Particuology 9 (2011) 458–464

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Vanadium oxide assisted synthesis of networked silicon oxide nanowires and their growth dependence

Mohammad Norouzi Banis[a], Yong Zhang[a], Ruying Li[a], Xueliang Sun[a,*], Xinxiang Jiang[b], Darius Nikanpour[b]

[a] Department of Mechanical and Materials Engineering, University of Western Ontario, London, Canada
[b] Spacecraft Engineering, Space Technologies, Canadian Space Agency, 6767 route de l'Aeroport, St-Hubert, Quebec J3Y 8Y9, Canada

ARTICLE INFO

Article history:
Received 15 December 2010
Received in revised form 14 February 2011
Accepted 21 February 2011

Keywords:
Networked SiO_2 nanowire
CVD
Vanadium dioxide
Gold

ABSTRACT

Networked silicon oxide nanowires have been synthesized by VO_2-assisted chemical vapor deposition at 1000 °C on silicon substrate without supplying any gaseous or liquid Si source. Systematic study on the nanowire growth has indicated that morphology and composition of the final products are sensitive to the catalyst components, reaction atmosphere and temperature. Compared to Au and VO_2 as catalysts individually, co-catalysts of Au and VO_2 play a critical role in the formation of networked SiO_2 nanowires. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) observations indicate that the silicon oxide nanowires have smooth surfaces with uniform diameters of 30–100 nm, and their lengths reach several hundred micrometers. X-ray photoelectron spectroscopy (XPS) results reveal the atomic ratio of silicon to oxygen is about 1:2. Growth dependence of the networked nanowires on hydrogen and temperature is also discussed. Vapor-liquid-solid (VLS) process is proposed for the growth mechanism of the networked nanowires. It is also found that the growth mechanism of SiO_2 nanowires by increasing the temperature up to 1200 °C changes to vapor–solid (VS) processes since wire-like structures can be formed without any catalyst or H_2 gas introduced into the system.

1. Introduction

In the past two decades, research on one-dimensional (1D) nanomaterials such as nanowires and nanotubes has increased dramatically due to their anisotropic shape and variable stoichiometry, which offer interesting physical and chemical properties and make them suitable for various applications.

Recently, 1D silicon oxide (SiO_x) nanostructures have attracted substantial interest because of their various morphology such as nanowires (Yang, Tay, Sun, Fan, & Shen, 2006), nanotubes (Zhang, Bando, Wada, & Kurashima, 1999), nanoflowers (Chen, Li, Han, & Dai, 2002), helical and nanosprings (Zhang et al., 2008). These diverse silicon oxide nanostructures show unique properties which make them potential candidates for various technologies such as optics (Hu, Jiang, Meng, Lee, & Lee, 2003; Kim, Shim, & Lee, 2007; Yang et al., 2006; Zhu et al., 1999), semiconductors (Park et al., 2007; Zhang et al., 1999) and catalysis (Zhang et al., 1999).

Up to now, different synthesis methods such as vapor transport (Yang et al., 2006), bio-mimetic strategies (Davis, Burkett, Mendelson, & Mann, 1997), laser ablation (Zhu et al., 1999), physical and thermal chemical evaporation (Ni, Ying, Luo, & Li, 2007), thermal oxidation (Hu et al., 2003) and solution methods (Zhang et al., 1999) have been used to prepare silicon based nanostructures with different morphologies. However, synthesis of silicon oxide nanostructures with controlled and predictable morphology for commercial application remains a challenge (Huang, Ostrikov, & Xu, 2008).

Among the synthesis methods, vapor transport methods are often used to grow silicon based nanostructures owing to their simple systems and fast growth rates as compared to solution based methods. In addition, various mechanisms have been proposed for the growth of silicon oxide nanowires using vapor transport methods such as VLS and VS mechanism. In these methods, a source material, e.g. Si powder, together with a catalyst like Pb (VLS process), is used to grow Si based nanowires (Zhang, Jiang, Yang, & Li, 2007). Recently, studies of growing silicon oxide nanowires directly from silicon substrate without any external silicon source have been reported. Park et al. (2007) synthesized amorphous SiO_x nanowires using Au and Pd–Au alloy as catalysts. Kim et al. (2007) found that SiO_x nanowires can be grown from Cu coated silicon substrates. Lee et al. (2004) reported the growth of silica nanowires from silicon substrates covered with thin films of TiN/Ni. Some

---

* Corresponding author. Tel.: +1 519 661 2111x87759; fax: +1 519 661 3020.
E-mail addresses: xsun@eng.uwo.ca, xsun9@uwo.ca (X. Sun).

1674-2001/$ – see front matter © 2011 Chinese Society of Particuology and Institute of Process Engineering, Chinese Academy of Sciences. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.partic.2011.02.005

reports of other catalysts such as Fe, Ga, Ga–In and Co have also been presented (Kim et al., 2007). Generally for these processes, metal particles have been commonly employed as the catalyst and the solid–liquid–solid (SLS) growth mechanism has been proposed to obtain silicon oxide nanowires (Park et al., 2007; Wang, Chan, Xiao, Lin, & Shih, 2006).

In this paper, we report the synthesis of uniform silicon oxide nanowires with distinct network features with the aid of VO_2 powder directly on a silicon substrate. We found that the network characteristic of silicon oxide nanowires can be significantly enhanced by combining VO_2 and gold as a co-catalyst. We have also investigated the effect of hydrogen and temperature on the nanostructures deposited on the substrate and discussed the possible growth mechanism with respect to the role of catalysts and hydrogen in the system.

