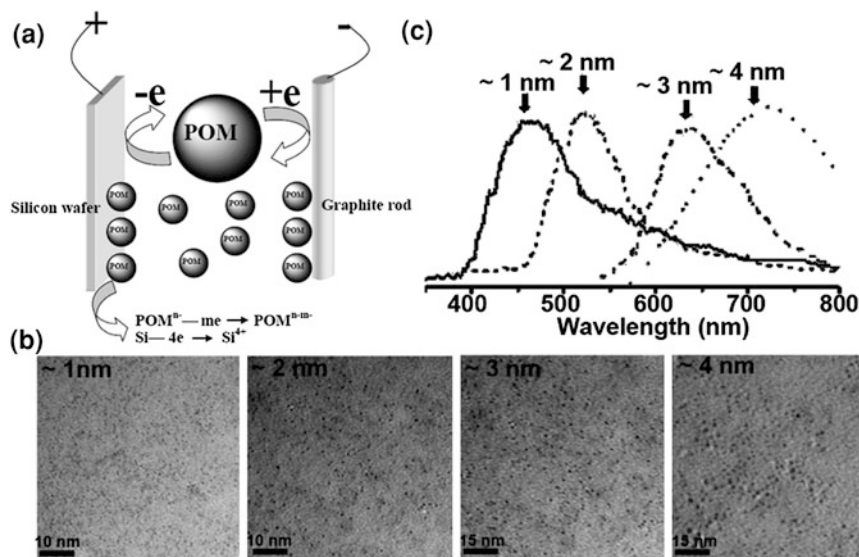


Fig. 2.1 **a** Schematic mode of preparation of fluorescent SiNPs through the electrochemical etching method. **b** Transmission electron microscopy (TEM) images and **c** representative PL spectra of the prepared SiNPs with controllable sizes ranging from ~ 1 to ~ 4 nm. Reprinted with permission from Ref. [27]. Copyright 2007 American Chemical Society

cell, respectively; besides, $\text{H}_3\text{PMo}_{12}\text{O}_{40}$ (POM) and H_2O_2 ($\text{POM} + \text{H}_2\text{O}_2 = \text{HPOM}$) are used as catalysts (Fig. 2.1a). Notably, the sizes of SiNPs are readily controllable via adjustment of current density, vastly facilitating the production of multi-color luminescent SiNPs with different sizes (Fig. 2.1b). Figure 2.1c displays SiNPs with sizes ranging from ~ 1 to ~ 4 nm, which feature wide-ranging emission spectra covering 450–740 nm. It is worthwhile to point out, in comparison to strong fluorescence of direct-band-gap semiconductors (e.g., CdTe and CdTe/CdS/ZnS QDs with high quantum yield (QY) of 60–80 %, [6, 7]), most of the prepared fluorescent SiNPs show relatively low QY (often lower than 20 %), which is possibly due to surface oxidation [35–39]. In 2006, Kortshagen et al. developed a plasma-assisted synthesis method to efficiently protect surface oxidation of SiNPs, yielding the highly luminescent SiNPs with a high QY value larger than 60 % [23]. Very recently, Li, He and coworkers reported a class of SiNPs with ultrabright photoluminescence, whose quantum yield was remarkably as high as 75 %. Specifically, the SiNPs were synthesized by the solution-reduction method, followed by modifying with diphenylamine (di) and carbazole (ca). After such a surface modification, the optical properties of SiNPs were significantly changed, e.g., the maximum emission peak of carbazole-modified SiNPs (ca-SiNPs) shifted from 405 to 480 nm, and more significantly, the photoluminescence quantum yield (PLQY) was remarkably enhanced up to 75 % [40].

It is worth pointing out that, SiNPs prepared via the above-mentioned methods often possess poor aqueous dispersibility since their surface is covered by hydrophobic ligands, which severely hampers their biological and biomedical applications [41, 42]. Tremendous efforts have been made to improve aqueous dispersibility of the hydrophobic SiNPs and develop new synthetic strategies for direct preparation of hydrophilic SiNPs. In the former case, several kind of hydrophilic species (e.g., acrylic acid and allylamine) are employed to modify SiNPs surface, effectively improving the water dispersibility of the SiNPs [43–45]. For example, in 2004, Ruckenstein et al. grafted the red-emitting SiNPs with hydrophilic poly(acrylic acid) under UV irradiation, producing poly(acrylic acid)-modified SiNPs with good aqueous dispersibility [43]. Thereafter, Tilley and coworkers reported the synthesis of blue-emitting SiNPs with good aqueous dispersibility due to surface-covered water-soluble allylamine molecules [18, 45]. Swihart's group functionalized multi-color fluorescent SiNPs with acrylic acid to render them hydrophilic [44]. While these resultant SiNPs are water-dispersible, their fluorescence is often severely quenched when pH changed, which is not suitable for applications in complicated biological environments.

To improve pH stability of the SiNPs, He et al. and Swihart et al. independently reported polymer-coated or micelle-encapsulated water-dispersible SiNPs featuring robust pH stability [29, 30, 46]. Typically, the micelle-encapsulated SiNPs maintained stable fluorescence in acidic-to-basic pH environments (pH 2–12). However, the QY value of such micelle-encapsulated SiNPs reduced to 2–4 % from ~17 % of pure SiNPs, since SiNPs surface was deteriorated during micelle encapsulation procedure [46]. In the case of polymer-coated SiNPs, different SiNPs were linked together by polymer chains under light irradiation, producing silicon nanospheres (SiNSs) containing tens to hundreds of SiNPs [29]. Figure 2.2a presents typical TEM images showing that the prepared nanospheres exhibit spherical structure with controllable diameters of approximately 59, 121, and 207 nm. The high-resolution TEM images (Fig. 2.2b) reveal the SiNP inside the nanosphere have the characteristic silicon nanocrystal lattice and high crystallinity. Notably, the authors demonstrated that the optical properties of the nanospheres were improved (Fig. 2.2c), whose quantum yield reached 20–25 %. On the basis of which, the same authors further introduced a kind of water-dispersed oxidized SiNSs (O-SiNSs) via thermal oxidation of the precursor SiNSs [30]. Significantly, in addition to strong fluorescence, the prepared O-SiNSs was ultrahighly stable under high-power UN irradiation (Fig. 2.2d) and in acidic-to-basic environments covering pHs 2–12 (Fig. 2.2e).

It is worth pointing out that, despite distinctly improved pH stability, the polymer-coated or micelle-encapsulated SiNPs are relatively not suitable for bioapplication due to relatively large sizes (50–200 nm) [29, 30, 46] (recent reports reveal that small-sized (<10 nm) nanoparticles are more readily to be excluded via renal clearance [47, 48]). Consequently, small-sized, fluorescent, and water-dispersible SiNPs are required for broad bioapplications. Recently, He's group presented a microwave-assisted one-pot method for synthesizing water-dispersible SiNPs using SiNWs and glutaric acid as reaction precursors [31]. In

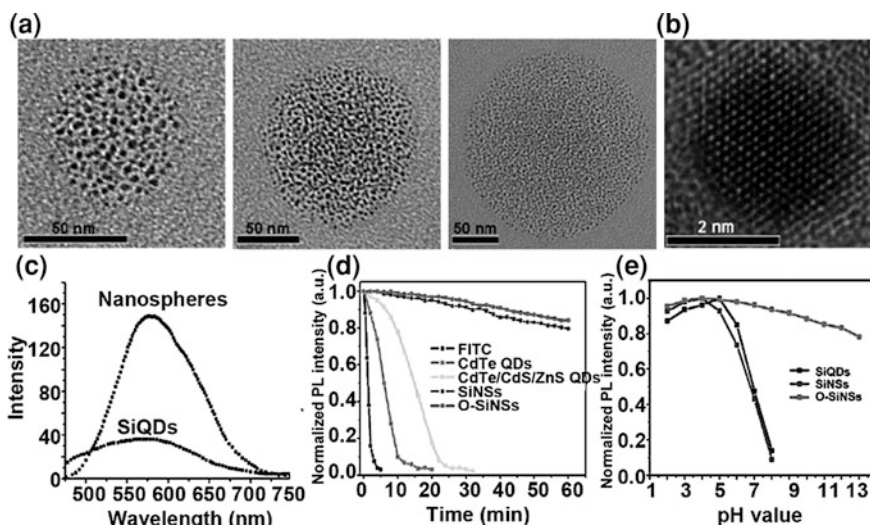


Fig. 2.2 **a** TEM images of three kinds of SiNWs with sizes of ~ 60 nm (*left*), 120 nm (*middle*), and 200 nm (*right*). **b** HRTEM image of a single SiNP inside the prepared SiNSs. **c** Comparison of Fluorescent intensities of the resultant SiNSs and pure SiNPs. **a–c** Reproduced from ref. [29] by permission of John Wiley & Sons Inc. **d** Temporal evolution of photoluminescence intensity of FITC, II/VI QDs, the prepared SiNSs, and O-SiNSs under long-term UV irradiation or **e** various pH values. **d–e** Reprinted with permission from Ref. [30]. Copyright 2009 American Chemical Society

