One-dimensional polycrystalline Ta₂O₅ nanostructures are synthesized by the annealing of SiO₂ nanowires at 950°C in a reductive Ta vapor ambiance. The formation mechanism of Ta₂O₅ nanostructures is discussed and illustrated in detail. The nucleation and grain growth of Ta₂O₅ crystals were investigated during the formation of the SiO₂/Ta₂O₅ core-shelled structures. The diffusion-controlled growth is suggested to be the rate-determining step for the diffusion of the Ta atoms through the ash layer to react with O atoms and substitute Si atoms.

1. Introduction

One-dimensional nanomaterials such as nanowires, nanorods, nanobelts, and nanotubes are much attractive owing to their unique optical, electronic, and mechanical properties [1–5]. Among them, the metal oxides so-called functional materials, such as MgO [6], ZnO [7], SnO₂ [8], In₂O₃ [9], Ga₂O₃ [10], WO₃ [11], and Ta₂O₅ [12], are aimed to be extensively studied. The growth methods, including vapor-solid growth (VS) [7], vapor-liquid-solid growth (VLS) [13], oxide-assisted growth (OAG) [14], solution-based growth [15], solution-liquid-solid growth (SLS) [16], and template-assisted growth [17], have been adopted and reported to synthesize these one-dimensional nanostructures. Beyond synthesis, these kinds of materials are applied in electronic devices like field effect transistor [18–20].

So far, tantalum pentoxide (Ta₂O₅) has been a hot subject both in the industry and the academic world. It is the best candidate for the dielectric materials used in the next generation dynamic random access memory (DRAM) due to its high dielectric constant. In addition, the Ta₂O₅ applied to optical waveguide [21], antireflective coating layer [22], anticorrosion layer [23], chemical or biological sensitive layer [24, 25], and photocatalyst [26] possesses high refractive index, high chemical stability, and high temperature piezoelectric property. In Ta-O system, the Ta₂O₅ can be categorized into two equilibrium phases, including α-Ta₂O₅ at high temperature and β-Ta₂O₅ at low temperature, respectively. Besides, Fukumoto and Miwa claimed that hexagonal δ-Ta₂O₅ may exist through the first principle ultrasoft pseudopotential calculation [27]. Even if the amorphous and polycrystalline Ta₂O₅ thin films have been widely studied and synthesized, nevertheless, its one-dimensional nanostructures are still lacking in reports.

In this letter, we demonstrate how to fabricate the Ta₂O₅/SiO₂ core-shelled structures and the Ta₂O₅ NWs as well as the Ta₂O₅ nanotube via the annealing of SiO₂ NWs in a Ta reductive ambiance. The main idea is based on the lower heat formation of Ta₂O₅, which can be formed by the oxidation of Ta and the reduction of SiO₂ at the same time. The growth mechanism of SiO₂/Ta₂O₅ core-shelled structures was constructed and investigated. On the other hand, we first illustrated the electronic structure of Ta₂O₅/SiO₂ core-shelled nanowire by using the electron energy loss spectroscopy (EELS). A couple of sequential experiments under different annealing conditions were performed to realize the growth mechanisms.

2. Experiments

The single crystal (100) Si (1–30 Ω-cm) wafers were cleaned by the standard RCA procedures. The Si substrate capped by
a 2 nm thick Au layer deposited at a pressure of $5 \times 10^{-6}$ Torr with a deposition rate of 0.01 nm/sec was annealed in a horizontal furnace at 1150°C for 2 hours in a N$_2$ ambient to grow SiO$_2$ nanowires. The SiO$_2$ nanowires produced by our approach were transferred into a Ta filament heating chamber where the Ta atoms were constantly vaporized as the supplementary source for annealing at a pressure $< 1 \times 10^{-6}$ Torr at 950°C for 1–32 hours. The core-shelled structures of SiO$_2$ nanowires surrounded by a Ta$_2$O$_5$ layer could be synthesized. In addition, the Ta$_2$O$_5$ nanotube could be formed by dipping the Ta$_2$O$_5$/SiO$_2$ core-shelled nanowires in diluted HF solution (HF: H$_2$O = 1:50) to remove the inner SiO$_2$ nanowire. The wide angle X-ray diffraction spectrometer (Shimadzu) and the grazing incidence X-ray diffraction spectrometer (GIXRD, MAC) with a fixed incident angle of 0.5° were used to identify the phases of the nanowires. Field-emission transmission electron microscope (JEM-3000F, operated at 300 kV with point-to-point resolution of 0.17 nm) equipped with an energy dispersion spectrometer (EDS) was used to obtain the information of the nanostructures and the chemical compositions. The surface morphology examined by a field-emission scanning electron microscope (JSM-6500F) was operated at 15 kV. In TEM, the electronic structure of a single NW can be investigated by EELS. The electronic structure in the valence band can be qualitatively identified from the fine structures in the ionization edges. All of the raw EELS spectra were calibrated in the relative energy position by zero-loss peak and then subtracted by power law to remove the background signal generated by plural-scattering events. After recalibration of energy positions and removal of multiple scattering effects, EELS spectra were deconvoluted by the plasma and the low loss spectra by Fourier-log method to obtain the true single-scattering spectrum.