2. Materials and methods

The synthesis of silicon oxide nanowires was carried out in a horizontal tube furnace. In this study different combinations of catalysts were investigated including gold (Au), VO_2 powder and Au–VO_2 systems. Depending on the catalyst employed, bare or Au sputtered silicon (1 0 0) wafers were used as the substrate and silicon source. The Au layer with a thickness of 5 nm was sputtered on the silicon wafers using an Emitech K550X sputter coater. To synthesize silicon oxide nanowires, a silicon substrate with a catalyst layer was placed in an alumina boat which was transferred into the furnace. The furnace was heated to 1000 °C at a rate of 20 °C/min and kept at this temperature for 5 h. During the experiment a constant flow of high purity argon (200 sccm) and hydrogen (20 sccm) was maintained in the chamber. At the end of the experiment, white wool-like products were found on the silicon substrate.

The synthesized nanostructures were characterized using Hitachi S-4500 field-emission scanning electron microscope (SEM) operated at 5.0 kV, Oxford INCA energy dispersive X-ray spectrometer (EDX) operated at 20 kV, JEOL 2010F transmission electron microscope (TEM) operated at 200 kV, and Kratos Axis Ultra Al(alpha) X-ray photoelectron spectrometer (XPS) operated at 14 kV.

3. Results and discussion

3.1. Effect of catalyst

Fig. 1(a) and (b) shows SEM images of silicon oxide nanowires synthesized by heating the silicon substrates in the vicinity of only VO_2 powder at 1000 °C in an Ar/H_2 atmosphere. These images show randomly oriented nanowires and bundles formed in some areas completely covering the substrate (Fig. 1(a)). High magnification image of these bundles seen in Fig. 1(b) reveals highly tangled network structure of these nanowires. These nanostructures are similar to the nanostructures synthesized by Huang et al. (2008) and Kim et al. (2007), reporting the synthesis of helical silicon oxide nanostructures on silicon substrates.

SEM images of networked silicon oxide nanowires synthesized using co-catalysts of VO_2 and gold are shown in Fig. 1(c) and (d). As seen in the low magnification SEM image of these nanowires (Fig. 1(c)), application of VO_2 powder and a gold thin layer on silicon substrate together, results in the uniform synthesis of high-density networked silicon oxide nanowires (similar to morphologies synthesized using VO_2 powder) covering the substrate. SEM observations indicate, the diameter of these nanowires is between 30–70 nm and their length reaches up to tens of micrometers. High magnification image of these networked structures (Fig. 1(d)) reveals the silicon oxide nanowires have branched structures, suggesting simultaneous nucleation and growth of these nanowires. In some cases, these branched nanowires bundle together to form rope-like structures. Previously similar silicon oxide nanostructures have been reported by other researchers using metallic catalysts such as Ga (Pan, Dai, Beach, & Lowndes, 2003), Sn (Sun et al., 2003) and Fe (Liang, Zhang, Meng, Wang, & Chu, 2000; Xu et al., 2004).

SEM images of silicon oxide nanowires synthesized using gold as catalyst are demonstrated in Fig. 1(e) and (f). Fig. 1(e) shows dense formation of nanowires on the substrate. Close-up examination at these nanowires (Fig. 1(f)) reveals that the nanostructures are composed of thick nanowires and thin nanowire-bundles, possibly due to excess of gold on the surface of the silicon substrate. Compared to well dispersed network of nanowires grown by co-catalysts, these nanowires have shorter lengths and wider diameter distribution from 20 nm to 200 nm as seen in Fig. 1(e). The synthesis of silicon oxide nanowires using gold directly from silicon substrate was previously reported by Park et al. (2007), and Kim, Shalav, and Elliman (2010) without the use of hydrogen and at higher temperatures.

Based on the SEM observations it is seen that gold and VO_2 powder each plays an important role in shaping the morphology of the nanostructures. Park et al. (2007) reported a similar conclusion, when studying Pd and Au as catalysts. According to their reports, silicon oxide nanowires could be grown at a lower temperature of around 1000 °C using the alloy catalyst as compared to nanowires grown with the use of gold only at 1150 °C. For a detailed study of the effect of VO_2 powder on the synthesis of silicon oxide nanowires, TEM observations and XPS measurements were carried out. Fig. 2(a) is a typical TEM image of the silicon oxide nanowires, showing the branching of the silicon oxide nanowires which can result in the formation of network nanostructures. Furthermore these observations reveal that no catalyst particles were found at the tips of the nanowires and the nanowires were clean and with smooth and curved morphologies. As shown in the inset of Fig. 2(a), the highly dispersed selected area electron diffraction pattern indicates the amorphous nature of these structures. This is similar to reports using other catalysts at these temperatures (Kim et al., 2007; Lee et al., 2004; Park et al., 2007).

The composition of these nanostructures was determined using XPS (Fig. 2(b)), illustrating that the nanowires are mainly composed of silicon and oxygen with an atomic ratio close to 1:2. Further study of the valence state of the Si element (shown in inset of Fig. 2(b)), indicates the Si $2p_{3/2}$ peak is located at 103.4 eV, which is consistent with the Si^{4+} state of silicon. This confirms the nanowires synthesized by thermal heating of silicon substrates with VO_2 powder are mainly SiO_2 nanowires. The carbon peak seen in the XPS spectrum could be from impurities such as carbon oxides absorbed on the silicon oxide nanowires.