this strategy, microwave dielectric heating was utilized to take advantage of its rapid temperature elevation, homogenous heating and high reaction selectivity. Notably, the prepared SiNPs featured excellent aqueous dispersibility, small sizes (~ 4 nm), robust pH- (pHs 1–10) and photo-stability, and strong fluorescence (~ 15 –20 %) (Fig. 2.3). Thereafter, they further employed hydrophilic proteins (e.g., goat anti-mouse immunoglobulin) as novel ligands to prepare fluorescent SiNPs [33]. Significantly, the prepared SiNPs simultaneously possessed good aqueous dispersibility and biospecific properties owing to plenty of surface-covered protein ligands. Therefore, the as-prepared fluorescent SiNPs with bio-specific properties was efficacious for immunofluorescent cellular targeting.

For all the above “top-down” strategies, two independent procedures are often required, that is, hydrophobic SiNPs are first prepared using large-size silicon source (e.g., crystalline Si particles, SiOx powders, bulk silicon, or SiNWs, etc.), followed by surface modification with hydrophilic ligands, which nevertheless involves relatively complicated and time-consuming procedures and sometimes degrades the optical properties of SiNPs. More recently, He, Lee, and coworkers developed a facile “bottom-up” strategy for preparing fluorescent water-dispersible SiNPs by using silicon-based organic molecules (e.g., 3-(aminopropyl) trimethoxysilane, $C_6H_{17}NO_3Si$) as the reaction precursor (Fig. 2.4) [34]. The highly luminescent (PLQY: 20–25 %), water-dispersible and ultrasmall (diameter:

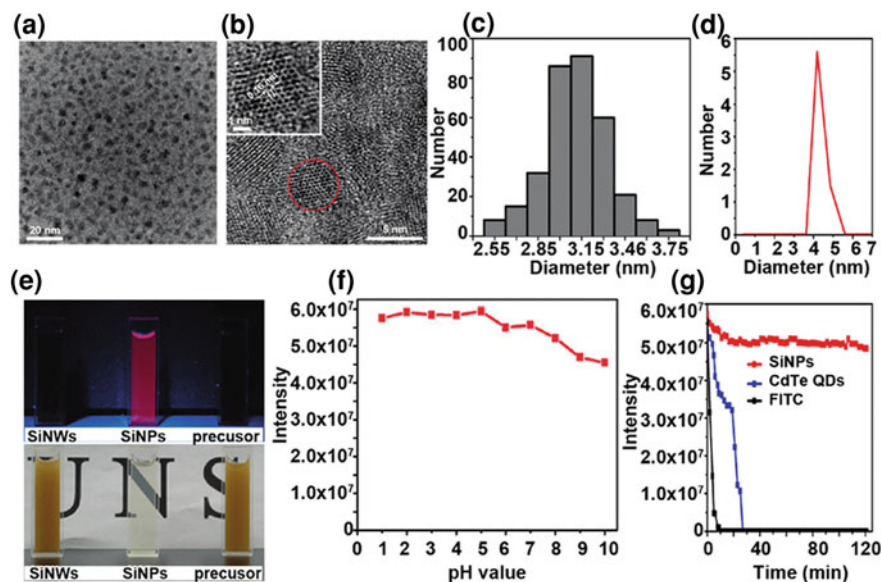


Fig. 2.3 **a** TEM and **b** HRTEM images, **c** size distribution, and **d** representative dynamic light scattering (DLS) histogram of the as-prepared SiNPs. Inset in **(b)** presents the HRTEM image of a single SiNP. **e** Photos of the SiNWs (*left*), fluorescent SiNPs (*middle*), and reaction precursor (*right*) aqueous samples irradiated by UV lamp (*up*) or ambient light (*bottom*). **f** Fluorescent intensity of the prepared SiNPs under different pH values ranging from 1 to 10. **g** Temporal evolution of fluorescent intensity of FITC, CdTe QDs, the as-prepared SiNPs during 120-min UV irradiation. Reprinted with permission from Ref. [31]. Copyright 2011 American Chemical Society

~ 2.2 nm) SiNPs were facilely achieved via in situ growth under microwave reaction. Of particular significance, this microwave-assisted method holds high promise for large-scale synthesis of fluorescence SiNPs (e.g., only 10 min were required for preparation of 0.1 g SiNPs by using this strategy).

2.2 Silicon Nanowires

SiNWs are regarded as the most important one-dimensional silicon nanostructure, and have obtained giant attentions thus far [49, 50]. Through the past 50-year development, significant progress has been achieved to fabricate SiNWs with controlled morphologies and properties.

As early as 1957, Treuting et al. reported the first preparation of Si whiskers with $\langle 111 \rangle$ orientation, or filamentary Si crystals with macroscopic dimensions [51]. Thereafter, Wagner and Ellis performed the illuminating work and established the vapor-liquid-solid (VLS) mechanism of the Si whisker growth [52]. These pioneer studies open exciting avenues for fabrication of SiNWs. The second

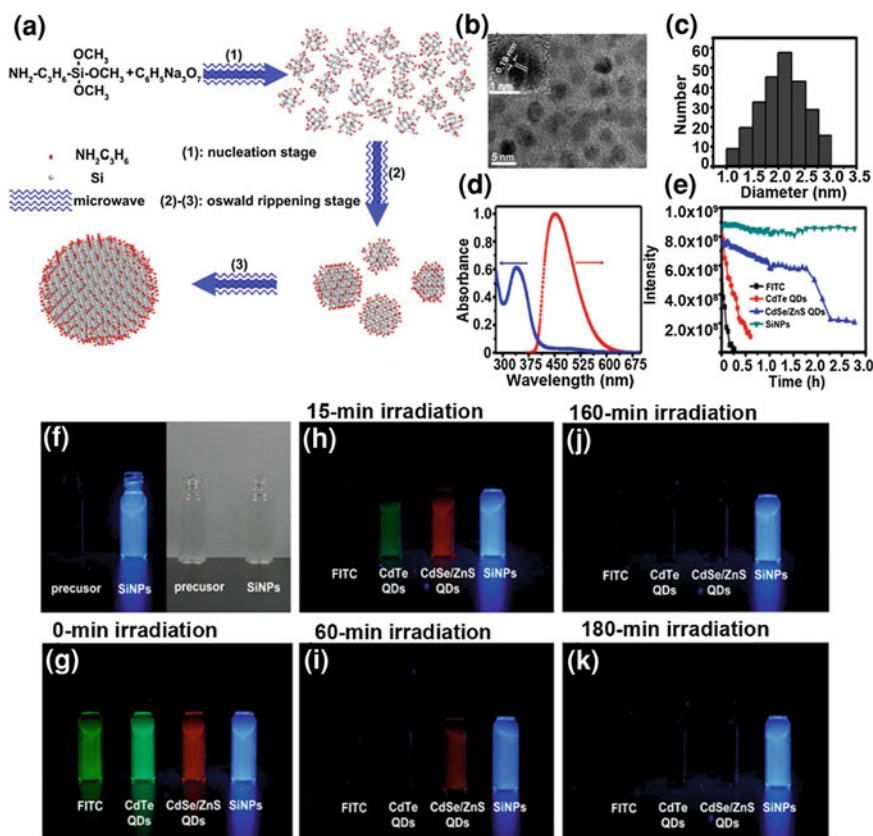
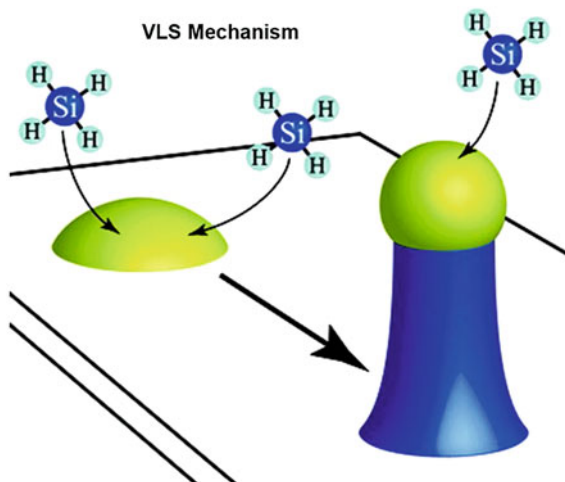