3. Results and Discussion

Figure I(a) shows the SEM image of SiO$_2$ NWs synthesized by annealing the Au thin layer at 1150°C for 2 hours in a N$_2$ ambience. The SiO$_2$ NWs with diameter of about 200 nm are uniformly distributed over all the substrate. However, we can obviously find out that all the SiO$_2$ NWs are almost wrinkled and tangled together. After annealing in a Ta reductive ambience for 4 hours, the morphology is still identical, as shown in Figure I(b). The corresponding TEM image is shown in Figure I(c) where the selected area diffraction (SAD) is identified and shown in the inset. This SAD analysis unambiguously gives us an evidence of the SiO$_2$ NWs surrounded by Ta$_2$O$_5$ uniformly. Moreover, the morphology of Ta$_2$O$_5$/SiO$_2$ core-shelled structures can be alternated by tuning the morphology of SiO$_2$ NWs. For the
present case, the SiO₂ NWs formed by annealing the Au thin layer at high temperature in a N₂ ambiance are almost tangled together so that the core-shelled structures mostly form multijunctions with 9~11 nm thickness of the Ta₂O₅ shell after annealing in a Ta reductive ambiance. Furthermore, the Ta₂O₅ nanotubes can be formed after dipping the sample into the dilute HF solution. An example is shown in Figure 1(d) and the magnified SEM image is also shown in the inset.

The EELS spectrum can give us the information of chemical bonding and relative electron configuration. Figure 2(a) reveals the Ta₂O₅/SiO₂ core-shelled structures formed by annealing the SiO₂ NWs in a Ta ambiance for 8 hours and the corresponding high resolution TEM image taken from a rectangular area marked as 1 in Figure 2(a) is shown in Figure 2(b). The interplanar distances of 0.3 and 0.34 nm, which are consistent with planes of (110) and (101), are indexed. Figure 2(c) shows the three different EELS spectra of oxygen K-edge energy loss near edge fine structure (ELNES) recorded from a and b positions of (a) and the as-synthesized SiO₂ NWs. (d), (e) Other EELS spectra of the Ta₂O₅ shell.

Figure 2: (a) A TEM image of the Ta₂O₅/SiO₂ core-shelled structures formed by annealing the Si NWs in a Ta ambient for 8 hours. (b) The corresponding HRTEM image taken from the rectangular area marked as 1 of (a). (c) The EELS spectra of oxygen K-edge ELNES recorded from a and b positions of (a) and the as-synthesized SiO₂ NWs. (d), (e) Other EELS spectra of the Ta₂O₅ shell.
from the position b in Figure 2(a), as shown in the upper part of Figure 2(c), is different from the results of position a. In order to make a comparison, the as-synthesized oxygen K-edge ELNES of SiO$_2$ NWs was acquired as shown in the middle of the Figure 2(c). Obviously, it suggests that the oxygen K-edge ELNES recorded from the position b in Figure 2(c) is superimposed by that of SiO$_2$ and Ta$_2$O$_5$, revealing that the inner is a SiO$_2$ nanowire surrounded by a uniform coating of Ta$_2$O$_5$ shell. Other EELS spectra of the shell shown in Figures 2(d) and 2(e) provide electronic structure of Ta$_2$O$_5$ as well. The peaks located at around 2200 eV and 1800 eV correspond to the Ta 3p$^{3/2}$ and Ta 3d$^{3/2}$, respectively. The peaks of Ta 4s and Ta 5p orbits are also exhibited in the spectrum. Besides, the Si K-edge signal comes from the SiO$_2$ core.