No catalyst peaks can be observed in the XPS spectrum, which is consistent with the TEM and SEM observations. This is different from the result reported by Yang et al. (2006), who synthesized amorphous silica nanowires by heating the silicon with a mixture of hydrous zinc chloride and vanadium dioxide powder. In their case, vanadium particles were detected on the tip of the silicon oxide nanowires.

3.2. Effect of hydrogen

A number of groups have reported the synthesis of silicon based nanowires under H_2 atmosphere from silicon substrate with various catalysts. Lee et al. (2004) used TiN/Ni coated

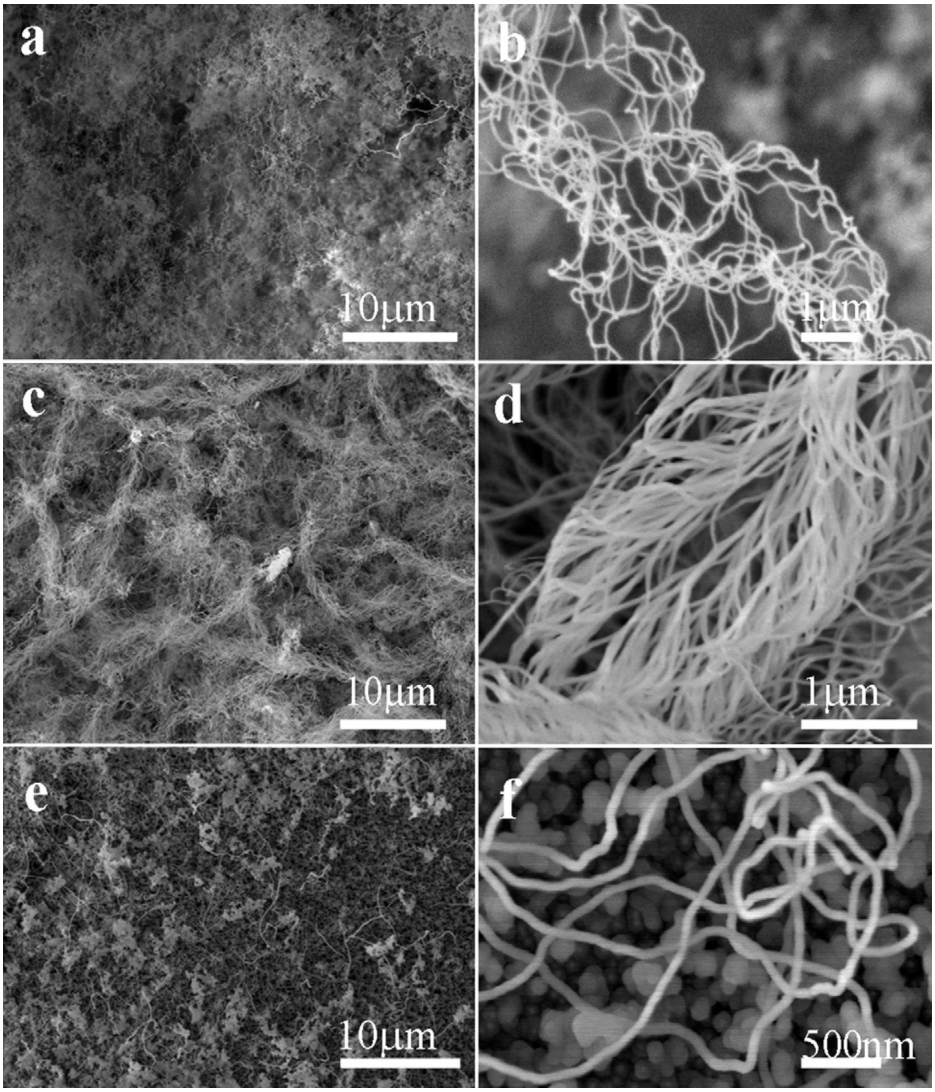

Fig. 1. Typical SEM images of silicon oxide nanostructures synthesized using (a) and (b) VO_2 powder, (c) and (d) VO_2–Au co-catalyst, (e) and (f) Au catalyst by simple thermal annealing of silicon substrate.