Fig. 2.4 **a** Schematic mode of the "bottom-up" strategy. **b** TEM/HRTEM, **c** size distribution, and **d** absorption and photoluminescence (UV-PL) spectra of the SiNPs prepared through microwave-assisted strategy. Inset in **(b)** presents the enlarged HRTEM image of a single SiNP. **e** Temporal evolution of fluorescence intensity of FITC, CdTe and CdSe/ZnS QDs, and the as-prepared SiNPs under long-term UV irradiation. **f** Photos of reaction precursors and the prepared SiNPs aqueous solution irradiated by UV light (*left*) or ambient light (*right*). **g–k** Pictures of four aqueous samples (i.e., FITC, CdTe and CdSe/ZnS QDs, and SiNPs), persistently irradiated by UV lamp (365 nm, 450 W) for 180 min. Reprinted with permission from Ref. [34]. Copyright 2013 American Chemical Society

phase in silicon-wire studies were launched in the mid 1990s triggered by development in microelectronics. In 1998, Lieber's [53] and Lee's groups [54] independently reported the strategy of VLS growth assisted by laser ablation, which is especially suitable for large-quantity preparation of single-crystal SiNWs with controllable diameters and lengths (diameter: 6–20 nm, lengths: 1–30 μm). In general, the VLS process involves four steps as follows (Fig. 2.5) [55], silicon precursor is first decomposed using metal catalysts. The liquid alloy made of silicon and metal is formed in the second step. Afterwards, the resultant silicon-metal alloy is diffused with silicon. In the final step, Si supersaturation leads to

Fig. 2.5 Schematic illustration of the VLS growth mechanism. Reprinted with permission from Ref. [55]. Copyright 2010 American Chemical Society



nucleation at the liquid/solid interface and production of SiNWs. Since then, a number of approaches have been developed to synthesize SiNPs, which can be categorized as two typical types of growth, that is, the bottom-up or top-down growth of SiNWs. For the former strategy, SiNWs growth is triggered by an assembly process joining ultrasmall Si atoms, such as metal-catalyzed VLS growth [52, 56, 57], oxide-assisted growth (OAG) [49, 58], supercritical-fluid-based and solution-based growth [59–62], laser ablation [63, 64], and thermal evaporation with catalyst [65, 66]. In contrary, for the top-down approaches (e.g., electron beam lithography (EBL), reaction ion etching (RIE), and metal-catalyzed electroless etching, etc.), large-sized bulk silicon precursor is employed for synthesizing SiNWs via lithography and etching [67–72]. Several representative strategies will be introduced in detail in the following pages.

2.2.1 Chemical Vapor Deposition

Chemical vapor deposition (CVD) is another established strategy especially suitable for preparing vertically aligned SiNWs with high aspect ratio. Metal catalyst (e.g., gold) and gaseous silicon reactants (e.g., silane, SiH_4 , disilane, Si_2H_6 , silicon dichloride, SiH_2Cl_2 , or silicon tetrachloride, SiCl_4 , etc.) are generally used in the CVD growth. Different reaction temperatures are required to produce SiNWs when the silicon precursors are varied because of their distinct chemical stability. For example, the temperature ranging from 800 to 1000 °C is often required for SiNWs growth by using SiCl_4 as silicon precursor. In terms of silane-based silicon precursor, the growth temperature reduces to 400–600 °C [73, 74].

In 2004, Lieber and coworkers employed gold nanoclusters and silane (SiH_4), serving as catalysts and precursors, respectively, to produce ~ 3 nm SiNWs with

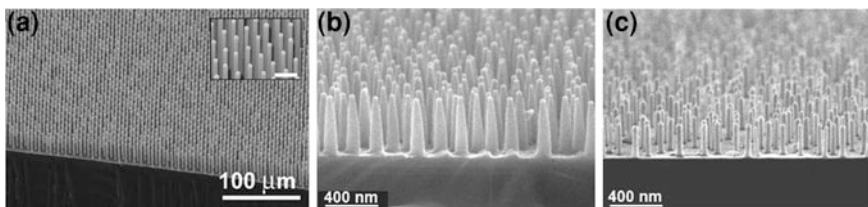


Fig. 2.6 **a** Tilted SEM overviews of the SiNW arrays with a large area ($>1 \text{ cm}^2$) using Cu as catalyst. Reprinted with permission from Ref. [79]. Copyright 2007, American Institute of Physics. SEM images of the SiNW arrays prepared at 490 °C **(b)** and 430 °C **(c)**. Reprinted with permission from Nature Publishing Group, a division of Macmillan Publishers Ltd. Ref. [82]. Copyright 2006

undetectable amorphous oxide [75]. In this case, hydrogen was utilized since it could passivate the nanowire surface and reduce surface roughness. In 2005, Yang and coworkers used SiCl_4 and gold colloids as the precursor and catalyst, respectively, for SiNWs growth under 800–850 °C in the VLS-CVD process [76]. In this method, the gold colloids were capable of defining the size and position of the SiNWs. Notably, the oxide layer on the Si surface could be readily removed by gaseous HCl, which was the byproduct SiCl_4 decomposition in H_2 , facilitating homoepitaxial growth of SiNWs and production of the SiNWs with clean Si crystal surface. As mentioned above, gold is employed as the most frequently used metal catalyst in the VLS growth, unavoidably leading to gold contamination in the prepared SiNWs [77]. The presence of metallic contaminations may often induce deep-level electronic states of the silicon band gap and degradation of the minority-carrier lifetime, which is adverse to photovoltaic applications. To address this issue, other kinds of metals (e.g., Cu, Al, and Pt, etc.) have been employed as alternative catalysts for synthesizing SiNWs [78–83].

In 2007, using Cu and SiCl_4 as catalyst and Si as precursor, respectively, Atwater and coworkers grew large-area ($>1 \text{ cm}^2$) SiNWs (diameter: $\sim 1.5 \text{ }\mu\text{m}$, lengths: $>75 \text{ }\mu\text{m}$) arrays with vertical orientation [79]. Note that a patterned oxide buffer layer was used in this work to avoid migration of catalysts during the synthetic process, which was favorable for controlling size, position, and uniformity of the SiNWs arrays (Fig. 2.6a). Wang et al. demonstrated that Al could be used as another kind of available catalyst for VLS SiNWs growth, due to similar binary phase diagram of Al-Si [82]. They further revealed that the growth process was probably via CVD-vapor-solid-solid (VSS) mechanism rather than CVD-VLS, because the eutectic temperature of aluminum-silicon binary phase diagram (577 °C) is considerably higher than that employed in the reported method. Moreover, the wires tended to be tapered by using Al as the catalyst. However, the tendency of tapering was found to be reduced by lowering the growth temperature (Fig. 2.6b, c).