The heat of formation for transition metal oxides such as HfO$_2$, TiO$_2$, and Ta$_2$O$_5$ is lower than that of SiO$_2$ [29], resulting in the reduction of SiO$_2$ at high annealing temperatures. Oppositely, the reduction of SiO$_2$ is prohibited if the heat of formation for transition metal oxides is higher than that of SiO$_2$. The formation of Ta$_2$O$_5$ phase is accomplished by the Ta vapor to react with SiO$_2$ and the oxidation-reduction reaction is given by

$$4\text{Ta} + 5\text{SiO}_2 \rightarrow 2\text{Ta}_2\text{O}_5 + 5\text{Si}. \quad (1)$$

According to the thermodynamic calculation, the equilibrium phases of Ta-SiO$_2$ system are Ta$_2$O$_5$ and Ta$_2$Si in the temperature range from 700 to 1300°C [30]. In our case, the Ta$_2$Si phase was not formed inside the Ta$_2$O$_5$ nanowires examined by the XRD spectra and the TEM diffraction pattern. This result might be attributed to the activation energy for the nucleation of the Ta$_2$Si phase [31] in the reaction of Ta-Si system, for which Ta atoms are difficult to react with Si atoms at the annealing temperature below 1100°C. Therefore, in our process, the annealing temperature of 950°C would not be high enough for the nucleation of Ta$_2$Si.

The polycrystalline feature is suggested to be caused by two probable mechanisms: the segregation of Si via the grain boundaries of Ta$_2$O$_5$ nanowires and the anisotropic reduction along the SiO$_2$ nanowires. The dislocations, which may be caused by the Si atoms in the substitutional or interstitial sites of the sublattice of Ta$_2$O$_5$, can be found inside the grain of Ta$_2$O$_5$. The sequential formation mechanisms of the polycrystalline Ta$_2$O$_5$ nanowires via reduction of SiO$_2$ nanowires in the Ta vapor ambient are illustrated in Figures 3(a) to 3(c). The Ta$_2$O$_5$ nanocrystals first nucleated via reducing amorphous outer layer of the SiO$_2$ nanowires by Ta atoms. The Ta$_2$O$_5$ grain growth is through growth of the smaller grains to reduce the grain boundary energy during the continuous shrinking process of the inner SiO$_2$ nanowires; consequently, the polycrystalline Ta$_2$O$_5$ outer shells and Ta$_2$O$_5$/SiO$_2$ core-shelled structures were obtained. As the shrinking process proceeded, the pearl-like string of the polycrystalline Ta$_2$O$_5$ nanowires is the final form of the feature.

Figure 4(a) illustrates the TEM image of Ta$_2$O$_5$/SiO$_2$ core-shell nanowire whose granular morphology of the surface exhibits the sizes of the nanocrystals below 3 nm after annealing for 30 minutes. Figures 4(b) and 4(d) reveal the amorphous-like regions between Ta$_2$O$_5$ grains taken from the magnified image of rectangular area in Figure 4(a), respectively. Autocorrelation function (ACF) analysis was used to study the amorphous-like region for realizing whether it is a purely amorphous structure or not. Figures 4(c) and 4(e) illustrate the ACF analytical results, which make a comparison of the square areas of numbers (1) to (25), respectively. The ACF data in Figure 4(c) indicates that fine Ta$_2$O$_5$ grains exist in the outer periphery areas of the nanowire and the core region of the nanowire still retains amorphous structure. The lattice fringes shown in Figure 4(e) are
clearly observed in the ACF results, which reveal that the crystal structure in this area should be purely amorphous or very short-range order. The ACF results strongly suggest that there are fine grains in the amorphous-like region and their phases are identified to be $\text{Ta}_2\text{O}_5$ by verifying the spacing and angle of plane. The data also indicates that the nearby fine grains tend to orientate in the same direction for reducing the total free energy. The grain growth proceeds via an agglomeration mechanism during the annealing process.