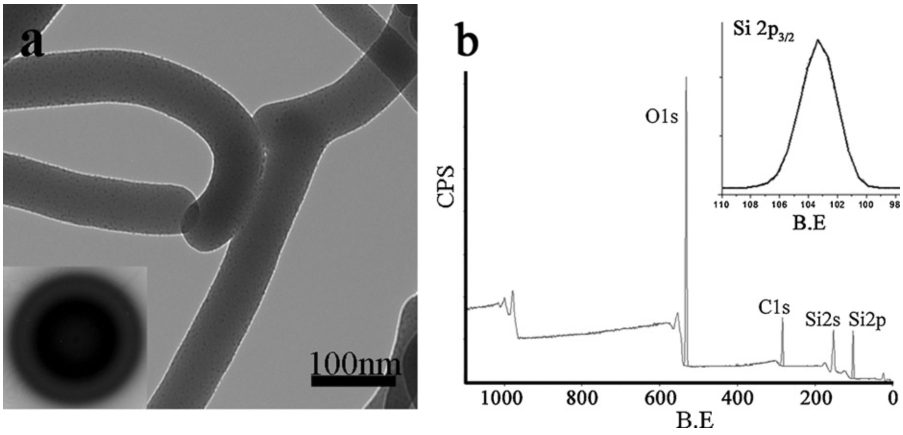

Fig. 2. (a) TEM image of silicon oxide nanowires (synthesized using VO_2 powder under H_2 and Ar flow at 1000 °C) showing smooth morphology and a diameter of 50–70 nm. The SAED pattern shown in the inset reveals a characteristic diffusive ring pattern indicating that silicon oxide nanowires are completely amorphous. (b) XPS spectrum of silicon oxide nanowires with silicon to oxygen peak ratio of approximately 0.5. There are no peaks for VO_2, suggesting that the nanowires are pure silicon oxide nanowires. The inset shows a detailed study of valence state of silicon indicating the presence of only Si^{4+} state.

silicon substrate in H_2 atmosphere and synthesized amorphous silica nanowires. Xing, Yu, Xi, and Xue (2003) reported the growth of silicon nanowires from silicon coated with gold in H_2 atmosphere, a condition similar to our experiment. Recently, Shao, Hu, Ban, Li, and Gao (2007) reported the synthesis of low oxygen content silicon nanowires from a single quartz crystal in H_2 atmosphere at relatively high temperatures.

In this study, it was found the presence of H_2 is essential for the growth of high-density nanowires at temperatures around 1000 °C. Fig. 3(a) shows an SEM image of silicon substrate heated with VO_2 powder in only Ar atmosphere at 1000 °C. Unlike previous results using H_2 (Fig. 1(a) and (b)), the substrate is covered by rod like structures with different diameters. EDX results (inset of Fig. 3(a)) on these structures reveal that these structures comprise vanadium and oxygen, the silicon peak being mainly due to the substrate itself. According to these observations, H_2 inhibits the deposition of vanadium oxide on the silicon and results in the growth of silicon oxide nanowires. In addition, controlled experiments were conducted with only Ar/H_2 gas and silicon substrate in the chamber and no products were found deposited on the substrate. It can therefore be concluded that both H_2 and VO_2 powder are crucial for the growth of high-density networked silicon oxide nanowires.

SEM image of the silicon substrate coated with gold in Ar atmosphere at 1000 °C (Fig. 3(b)) shows that very small nanowires are synthesized on the substrate and there are a few bundles of silicon oxide nanowires non-uniformly distributed on the substrate. EDX result shown in inset of Fig. 3(b) confirms that these nanostructures are composed of silicon and oxygen. Therefore, the results point out that H_2 in the atmosphere can contribute a positive effect to the density of silicon oxide nanowires synthesized from the substrate.

It should be noted that in the above two cases, a wide range of H_2 flow rate has been applied (60–180 sccm) and the results show the growth of the silicon oxide nanowires is not sensitive to the amount of hydrogen.

3.3. *Effect of temperature*

Temperature also plays an important role in the synthesis and growth mechanism of silicon oxide nanowires. Studies of synthesizing silicon oxide nanowires directly from the substrate in a temperatures range from 950 °C to 1400 °C were reported earlier (Davis et al., 1997; Hu et al., 2003; Shao et al., 2007). In the present study, a series of experiments were conducted to study the effect of temperature on the synthesis of silicon oxide nanowires. It was found that silicon oxide nanowires were synthesized above 950 °C using gold and VO_2–gold co-catalyst in an Ar/H_2 atmosphere. The main difference between the nanowires grown at different temperatures lies in their density and diameter. With increasing temperature, both the density and average diameter of nanowires increase dramatically. However, at temperatures higher than 1200 °C, silicon oxide wire-like structures with large diameters can be synthesized in the absence of catalysts or H_2 gas (Fig. 4). It is seen in Fig. 4(a) that the products on the substrate are a mixture of microfibers and nanowires and have a wide range of diameters from 100 nm to over 1 μm. Closer look at these structures, as shown in Fig. 4(b), indicates helical morphologies of the products, similar to the nanostructures reported by Zhang et al. (2008).

Based on these results, it can be concluded that the presence of catalyst and H_2 is necessary in generating silicon oxide nanowires at lower temperatures (∼950 °C). At higher temperatures (∼1200 °C), neither catalyst nor H_2 is necessary for growing silicon oxide micro- and nanowires.

3.4. *Growth mechanism*

Table 1 summarizes the effect of different growth parameters on the morphology of nanostructures synthesized on silicon substrate. Based on these results a growth mechanism can be proposed for the synthesis of silicon oxide nanostructures.

Different mechanisms have been proposed for the growth of silicon oxide nanowires such as VLS (Kwak, Cho, & Yang, 2007; Sekhar, Ramgir, Joshi, & Bhansali, 2008; Xiao et al., 2006), VS (Lee, Lee, Vanfleet, & Sigmund, 2003) and SLS (Park et al., 2007). In all these growth mechanisms, the most important parameter is the silicon source for the growth of nanowires. Since in the present study no external silicon source is employed, silicon substrate can be considered as the sole source for the growth of nanowires.