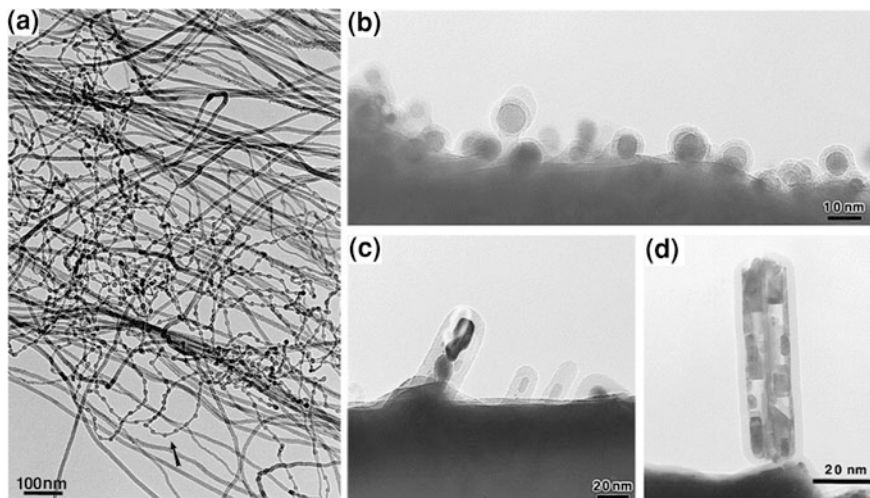


Fig. 2.7 **a** TEM image of SiNWs prepared through the evaporation method. **b–d** Different nucleation stages of the SiNWs. Reprinted from Ref. [84]. Copyright 1999, with permission from Elsevier

2.2.2 Oxide-Assisted Growth

The OAG method is widely regarded as another popular strategy for fabricating SiNWs. Compared to the metal catalysts-assisted VLS method, oxides are employed in the OAG methods to induce the nucleation and growth of nanowires, producing the SiNWs free of metal contamination. In addition, the OAG method is highly efficacious for producing small-sized SiNWs in large quantities. Moreover, a variety of well-defined silicon structures (e.g., rods, chains, and ribbons, etc.) are readily fabricated using the OAG method [58]. Notwithstanding, the VLS method is more suitable for synthesizing SiNWs with controllable diameters and growth alignment via adjusting sizes and distribution of metal seeds [53, 54, 58, 65, 66]. Consequently, VLS and OAG methods with different shortcomings and advantages are well complementary to each other, and serve as both well-established strategies for synthesis of high-quality SiNWs.

In 1999, Lee and coworkers synthesized bulk-quantity SiNWs by thermal evaporation of a powder mixture of silicon and SiO_2 [84], in which SiNW nucleus containing a polycrystalline Si core was formed at the initial nucleation stage (Fig. 2.7). In their following study, they further fabricated the ultrasmall (diameter: ~ 1 nm) SiNWs via the optimized OAG approach [49], whose surfaces were terminated with hydrogen by a hydrofluoric acid dip. They also observed Si(111) facet and SiH_2 on Si(001) facet in the prepared SiNWs sample via scanning tunneling microscopy (STM) characterization. Besides, the authors found that, in comparison to regular silicon wafer whose surface was easily to be oxidized, the

surface of as-prepared SiNWs seemed to be more resistant to oxidation. They further revealed that the electronic energy gaps decreased with increasing SiNW diameter from 3.5 electron volts for 1.3 nm to 1.1 electron volts for 7 nm [49].

2.2.3 Metal-Catalyzed Electroless Etching

Top-down SiNWs growth has recently emerged as an attractive method for preparing SiNWs with desirable flexibility and precision, which is capable of massive and facile production of SiNWs in a low-cost manner.

In 2002, Peng and coworkers introduced a HF-etching-assisted nanoelectrochemical strategy to synthesize wafer-scale aligned SiNWs [69], and further investigated the mechanisms in their following studies [85–88]. The fabrication process is typically divided into two steps: metal catalyst film is first deposited on silicon wafer via electroless metal deposition. Afterwards, the resultant silicon wafer is etched using aqueous HF solution containing oxidizing agents (e.g., H_2O_2 , $\text{Fe}(\text{NO}_3)_3$, or HNO_3 , etc.). This metal-catalyzed electroless etching process is basically based on noble metal catalysts-assisted selective oxidization of Si, followed by oxidizing HF solution-induced exclusive etching of silicon at the metal-silicon interface, and eventually yields the SiNWs of controllable lengths (Fig. 2.8) [69–71, 89, 90]. It is worthwhile to point out that this HF-etching method is superbly suited to mild, facile and low-cost fabrication of SiNWs at room temperature and atmospheric pressure, without requiring expensive instruments and reagents.

2.3 Silicon Nanohybrid

Hybrid nanomaterials (nanohybrids) that combine with various types of nanostructures (e.g., nanoparticles, nanowires, and nanotubes) have recently gained great attentions [91–95]. Notably, rational design of the architecture would endow the nanohybrids with desirable features, facilitating investigation of the relationship between nanostructures and electronic/optical/magnetic properties [91–93]. Moreover, to meet the increasing demands of various applications, nanohybrids with multifunctional properties have been fabricated by combinations of various functional nanostructures. In recent years, silicon-based nanohybrids made of metal NPs (e.g., AuNPs, AgNPs, PtNPs, and CdTe QDs, etc.)-decorated SiNWs or SiNPs doped with magnetic materials (e.g., Mn, Fe, Fe_2O_3 , Fe_3O_4) have been well developed and utilized for solar cells, catalysts, chemical/biological sensors, cancer therapy, and bioimaging, etc. [10, 96–109].

Basically, noble metal (Pt, Au, and Ag) ions can be facilely reduced by surface-covered Si-H bonds of SiNWs, yielding Pt/Au/Ag NPs-decorated SiNWs. Such resultant metallic nanoparticles decorated-SiNWs have been extensively explored

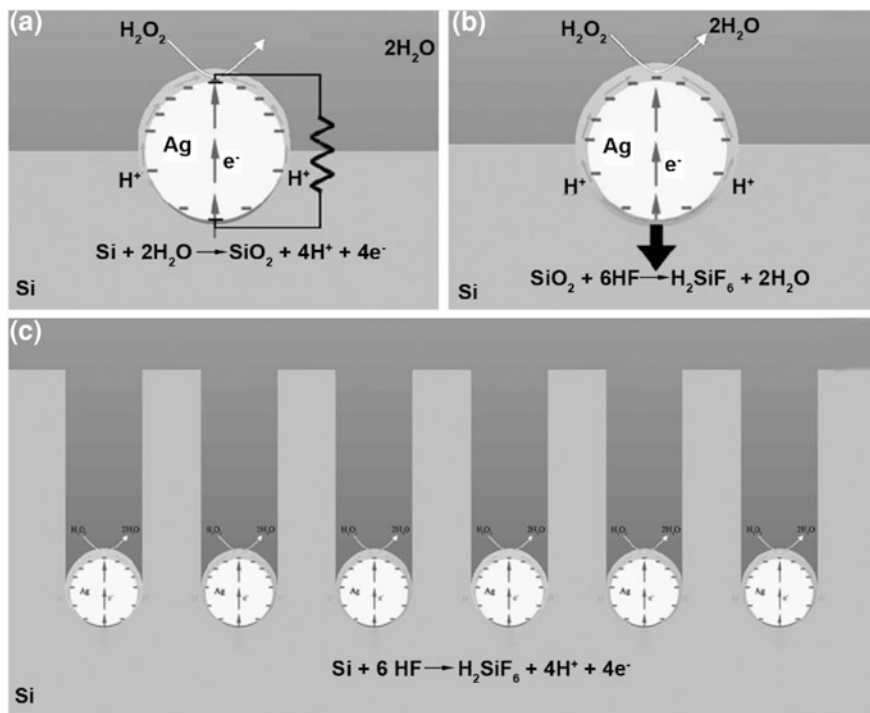


Fig. 2.8 Schematics of Ag particle movement in bulk Si induced by catalysts: **a** A hydrated proton gradient across the Ag particle leads to self-electrophoresis-driven motion. **b** Self-electrophoresis-driven motion of Ag particles. **c** Silicon nanostructures are formed due to tunneling motion of Ag particles in a silicon substrate. Reproduced from Ref. [71] with permission from John Wiley & Sons Inc

for myriad applications (e.g., surface-enhanced Raman scattering (SERS), catalysis, solar cell, and cancer therapy) due to their unique photo/electronic/catalytic properties. For example, in 2011, He and coworkers developed a well-defined SERS platform for DNA detection by using SiNWs decorated with AgNPs (AgNPs@SiNWs). The AgNPs@SiNWs nanohybrid-based biosensor achieved the detection of DNA with a remarkably low concentration (~ 1 fM) due to their very high SERS enhancement factor (up to $\sim 10^{10}$) [100]. Lee and coworkers employed PtNPs-decorated SiNW arrays for fabricating photoelectrochemical solar cells, yielding distinctly improved photoconversion efficiency with high energy conversion efficiency (8.14 %) (Fig. 2.9a, b) [97]. In 2011, He et al. presented a kind of highly fluorescent (QY: ~ 30 %) SiNWs coated with multi-color QDs, capable of cell imaging in long-term manner to take advantage of the excellent anti-photobleaching property of the resultant QDs-decorated SiNWs (Fig. 2.9c, d) [101]. More recently, Su et al. decorated AuNPs on SiNWs surface, and further demonstrated that the prepared AuNPs-decorated SiNWs could produce sufficient heat under near-infrared (NIR) irradiation [103]. In this case, the SiNWs had high