Figures 5(a) to 5(e) show TEM images of the $\text{SiO}_2$/Ta$_2$O$_5$ core-shelled nanowire formed by annealing the $\text{SiO}_2$ nanowire in the Ta ambient for 1, 2, 4, 8, and 16 hr, respectively. The TEM images indicate that the thickness of Ta$_2$O$_5$ shell layer increases and the diameter of SiO$_2$ core decreases simultaneously with the annealing time. The number of Ta$_2$O$_5$ grains decreases while the size increases during the annealing process. This phenomenon also indicates occurrence of agglomeration process during the grain growth. Figure 5(f) shows the relationship between the thickness of Ta$_2$O$_5$ shell layer and the annealing time at 950°C. The thickness of Ta$_2$O$_5$ shell layer increases since the Ta atoms diffuse through the shell layer and then reduce SiO$_2$ core layer. The growth rate of Ta$_2$O$_5$ shell layer could be dominated by either diffusion or reaction mechanism. As shown in Figure 5(f), the growth rate of Ta$_2$O$_5$ shell layer decreases with the annealing time, suggesting that the diffusion through the shell layer would dominate the reduction process. Szekely and Themelis proposed a cylinder [32] growth model, which considers the reaction of a cylinder material B reduced by another material A to form products as given by

$$A + bB \rightarrow \text{products}$$

(2)
Figure 5: (a) to (e) TEM images of Ta$_2$O$_5$/SiO$_2$ core-shelled nanowire formed under different annealing time of 1, 2, 4, 8, and 16 hours, respectively. (f) The annealing time as the function of the thickness of Ta$_2$O$_5$ shell layer. (g) The annealing time as the function of $X_B + (1 - X_B) \ln(1 - X_B)$, from (3), with the corresponding fitting line.

\[
\frac{t}{\tau} = X_B + (1 - X_B) \ln(1 - X_B) 
\]  

\[
\tau = \frac{\rho_B R^2}{6b D_e C_{Ag}} 
\]  

\[
X_B = 1 - \left(\frac{r_c}{R}\right)^2, 
\]  

where $t$ is the reaction time, $\tau$ is the complete reaction time, $X_B$ is the mole fraction of $B$ cylinder, $\rho_B$ is the molar density of $B$ cylinder, $R$ is the cylinder radius, $b$ is the equilibrium constant of reaction, $D_e$ is the effective diffusion coefficient of gaseous reactant in the ash layer, $C_{Ag}$ is the concentration of $A$ vapor at cylinder surface, and $r_c$ is the radius of unreacted core, respectively. By applying the growth model, the diameters of SiO$_2$ nanowires are assumed to be 60 nm and the Ta vapor pressure source is a constant. The corresponding relationship between the value of $X_B + (1 + X_B) \ln(1 - X_B)$ and the annealing time by fitting our experimental data is shown in Figure 5(g). The complete reaction time computed from the fitting line is about 30 hours, which quite matches with the 32 hours for annealing of our experiments.

So far, we can confirm that the growth of the Ta$_2$O$_5$/SiO$_2$ core-shelled nanowires is controlled by diffusion through the ash layer. But the problem, whether Ta atoms or Si atoms are the most effective diffusion species during the reduction process, still needs to be answered. It suggested that the diffusion velocity of Si atoms should be larger than that of Ta atoms. The gradient of the Si concentration between the shell layer and the core causes the higher driving force for diffusion of the Si atoms out of the ash layer. Also, the atomic radius of the Ta (146 pm) is larger than that of the Si (117.6 pm); furthermore, the difference of the electronegativity between the Ta (1.5) and O (3.44) is higher than that of the Si (1.9) and O (3.44). This suggests that the diffusion of the Ta atoms through the Ta$_2$O$_5$ shell layer should be more difficult than that of the Si atoms. Consequently, the diffusion of the Ta atoms should be the rate-determining step of the diffusion-controlled growth.

4. Conclusions

Polycrystalline Ta$_2$O$_5$ nanostructures including nanowires, nanotubes, and SiO$_2$/Ta$_2$O$_5$ core-shelled nanowires were successfully synthesized via annealing of the SiO$_2$ nanowires at 950°C in a reductive Ta vapor ambiance. The Ta$_2$O$_5$ phase was formed from SiO$_2$ template reduced by Ta and the formation mechanism of Ta$_2$O$_5$ nanostructures was discussed.
The sequential investigations of the nucleation and grain growth of the Ta$_2$O$_5$ crystals were monitored by the HRTEM during the formation of the SiO$_2$/Ta$_2$O$_5$ core-shell structures. The diffusion-controlled growth is suggested to be the rate-determining step for the diffusion of the Ta atoms through the ash layer to react with the oxygen atoms and replace the Si atoms. This novel synthesis method may provide the solution to produce other functional metal oxides nanostructures for the future applications.

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

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