Based on SEM observation of silicon substrate at the initial growth stage of the synthesis procedure, etched pits were seen at random areas of the substrate when the three types of catalysts were used, shown in Fig. 5. As reported by Kim et al. (2010), these etched pits are related to the oxidation and evaporation of silicon monoxide species. Based on previous studies on the oxidation of silicon (Engstrom, Bonser, Nelson, & Engel, 1991), such oxidation occurs through the formation of a passive SiO_2 layer under high oxygen partial pressures. However, volatile $SiO_{(g)}$ instead of SiO_2 is formed under low oxygen pressure. Kim et al. (2010) related the etched pits to the formation of these species. In this study the oxygen content in the chamber is decreased by the introduction of H_2 into the growth chamber. Hence the condition is favorable for the formation of $SiO_{(g)}$ and etched pits.

Furthermore there have been a number of studies on the synthesis of silicon based nanowires in H_2 atmosphere using catalyst at relatively low temperatures or without the use of catalysts at higher temperatures (Shao et al., 2007; Xing et al., 2002; Yan et al., 2000). Previous reports proposed that the role of H_2 is to enhance the supersaturation of liquid droplet thus building up the driving force for the precipitation of silicon as silicon nanowires (Xing et al., 2003; Yan et al., 2000). In addition, Choi, Johnson, and Ural (2009) reported the increase in the catalyst nanoparticle size and density when H_2 is introduced during the growth of SiO_2 nanowires. They attributed this to the enhancement of diffusion of impurities in SiO_2 in the presence of H_2 on the basis of previous studies (Grove, Leistiko, & Sah, 1964). In this study, H_2 gas plays a crucial role in the formation of $SiO_{(g)}$ species from silicon substrate. In addition, H_2 prevents the large scale deposition of VO_x nanostructures (as seen in Fig. 3(a)) by reducing the oxygen partial pressure and inhibiting the oxidation and evaporation of VO_2 (melting point ∼1970 °C) to other oxides, such as V_2O_5 (melting point ∼690 °C).

In the presence of a catalyst such as gold on the surface of the silicon substrate, silicon oxide nanowires can be grown following the VLS growth mechanism proposed in several studies (Yan et al., 2000). In this process, Si atoms in the vapor phase are dissolved into the mediating alloy liquid droplets formed at high temperature, and then SiO_x nanowires precipitate from the supersaturated alloy droplets (Kwak et al., 2007). Usually droplets of catalyst are observed on the top of the nanostructures in a VLS based growth system, although the position of catalyst, at the tip or root of the nanostructure, depends on the interaction of catalyst nanoparticles and the substrate as reported by Sohn, Ok, Seong, and Lee (2007).

In the absence of obvious catalysis of Au in the growth procedure, such as in VO_2 assisted synthesis of silicon oxide nanostructures, it is possible for the nanostructures to be deposited on silicon substrate using VO_x as the catalyst. To further confirm this assumption, SEM observations on the vanadium oxide powder in the vicinity of the silicon substrates showed the growth of silicon oxide network structures directly from the VO_2 powder, indicating the catalytic effect of these powders (Fig. 6). This

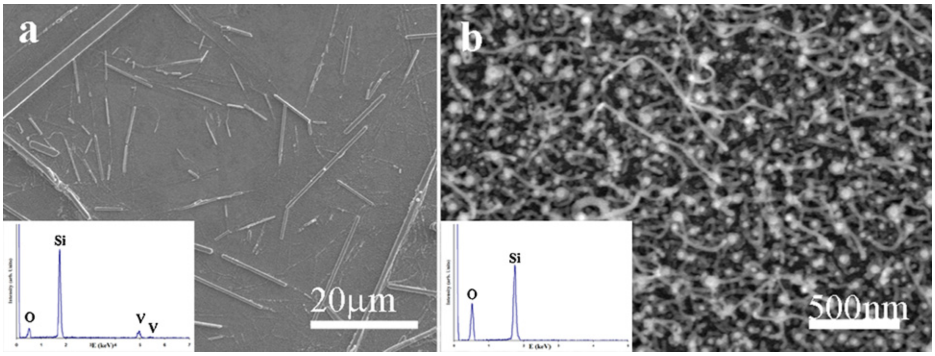

Fig. 3. SEM images showing the effect of hydrogen in the synthesis of silicon oxide nanowires. (a) Vanadium oxide structures synthesized by thermal annealing of silicon substrates in vicinity of VO_2 powder without the presence of H_2 in atmosphere. Inset shows EDX spectrum of nanowires deposited on silicon substrate. (b) SEM image of low density of silicon oxide nanowires synthesized on silicon substrate coated with gold without the use of H_2 gas. Inset shows EDX spectrum of nanostructures on the substrate.

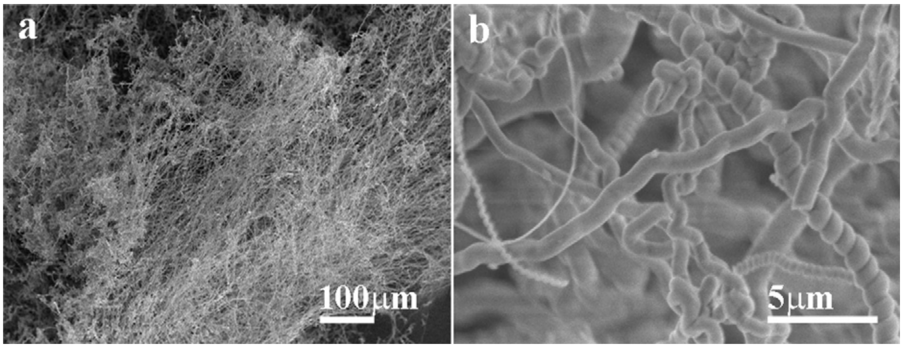

Fig. 4. SEM images of nanostructures synthesized on silicon substrate in the absence of any catalysts and H_2 at high temperatures (1200 °C).