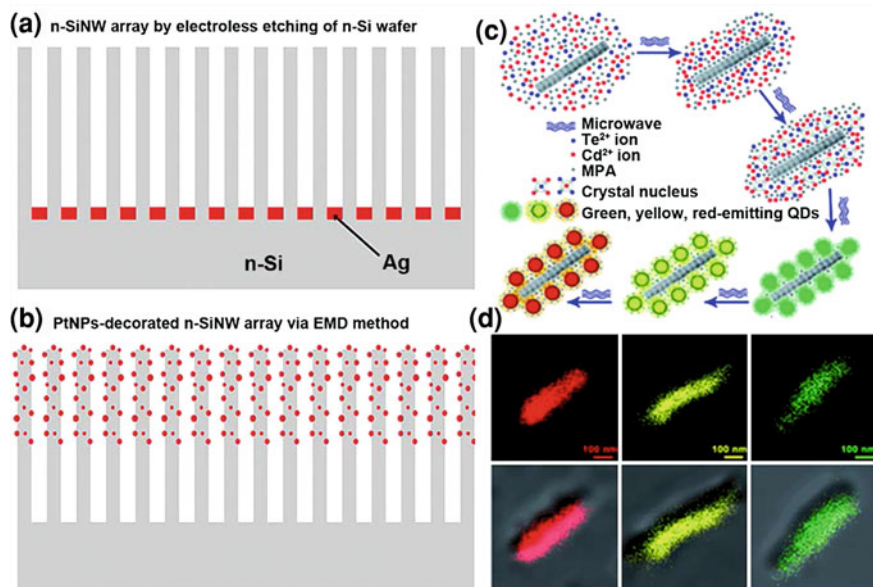


Fig. 2.9 **a** and **b** Schematic illustration of the SiNW arrays whose surface is coated with PtNPs. Reprinted with the permission from Ref. [97]. Copyright 2009 American Chemical Society. **c** Schematics of the preparation of three-color fluorescent QDs-coated SiNWs. **d** Confocal images of the as-prepared three-color (i.e., green, yellow, and red) fluorescent SiNWs. Reproduced from ref. [101] with permission from John Wiley & Sons Inc

absorption at NIR region and converted NIR light into heat, whereas AuNPs coated on surface of SiNWs significantly improve the conversion of light to heat. As a result, such SiNWs-based nanohybrids, served as novel hyperthermia nanoagents, were efficacious for treatment of tumor cells. More examples of silicon nanohybrids-based applications will be introduced in following Chapters (i.e., Chaps. 3, 4 and 5) in a detailed way.

In another aspect, by adding paramagnetism to fluorescent SiNPs, researchers can realize concurrent optical and magnetic (e.g., magnetic resonance imaging (MRI)) detection. Magnetic impurity doping is known as an available approach for offering semiconductor with magnetic properties [110]. In contrast to their single-component counterparts, the resultant doped nanomaterials feature enhanced and multiple functionalities [111]. In 2007, Kauzlarich and coworkers synthesized Mn-doped SiNPs with fluorescent and magnetic properties [105]. In their study, Mn doped Zintl salts ($\text{NaSi}_{1-x}\text{Mn}_x$, $x = 0.05, 0.1, 0.15$) were reacted with NH_4Br to produce H-terminated nanohybrid. Later, the same group developed another approach to produce fluorescent and paramagnetic Mn-doped SiNPs ($\text{Si}_{\text{Mn}}\text{NPs}$) [107]. In this case, the precursor Mn-doped sodium silicide was first obtained, followed by the reaction with NH_4Br and N,N-dimethylformamide (DMF) to prepare the hydrophobic $\text{Si}_{\text{Mn}}\text{NPs}$. Finally, the allylamine was added to the reaction mixture to obtain water-soluble $\text{Si}_{\text{Mn}}\text{NPs}$. In 2012, they further

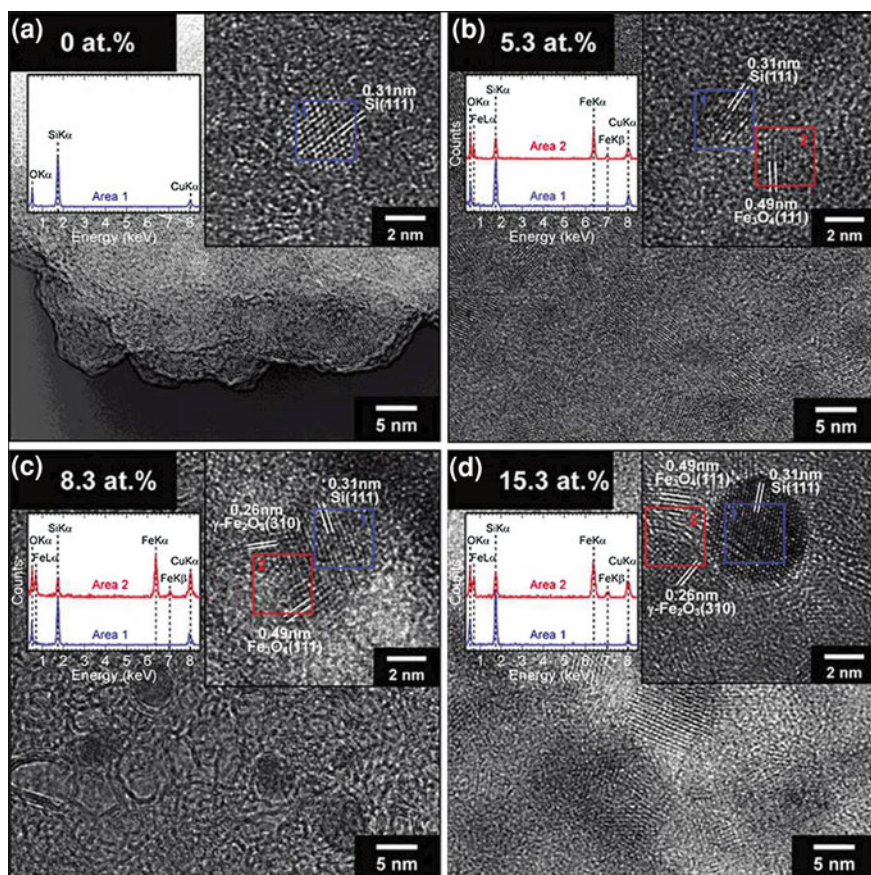


Fig. 2.10 TEM images of the pure SiNPs (a) and SiNPs doped with Fe different contents of 5.3 % (b), 8.3 % (c), and 15.3 % (d). Insets in a–d show HRTEM and energy dispersive X-ray (EDX) spectra of the mentioned four samples. Reprinted with permission from Ref. [108]. Copyright 2011 American Chemical Society

demonstrated the preparation of allylamine-terminated Fe-doped SiNPs featuring strong fluorescence (QY: $\sim 10\%$) and significant T_2 contrast, which was suitable for simultaneous fluorescent and magnetic imaging [109].

Another alternative means for fabricating SiNPs with magnetic properties is to encapsulate SiNPs with magnetic NPs, providing higher magnetization with less effect on the luminescence. In 2011, Fukata and coworkers designed the nanohybrids that combined silicon and magnetic iron oxides (e.g., Fe_3O_4 ($\gamma\text{-Fe}_2\text{O}_3$)) with size-dependent optical and magnetic behaviors (Fig. 2.10) [108]. For example, the as-prepared nanohybrids with the mean size of 3.0 nm exhibited superparamagnetic behavior and green fluorescence, but showed ferromagnetic behavior without fluorescence when the mean diameter was larger than 5.0 nm.

2.4 Conclusions

In this chapter, we first summarized the representative achievements in the synthesis of fluorescent SiNPs. Several important synthetic strategies (e.g., solution-phase reduction synthesis strategy, electrochemical etching approach, microwave-assisted method, etc.) were reviewed in details. On the basis of which, we further discussed the surface modification of SiNPs and relationship between optical and surface properties of SiNPs. Typically, quantum yield of SiNPs can be distinctly enhanced via proper surface modification (e.g., introducing novel surface ligands). Moreover, we suggested “bottom-up” methods as the highly promising route for large-scale preparation of highly luminescent SiNPs. In the second section, we gave a detailed introduction to three classic methods for synthesizing SiNWs, i.e., CVD, OAG, and electroless etching. We further analyzed advantages and shortcomings of these methods from the viewpoints of synthetic procedures, growth mechanism, catalysts, production cost, etc. We also briefly introduced typical kinds of silicon-based nanohybrids (e.g., metal nanoparticles-decorated SiNWs and magnetic materials-doped SiNPs). These high-quality silicon nanomaterials and their nanohybrids featuring unique optical/electronic/thermal properties afford exciting and new possibilities for myriad biological and biomedical, electronical, catalytic, and energetic applications.

References

1. Michalet X, Pinaud F, Bentolila L, Tsay J, Doose S, Li J, Sundaresan G, Wu A, Gambhir S, Weiss S (2005) Quantum dots for live cells, in vivo imaging, and diagnostics. *Science* 307(5709):538–544
2. Kostarelos K, Bianco A, Prato M (2009) Promises, facts and challenges for carbon nanotubes in imaging and therapeutics. *Nat Nanotechnol* 4(10):627–633
3. Riehemann K, Schneider SW, Luger TA, Godin B, Ferrari M, Fuchs H (2009) Nanomedicine-challenge and perspectives. *Angew Chem Int Ed* 48(5):872–897
4. Hong H, Zhang Y, Sun J, Cai W (2009) Molecular imaging and therapy of cancer with radiolabeled nanoparticles. *Nano Today* 4(5):399–413
5. Rothenfluh DA, Bermudez H, O’Neil CP, Hubbell JA (2008) Biofunctional polymer nanoparticles for intra-articular targeting and retention in cartilage. *Nat Mater* 7(3):248–254
6. De M, Ghosh PS, Rotello VM (2008) Applications of nanoparticles in biology. *Adv Mater* 20(22):4225–4241
7. Pavesi L, Dal Negro L, Mazzoleni C, Franzo G, Priolo F (2000) Optical gain in silicon nanocrystals. *Nature* 408(6811):440–444
8. Ding Z, Quinn BM, Haram SK, Pell LE, Korgel BA, Bard AJ (2002) Electrochemistry and electrogenerated chemiluminescence from silicon nanocrystal quantum dots. *Science* 296(5571):1293–1297
9. Grom GF, Lockwood DJ, McCaffrey JP, Labbe HJ, Fauchet PM, White B, Diener J, Kovalev D, Koch F, Tsybeskov L (2000) Ordering and self-organization in nanocrystalline silicon. *Nature* 407(6802):358–361

10. Allen JE, Hemesath ER, Perea DE, Lensch-Falk JL, LiZ Y, Yin F, Gass MH, Wang P, Bleloch AL, Palmer RE, Lauhon LJ (2008) High-resolution detection of Au catalyst atoms in Si nanowires. *Nat Nanotechnol* 3(3):168–173
11. Brus L, Szajowski P, Wilson W, Harris T, Schuppler S, Citrin P (1995) Electronic spectroscopy and photophysics of Si nanocrystals: relationship to bulk c-Si and porous Si. *J Am Chem Soc* 117(10):2915–2922
12. Wilson WL, Szajowski P, Brus L (1993) Quantum confinement in size-selected, surface-oxidized silicon nanocrystals. *Science* 262:1242–1244
13. Park N-M, Choi C-J, Seong T-Y, Park S-J (2001) Quantum confinement in amorphous silicon quantum dots embedded in silicon nitride. *Phys Rev Lett* 86(7):1355–1357
14. Canham LT (1990) Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers. *Appl Phys Lett* 57(10):1046–1048
15. Cullis A, Canham L (1991) Visible light emission due to quantum size effects in highly porous crystalline silicon. *Nature* 353:335–338
16. Yang C-S, Bley RA, Kauzlarich SM, Lee HW, Delgado GR (1999) Synthesis of alkyl-terminated silicon nanoclusters by a solution route. *J Am Chem Soc* 121(22):5191–5195
17. Baldwin RK, Pettigrew KA, Ratai E, Augustine MP, Kauzlarich SM (2002) Solution reduction synthesis of surface stabilized silicon nanoparticles. *Chem Commun* 17:1822–1823
18. Tilley RD, Yamamoto K (2006) The microemulsion synthesis of hydrophobic and hydrophilic silicon nanocrystals. *Adv Mater* 18(15):2053–2056
19. Shiohara A, Hanada S, Prabakar S, Fujioka K, Lim TH, Yamamoto K, Northcote PT, Tilley RD (2010) Chemical reactions on surface molecules attached to silicon quantum dots. *J Am Chem Soc* 132(1):248–253
20. Arul Dhas N, Raj CP, Gedanken A (1998) Preparation of luminescent silicon nanoparticles: a novel sonochemical approach. *Chem Mater* 10(11):3278–3281
21. Heintz AS, Fink MJ, Mitchell BS (2007) Mechanochemical synthesis of blue luminescent alkyl/alkenyl-passivated silicon nanoparticles. *Adv Mater* 19(22):3984–3988
22. Riabinina D, Durand C, Chaker M, Rosei F (2006) Photoluminescent silicon nanocrystals synthesized by reactive laser ablation. *Appl Phys Lett* 88(7):073105
23. Jurbergs D, Rogojina E, Mangolini L, Kortshagen U (2006) Silicon nanocrystals with ensemble quantum yields exceeding 60 %. *Appl Phys Lett* 88(23):233116
24. Mangolini L, Thimsen E, Kortshagen U (2005) High-yield plasma synthesis of luminescent silicon nanocrystals. *Nano Lett* 5(4):655–659
25. Mangolini L, Kortshagen U (2007) Plasma-assisted synthesis of silicon nanocrystal inks. *Adv Mater* 19(18):2513–2519
26. Kim NY, Laibinis PE (1997) Thermal derivatization of porous silicon with alcohols. *J Am Chem Soc* 119(9):2297–2298
27. Kang Z, Tsang CHA, Zhang Z, Zhang M, Wong N-b, Zapien JA, Shan Y, Lee S-T (2007) A polyoxometalate-assisted electrochemical method for silicon nanostructures preparation: from quantum dots to nanowires. *J Am Chem Soc* 129(17):5326–5327
28. Kang Z, Liu Y, Tsang CHA, Ma DDD, Fan X, Wong NB, Lee S-T (2009) Water-soluble silicon quantum dots with wavelength-tunable photoluminescence. *Adv Mater* 21(6):661–664
29. He Y, Kang ZH, Li QS, Tsang CHA, Fan CH, Lee S-T (2009) Ultrastable, highly Fluorescent, and water-dispersed silicon-based nanospheres as cellular probes. *Angew Chem Int Ed* 48:128–132
30. He Y, Su Y, Yang X, Kang Z, Xu T, Zhang R, Fan C, Lee S-T (2009) Photo and pH stable, highly-luminescent silicon nanospheres and their bioconjugates for immunofluorescent cell imaging. *J Am Chem Soc* 131(12):4434–4438
31. He Y, Zhong Y, Peng F, Wei X, Su Y, Lu Y, Su S, Gu W, Liao L, Lee S-T (2011) One-pot microwave synthesis of water-dispersible, ultraphoto-and pH-stable, and highly fluorescent silicon quantum dots. *J Am Chem Soc* 133(36):14192–14195