Table 1
Effect of different parameters on the synthesis of SiO_2 nanostructures.

Temperature (°C)	Gas	Additives	Final morphology
950–1000	Ar/H_2	VO_2 powder	SiO_2 networked nanowires
950–1000	Ar/H_2	Au layer (3–5 nm)	SiO_2 nanowires
950–1000	Ar/H_2	VO_2 powder/Au	High density SiO_2 networked nanowires
950–1000	Ar	VO_2 powder	VO_x microrods
950–1000	Ar	Au layer (3–5 nm)	Non-uniform short SiO_2 nanowires
950–1000	Ar/H_2	–	None
1200	Ar/H_2	VO_2 powder	SiO_2 microfibers
1200	Ar/H_2	Au layer (3–5 nm)	SiO_2 microfibers
1200	Ar/H_2	–	SiO_2 microfibers

is similar to the results Yang et al. (2006) reported, in which VO_2 nanoparticle acted as the catalyst for the growth of silicon oxide nanowires. They proposed a VLS mechanism for the growth of silicon oxide nanowires which can be applied to the results in this study. Under the current experimental conditions, small fraction of VO_2 powder can be oxidized and evaporated and reduced to VO_x depositing as nanoparticles on the silicon substrate. These nanoparticles can then act as catalyst for the growth of silicon

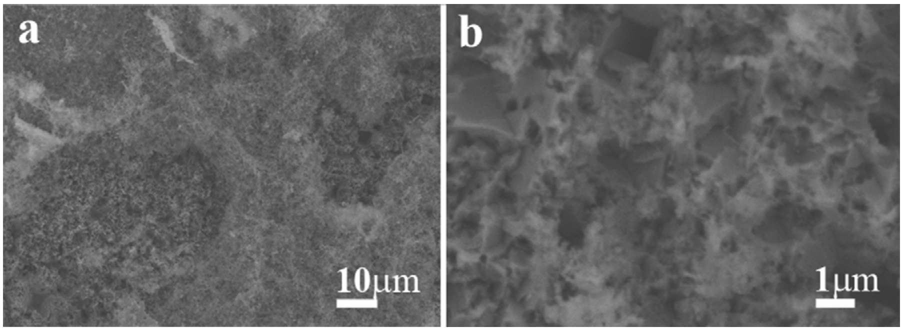

Fig. 5. SEM images of etched pits on the surface of silicon substrate formed via VO_2 powder under H_2 and Ar gas flow at 1000 °C for 2 h. These pits are formed due to evaporation of $SiO_{(g)}$ species under low oxygen partial pressure using VO_2 as catalyst for growth of SiO_x nanostructures.

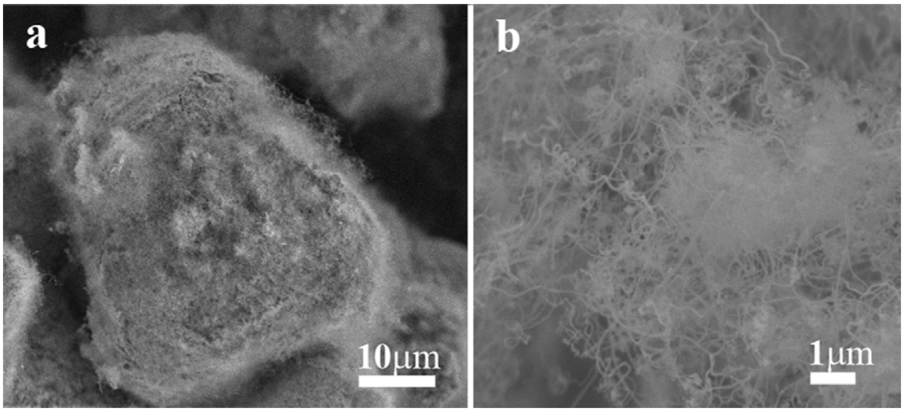

Fig. 6. SEM images of silicon oxide network nanostructures synthesized directly on VO_2 powder under H_2 and Ar gas flow at 1000 °C for 5 h.

oxide network structures. However, unlike the findings of Yang et al. (2006), no catalyst particles were found at the tip of silicon oxide network structures (Fig. 2). This can be explained by the base growth VLS mechanism similar to nanostructures synthesized by Au.

This growth mechanism can be further extended to the Au–VO_2 powder experimental conditions to explain the synthesis of enhanced networked silicon oxide nanostructures. Under these conditions, it is possible for VO_x to be deposited on silicon substrate with Au semisolid droplets. Au–Si alloy can be formed as in the previously reported growth of SiO_2 following the VLS mechanism. Each Au droplet can absorb several VO_x nanoparticles on its surface, consequently increasing the possibility of multiple silicon oxide nanowires growing from a single Au droplet. In addition, as reported in many studies, gold can absorb the $SiO_{(g)}$ in the atmosphere, thus further increasing the source of silicon oxide species for silicon oxide network nanostructure growth.