32. Atkins TM, Thibert A, Larsen DS, Dey S, Browning ND, Kauzlarich SM (2011) Femtosecond ligand/core dynamics of microwave-assisted synthesized silicon quantum dots in aqueous solution. *J Am Chem Soc* 133(51):20664–20667
33. Zhong Y, Peng F, Wei X, Zhou Y, Wang J, Jiang X, Su Y, Su S, Lee S-T, He Y (2012) Microwave-assisted synthesis of biofunctional and fluorescent silicon nanoparticles using proteins as hydrophilic ligands. *Angew Chem Int Ed* 51(34):8485–8489
34. Zhong Y, Peng F, Bao F, Wang S, Ji X, Yang L, Su Y, Lee S-T, He Y (2013) Large-scale aqueous synthesis of fluorescent and biocompatible silicon nanoparticles and their use as highly photostable biological probes. *J Am Chem Soc* 135(22):8350–8356
35. Li QS, Zhang RQ, Niehaus TA, Frauenheim T, Lee S-T (2007) Theoretical studies on optical and electronic properties of propionic-acid-terminated silicon quantum dots. *J Chem Theory Comput* 3(4):1518–1526
36. Li Q, Zhang R, Lee S, Niehaus TA, Frauenheim T (2008) Amine-capped silicon quantum dots. *Appl Phys Lett* 92(5):053107
37. Wang X, Zhang R, Niehaus TA, Frauenheim T (2007) Excited state properties of allylamine-capped silicon quantum dots. *J Phys Chem C* 111(6):2394–2400
38. Puzder A, Williamson AJ, Grossman JC, Galli G (2003) Computational studies of the optical emission of silicon nanocrystals. *J Am Chem Soc* 125(9):2786–2791
39. Zhou Z, Brus L, Friesner R (2003) Electronic structure and luminescence of 1.1- and 1.4-nm silicon nanocrystals: oxide shell versus hydrogen passivation. *Nano Lett* 3(2):163–167
40. Li Q, He Y, Chang J, Wang L, Chen H, Tan Y-W, Wang H, Shao Z (2013) Surface-modified silicon nanoparticles with ultrabright photoluminescence and single-exponential decay for nanoscale fluorescence lifetime imaging of temperature. *J Am Chem Soc* 135(40):14924–14927
41. Song S, Qin Y, He Y, Huang Q, Fan C, Chen H-Y (2010) Functional nanoprobe for ultrasensitive detection of biomolecules. *Chem Soc Rev* 39(11):4234–4243
42. He Y, Fan C, Lee S-T (2010) Silicon nanostructures for bioapplications. *Nano Today* 5(4):282–295
43. Li Z, Ruckenstein E (2004) Water-soluble poly (acrylic acid) grafted luminescent silicon nanoparticles and their use as fluorescent biological staining labels. *Nano Lett* 4(8):1463–1467
44. Sato S, Swihart MT (2006) Propionic-acid-terminated silicon nanoparticles: synthesis and optical characterization. *Chem Mater* 18(17):4083–4088
45. Warner JH, Hoshino A, Yamamoto K, Tilley RD (2005) Water-soluble photoluminescent silicon quantum dots. *Angew Chem Int Ed* 44(29):4550–4554
46. Erogbogbo F, Yong K-T, Roy I, Xu G, Prasad PN, Swihart MT (2008) Biocompatible luminescent silicon quantum dots for imaging of cancer cells. *ACS Nano* 2(5):873–878
47. Choi HS, Liu W, Misra P, Tanaka E, Zimmer JP, Ipe BI, Bawendi MG, Frangioni JV (2007) Renal clearance of quantum dots. *Nat Biotechnol* 25(10):1165–1170
48. Choi HS, Liu W, Liu F, Nasr K, Misra P, Bawendi MG, Frangioni JV (2010) Design considerations for tumour-targeted nanoparticles. *Nat Nanotechnol* 5(1):42–47
49. Ma D, Lee C, Au F, Tong S, Lee S-T (2003) Small-diameter silicon nanowire surfaces. *Science* 299(5614):1874–1877
50. Schmidt V, Wittemann JV, Senz S, Gösele U (2009) Silicon nanowires: A review on aspects of their growth and their electrical properties. *Adv Mater* 21(25–26):2681–2702
51. Treuting RG, Arnold SM (1957) Orientation habits of metal whiskers. *Acta Metall* 5(10):598
52. Wagner R, Ellis W (1964) Vapor-liquid-solid mechanism of single crystal growth. *Appl Phys Lett* 4(5):89–90
53. Morales AM, Lieber CM (1998) A laser ablation method for the synthesis of crystalline semiconductor nanowires. *Science* 279(5348):208–211
54. Zhang YF, Tang YH, Wang N, Yu DP, Lee CS, Bello I, Lee S-T (1998) Silicon nanowires prepared by laser ablation at high temperature. *Appl Phys Lett* 72(15):1835–1837

55. Schmidt V, Wittemann J, Gosele U (2010) Growth, thermodynamics, and electrical properties of silicon nanowires. *Chem Rev* 110(1):361–388
56. Wu Y, Yang P (2001) Direct observation of vapor-liquid-solid nanowire growth. *J Am Chem Soc* 123(13):3165–3166
57. Putnam MC, Filler MA, Kayes BM, Kelzenberg MD, Guan Y, Lewis NS, Eiler JM, Atwater HA (2008) Secondary ion mass spectrometry of vapor-liquid-solid grown, Au-catalyzed Si wires. *Nano Lett* 8(10):3109–3113
58. Zhang RQ, Lifshitz Y, Lee S-T (2003) Oxide-assisted growth of semiconducting nanowires. *Adv Mater* 15(7–8):635–640
59. Holmes JD, Johnston KP, Doty RC, Korgel BA (2000) Control of thickness and orientation of solution-grown silicon nanowires. *Science* 287(5457):1471–1473
60. Lu X, Hanrath T, Johnston KP, Korgel BA (2002) Growth of single crystal silicon nanowires in supercritical solution from tethered gold particles on a silicon substrate. *Nano Lett* 3(1):93–99
61. Heitsch AT, Fanfair DD, Tuan H-Y, Korgel BA (2008) Solution-liquid-solid (SLS) growth of silicon nanowires. *J Am Chem Soc* 130(16):5436–5437
62. Hanrath T, Korgel BA (2003) Supercritical fluid-liquid-solid (SFLS) synthesis of Si and Ge nanowires seeded by colloidal metal nanocrystals. *Adv Mater* 15(5):437–440
63. Zhang YF, Tang YH, Peng HY, Wang N, Lee CS, Bello I, Lee S-T (1999) Diameter modification of silicon nanowires by ambient gas. *Appl Phys Lett* 75(13):1842–1844
64. Tang YH, Zhang YF, Wang N, Lee CS, Han XD, Bello I, Lee S-T (1999) Morphology of Si nanowires synthesized by high-temperature laser ablation. *J Appl Phys* 85(11):7981–7983
65. Shi WS, Peng HY, Zheng YF, Wang N, Shang NG, Pan ZW, Lee CS, Lee S-T (2000) Synthesis of large areas of highly oriented, very long silicon nanowires. *Adv Mater* 12(18):1343–1345
66. Pan H, Lim S, Poh C, Sun H, Wu X, Feng Y, Lin J (2005) Growth of Si nanowires by thermal evaporation. *Nanotechnology* 16(4):417
67. Juhasz R, Elfström N, Linnros J (2005) Controlled fabrication of silicon nanowires by electron beam lithography and electrochemical size reduction. *Nano Lett* 5(2):275–280
68. Tong HD, Chen S, van der Wiel WG, Carlen ET, van den Berg A (2009) Novel top-down wafer-scale fabrication of single crystal silicon nanowires. *Nano Lett* 9(3):1015–1022
69. Peng KQ, Yan YJ, Gao SP, Zhu J (2002) Synthesis of large-area silicon nanowire arrays via self-assembling nanoelectrochemistry. *Adv Mater* 14(16):1164–1167
70. Peng K, Wu Y, Fang H, Zhong X, Xu Y, Zhu J (2005) Uniform, axial-orientation alignment of one-dimensional single-crystal silicon nanostructure arrays. *Angew Chem Int Ed* 44(18):2737–2742
71. Peng K, Lu A, Zhang R, Lee S-T (2008) Motility of metal nanoparticles in silicon and induced anisotropic silicon etching. *Adv Funct Mater* 18(19):3026–3035
72. Hsu C-M, Connor ST, Tang MX, Cui Y (2008) Wafer-scale silicon nanopillars and nanocones by Langmuir-Blodgett assembly and etching. *Appl Phys Lett* 93(13):133109
73. Lew K-K, Redwing JM (2003) Growth characteristics of silicon nanowires synthesized by vapor-liquid-solid growth in nanoporous alumina templates. *J Cryst Growth* 254(1–2):14–22
74. Chung S-W, Yu J-Y, Heath JR (2000) Silicon nanowire devices. *Appl Phys Lett* 76(15):2068–2070
75. Wu Y, Cui Y, Huynh L, Barrelet CJ, Bell DC, Lieber CM (2004) Controlled growth and structures of molecular-scale silicon nanowires. *Nano Lett* 4(3):433–436
76. Hochbaum AI, Fan R, He R, Yang P (2005) Controlled growth of Si nanowire arrays for device integration. *Nano Lett* 5(3):457–460
77. Hannon J, Kodambaka S, Ross F, Tromp R (2006) The influence of the surface migration of gold on the growth of silicon nanowires. *Nature* 440(7080):69–71
78. Garnett EC, Liang W, Yang P (2007) Growth and electrical characteristics of platinum-nanoparticle-catalyzed silicon nanowires. *Adv Mater* 19(19):2946–2950