At higher temperatures (~1000 °C), the production of $SiO_{(g)}$ from the silicon substrate is easier, and similar to what was reported by Zhang et al. (2001), a VS growth mechanism can be proposed for the growth of silicon oxide nanostructures when no catalyst is introduced into the system. In this growth mechanism, silicon oxide nanostructures are synthesized by oxidation of the volatile silicon monoxide vapor. The difference between the diameter and density of nanostructures synthesized under the two different conditions can be related to the partial pressure of $SiO_{(g)}$ produced during synthesis.

To explain the helical structure of the network nanostructures (synthesized at low temperature) and nanowires (at high temperatures), three growth models, viz., contact angle anisotropy (CAA) (Kim et al., 2007; Zhang et al., 2008), screw dislocation driven (SCD) (Zhang et al., 2008) and polar surface driven (PSD) (Kong, Ding, Yang, & Wang, 2004; Zhang et al., 2008), have been proposed. The CAA model is based on the angle anisotropy between the catalyst nanoparticles and nanowires interface. In the present study, however, the catalyst nanoparticles (Au) were not seen at the top of the nanostructures. In the SCD model, the helical formation of nanostructures is proposed to originate from screw dislocations in the crystal lattice. Since the nanostructures synthesized here are amorphous, this model cannot be used to explain the growth mechanism. In this study, the PSD model seems to be the most logical model which is based on the presence of polar SiO_2 surfaces as reported by Zhang et al. (2008). Based on this model, the asymmetrical charge distribution on the nanowires surface can lead to the formation of amorphous SiO_2 helical nanostructures.

4. Conclusions

In summary, we have successfully synthesized networked silicon oxide nanowire with diameters of 30–100 nm by heating the silicon substrate with VO_2 powder at temperatures around 1000 °C. In addition, it was found that the mixture of VO_2 and gold as co-catalysts enhances the achievement of silicon oxide nanowires with network characteristics. Microscopic characterization indicates that VLS mechanism governs the synthesis of these nanowires at lower temperatures (<1000 °C), while VS mechanism dominates at a higher temperature (~1200 °C). Further, the presence of H_2 gas is important in elevating nanowire density at temperatures below 1000 °C, but at higher temperatures (~1200 °C), mixtures of microfibers and nanowires are synthesized without the use of any metal catalyst or H_2.

Acknowledgments

This research was supported by Natural Sciences and Engineering Research Council of Canada (NSERC), Canadian Space Agency, NSERC Canada Research Chair (CRC) Program, Canada Foundation for Innovation (CFI), Ontario Research Fund (ORF), Ontario Early Researcher Award (ERA) and the University of Western Ontario.

References

Chen, Y. J., Li, J. B., Han, Y. S., & Dai, J. H. (2002). Self assembly of Si and SiO_x nanostructures. *Journal of Materials Science Letters*, *21*(2), 175–177.

Choi, Y., Johnson, J. L., & Ural, A. (2009). Patterned growth of silicon oxide nanowires from iron ion implanted SiO_2 substrates. *Nanotechnology*, *20*, 135307.

Davis, S. A., Burkett, S. L., Mendelson, N. H., & Mann, S. (1997). Bacterial templating of ordered macrostructures in silica and silica surfactant mesophases. *Nature*, *385*, 420–423.

Engstrom, J. R., Bonser, D. J., Nelson, M. M., & Engel, T. (1991). The reaction of atomic oxygen with Si(1 0 0) and Si(1 1 1): 1. Oxide decomposition, active oxidation and the transition to passive oxidation. *Surface Science*, *256*(3), 317–343.

Grove, A. S., Leistiko, O., & Sah, C. T. (1964). Redistribution of acceptor and donor impurities during thermal oxidation of silicon. *Journal of Applied Physics*, *35*(9), 2695–2701.

Hu, J. Q., Jiang, Y., Meng, X. M., Lee, C. S., & Lee, S. T. (2003). A simple large-scale synthesis of very long aligned silica nanowires. *Chemical Physics Letters*, *367*, 339–343.

Huang, S. Y., Ostrikov, K., & Xu, S. (2008). Plasma-enabled growth of ultralong straight, helical and branched silica photonic nanowires. *Journal of Applied Physics*, *104*, 033301.

Kim, H. W, Shim, S. H., & Lee, J. W. (2007). Characteristics of SiO_x nanowires synthesized via the thermal heating of Cu coated Si substrates. *Physica E*, *37*, 163–167.

Kim, T. H., Shalav, A., & Elliman, R. G. (2010). Active oxidation of Si as the source of vapor phase reactants in the growth of SiO_x nanowires on Si. *Journal of Applied Physics*, *108*, 076102.

Kong, X. Y., Ding, Y., Yang, R., & Wang, Z. L. (2004). Single-crystal nanorings formed by epitaxial self coiling of polar nanobelts. *Science*, *303*(5662), 1348–1351.

Kwak, D. W., Cho, H. Y., & Yang, W.-C. (2007). Dimensional evolution of silicon nanowires synthesized by Au–Si island catalyzed chemical vapor deposition. *Physica E*, *37*, 153–157.

Lee, K. H., Lee, S. W., Vanfleet, R. R., & Sigmund, W. (2003). Amorphous silica nanowires grown by the vapor–solid mechanism. *Chemical Physics Letters*, *376*, 498–503.