79. Kayes BM, Filler MA, Putnam MC, Kelzenberg MD, Lewis NS, Atwater HA (2007) Growth of vertically aligned Si wire arrays over large areas ($>1\text{ cm}^2$) with Au and Cu catalysts. *Appl Phys Lett* 91(10):103110
80. Renard VT, Jublot M, Gergaud P, Cherns P, Rouchon D, Chabli A, Jousseume V (2009) Catalyst preparation for CMOS-compatible silicon nanowire synthesis. *Nat Nanotechnol* 4(10):654–657
81. Putnam MC, Turner-Evans DB, Kelzenberg MD, Boettcher SW, Lewis NS, Atwater HA (2009) 10 μm minority-carrier diffusion lengths in Si wires synthesized by Cu-catalyzed vapor-liquid-solid growth. *Appl Phys Lett* 95:163116
82. Wang Y, Schmidt V, Senz S, Gösele U (2006) Epitaxial growth of silicon nanowires using an aluminium catalyst. *Nat Nanotechnol* 1(3):186–189
83. Wacaser BA, Reuter MC, Khayyat MM, Wen C-Y, Haight R, Guha S, Ross FM (2009) Growth system, structure, and doping of aluminum-seeded epitaxial silicon nanowires. *Nano Lett* 9(9):3296–3301
84. Wang N, Tang YH, Zhang YF, Lee CS, Bello I, Lee S-T (1999) Si nanowires grown from silicon oxide. *Chem Phys Lett* 299(2):237–242
85. Peng K, Zhu J (2003) Simultaneous gold deposition and formation of silicon nanowire arrays. *J Electroanal Chem* 558:35–39
86. Peng K, Zhu J (2004) Morphological selection of electroless metal deposits on silicon in aqueous fluoride solution. *Electrochim Acta* 49(16):2563–2568
87. Peng K, Fang H, Hu J, Wu Y, Zhu J, Yan Y, Lee S (2006) Metal-particle-induced, highly localized site-specific etching of Si and formation of single-crystalline Si nanowires in aqueous fluoride solution. *Chem Eur J* 12(30):7942–7947
88. Peng K, Hu J, Yan Y, Wu Y, Fang H, Xu Y, Lee S, Zhu J (2006) Fabrication of single-crystalline silicon nanowires by scratching a silicon surface with catalytic metal particles. *Adv Funct Mater* 16(3):387–394
89. Peng K, Xu Y, Wu Y, Yan Y, Lee S-T, Zhu J (2005) Aligned single-crystalline Si nanowire arrays for photovoltaic applications. *Small* 1(11):1062–1067
90. Peng K, Wang X, Lee S-T (2008) Silicon nanowire array photoelectrochemical solar cells. *Appl Phys Lett* 92(16):163103
91. Lam HY, Zangmeister CD, Kushmerick JG (2007) Origin of discrepancies in inelastic electron tunneling spectra of molecular junctions. *Phys Rev Lett* 98(20):206803
92. Mann S (2009) Self-assembly and transformation of hybrid nano-objects and nanostructures under equilibrium and non-equilibrium conditions. *Nat Mater* 8(10):781–792
93. Macdonald JE, Bar Sadan M, Houben L, Popov I, Banin U (2010) Hybrid nanoscale inorganic cages. *Nat Mater* 9(10):810–815
94. Peng X, Chen J, Misewich JA, Wong SS (2009) Carbon nanotube-nanocrystal heterostructures. *Chem Soc Rev* 38(4):1076–1098
95. Wada A, Tamaru S, Ikeda M, Hamachi I (2009) MCM-enzyme-supramolecular hydrogel hybrid as a fluorescence sensing material for polyanions of biological significance. *J Am Chem Soc* 131(14):5321–5330
96. Su S, Wei X, Zhong Y, Guo Y, Su Y, Huang Q, Lee S-T, Fan C, He Y (2012) Silicon nanowire-based molecular beacons for high-sensitivity and sequence-specific DNA multiplexed analysis. *ACS Nano* 6(3):2582–2590
97. Peng K-Q, Wang X, Wu X-L, Lee S-T (2009) Platinum nanoparticle decorated silicon nanowires for efficient solar energy conversion. *Nano Lett* 9(11):3704–3709
98. Peng K-Q, Lee S-T (2011) Silicon nanowires for photovoltaic solar energy conversion. *Adv Mater* 23(2):198–215
99. Peng Z, Hu H, Utama MIB, Wong LM, Ghosh K, Chen R, Wang S, Shen Z, Xiong Q (2010) Heteroepitaxial decoration of Ag nanoparticles on Si nanowires: a case study on Raman scattering and mapping. *Nano Lett* 10(10):3940–3947
100. He Y, Su S, Xu T, Zhong Y, Zapfen JA, Li J, Fan C, Lee S-T (2011) Silicon nanowires-based highly-efficient SERS-active platform for ultrasensitive DNA detection. *Nano Today* 6(2):122–130

101. He Y, Zhong Y, Peng F, Wei X, Su Y, Su S, Gu W, Liao L, Lee S-T (2011) Highly luminescent water-dispersible silicon nanowires for long-term immunofluorescent cellular imaging. *Angew Chem Int Ed* 50:3080–3083
102. Lv M, Su S, He Y, Huang Q, Hu W, Li D, Fan C, Lee S-T (2010) Long-term antimicrobial effect of silicon nanowires decorated with silver nanoparticles. *Adv Mater* 22(48):5463–5467
103. Su Y, Wei X, Peng F, Zhong Y, Lu Y, Su S, Xu T, Lee S-T, He Y (2012) Gold nanoparticles-decorated silicon nanowires as highly efficient near-infrared hyperthermia agents for cancer cells destruction. *Nano Lett* 12(4):1845–1850
104. Park G-S, Kwon H, Kwak DW, Park SY, Kim M, Lee J-H, Han H, Heo S, Li XS, Lee JH (2012) Full surface embedding of gold clusters on silicon nanowires for efficient capture and photothermal therapy of circulating tumor cells. *Nano Lett* 12(3):1638–1642
105. Zhang X, Brynda M, Britt RD, Carroll EC, Larsen DS, Louie AY, Kauzlarich SM (2007) Synthesis and characterization of manganese-doped silicon nanoparticles: bifunctional paramagnetic-optical nanomaterial. *J Am Chem Soc* 129(35):10668–10669
106. Erogbogbo F, Yong K-T, Hu R, Law W-C, Ding H, Chang C-W, Prasad PN, Swihart MT (2010) Biocompatible magnetofluorescent probes: luminescent silicon quantum dots coupled with superparamagnetic iron (III) oxide. *ACS Nano* 4(9):5131–5138
107. Tu C, Ma X, Pantazis P, Kauzlarich SM, Louie AY (2010) Paramagnetic, silicon quantum dots for magnetic resonance and two-photon imaging of macrophages. *J Am Chem Soc* 132(6):2016–2023
108. Sato K, Yokosuka S, Takigami Y, Hirakuri K, Fujioka K, Manome Y, Sukegawa H, Iwai H, Fukata N (2011) Size-tunable silicon/iron oxide hybrid nanoparticles with fluorescence, superparamagnetism, and biocompatibility. *J Am Chem Soc* 133(46):18626–18633
109. Singh MP, Atkins TM, Muthuswamy E, Kamali S, Tu C, Louie AY, Kauzlarich SM (2012) Development of iron-doped silicon nanoparticles as bimodal imaging agents. *ACS Nano* 6(6):5596–5604
110. Shi W, Zeng H, Sahoo Y, Ohulchanskyy TY, Ding Y, Wang ZL, Swihart M, Prasad PN (2006) A general approach to binary and ternary hybrid nanocrystals. *Nano Lett* 6(4):875–881
111. Wang S, Jarrett BR, Kauzlarich SM, Louie AY (2007) Core/shell quantum dots with high relaxivity and photoluminescence for multimodality imaging. *J Am Chem Soc* 129(13):3848–3856

Silicon Nano-biotechnology

He, Y.; Su, Y.

2014, VIII, 109 p. 47 illus., 26 illus. in color., Softcover

ISBN: 978-3-642-54667-9