Lee, K. H., Lofton, C., Kim, K., Seo, W. S., Lee, Y., Lee, M. H., et al. (2004). Photoluminescence from amorphous silica nanowires synthesized using TiN/Ni/SiO_2/Si and TiN/Ni/Si substrates. *Solid State Communications*, *131*, 687–692.

Liang, C. H., Zhang, L. D., Meng, G. W., Wang, Y. W., & Chu, Z. Q. (2000). Preparation and characterization of amorphous SiO_x nanowires. *Journal of Non-Crystal Solids*, *277*, 63–67.

Ni, Z.-F., Ying, P.-Z., Luo, Y., & Li, Z.-S. (2007). Preparation and characterization of amorphous silicon oxide nanowires. *Journal of China University of Mining & Technology*, *17*(4), 587–589.

Pan, Z., Dai, S., Beach, D. B., & Lowndes, D. H. (2003). Temperature dependence of morphologies of aligned silicon oxide nanowire assemblies catalyzed by molten gallium. *Nano Letters*, *3*, 1279–1284.

Park, H. K., Yang, B., Kim, S. W., Kim, G. H., Youn, D. H., Kim, S. H., et al. (2007). Formation of silicon oxide nanowires directly from Au/Si and Pd–Au/Si substrates. *Physica E*, *37*, 158–162.

Sekhar, P. K., Ramgir, N. S., Joshi, R. K., & Bhansali, S. (2008). Selective growth of silica nanowires using an Au catalyst for optical recognition of interleukin-10. *Nanotechnology*, *19*(24), 245502.

Shao, M., Hu, H., Ban, H., Li, M., & Gao, H. (2007). Fabrication of large scale, layer deposited low oxygen content and uniform silicon nanowires. *Journal of Crystal Growth*, *303*, 391–394.

Sohn, J. I, Ok, Y. W., Seong, T. Y., & Lee, S. (2007). Effect of different metal deposition methods on the growth behaviours of carbon nanotubes. *Journal of Applied Physics*, *102*(1), 14301.

Sun, S. H., Meng, G. W., Zhang, M. G., Hao, Y. F., Zhang, X. R., & Zhang, L. D. (2003). Microscopy study of the growth process and structural features of closely packed silica nanowires. *Journal of Physical Chemistry B*, *107*, 13029–13032.

Wang, C.-Y., Chan, L.-H., Xiao, D.-Q., Lin, T.-C., & Shih, H. C. (2006). Mechanism of solid liquid solid on the silicon oxide nanowire growth. *Journal of Vacuum Science and Technology B*, *24*(2), 613–617.

Xiao, Z., Zhang, L., Meng, G., Tian, X., Zeng, H., & Fang, M. (2006). High density, aligned SiO_2 nanowire arrays: Microscopic imaging of the unique growth style and their ultraviolet light emission properties. *Journal of Physical Chemistry B*, *110*(32), 15724–15728.

Xing, Y. J, Xi, Z. H., Yu, D. P., Hang, Q. L., Yan, H. F., Feng, S. Q., et al. (2002). Growth of silicon nanowires by heating Si substrate. *Chinese Physics Letters*, *19*(2), 240–242.

Xing, Y. J., Yu, D. P., Xi, Z. H., & Xue, Z. Q. (2003). Silicon nanowires grown from Au coated Si substrate. *Applied Physics A*, *76*, 551–553.

Xu, C. X., Sun, X. W., Yu, M. B., Xiong, Y. Z., Dong, Z. L., & Chen, J. S. (2004). Magnetic nanobraids of iron-doped amorphous silica. *Applied Physics Letters*, *85*(22), 5364–5366.

Yan, H. F., Xing, Y. J., Hang, Q. L., Yu, D. P., Wang, Y. P., Xu, J., et al. (2000). Growth of amorphous silicon nanowires via a solid–liquid–solid mechanism. *Chemical Physics Letters*, *323*, 224–228.

Yang, Y., Tay, B. K., Sun, X. W., Fan, H. M., & Shen, Z. X. (2006). Photoluminescence and growth mechanism of amorphous silica nanowires by vapor phase transport. *Physica E*, *31*, 218–223.

Zhang, J., Jiang, F., Yang, Y., & Li, J. (2007). Molten Pb as a catalyst for large-scale growth of highly aligned silicon oxide nanowires. *Journal of Crystal Growth*, *307*, 76–81.

Zhang, M., Bando, Y., Wada, K., & Kurashima, K. (1999). Synthesis of nanotubes and nanowires of silicon oxide. *Journal of Materials Science Letters*, *18*, 1911–1913.

Zhang, Y., Wang, N., He, R., Liu, J., Zhang, X., & Zhu, J. (2001). A simple method to synthesize Si_3N_4 and SiO_2 nanowires from Si or Si/SiO_2 mixture. *Journal of Crystal Growth*, *233*, 803–808.

Zhang, Z. Y., Wu, X. L., Xu, L. L., Shen, J. C., Siu, G. G., & Chu, P. K. (2008). Synthesis, growth mechanism and light emission properties of twisted SiO_2 nanobelts and nanosprings. *Journal of Chemical Physics*, *129*, 164702.

Zhu, Y. Q, Hu, W. B., Hsu, W. K., Torrones, M., Grobert, N., Karali, T., et al. (1999). A simple route to silicon-based nanostructures. *Advanced Materials*, *11*, 844–847.