

RUTILE TITANIUM DIOXIDE NANOPARTICLES AND ORDERED ACICULAR AGGREGATES OF SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Application No. 13/841,666, filed March 15, 2013, the entire contents of which are hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to a novel chemical structure comprising rutile titanium dioxide (TiO_2) nanoparticles, and, more particularly, to ordered acicular aggregates of elongated TiO_2 crystallites which resemble nano-sized flower bouquets and/or triangular funnels.

[0003] Titanium dioxide (TiO_2) is known as a typical solid compound having photocatalytic activity and having utility in electronic, photovoltaic and photonic applications. Rutile and anatase crystal forms are known as major crystal forms of TiO_2 which display higher chemical stability and larger refractive indices than those of amorphous TiO_2 . It has also been recognized that TiO_2 particles having a high degree of crystallinity can exhibit a desirable level of photocatalytic activity.

[0004] U.S. Patent Publication No. 2012/0132515, for example, describes rutile TiO_2 nanoparticles wherein each has an exposed crystal face, making the nanoparticles useful as a photocatalyst and oxidation catalyst. The TiO_2 nanoparticles are produced by subjecting a titanium compound to a hydrothermal treatment in an aqueous medium in the presence of a hydrophilic polymer, which is polyvinylpyrrolidone. The titanium compound, when hydrothermally treated in an aqueous medium, generally gives a rod-like crystal of rutile titanium dioxide having (110) and (111) faces. However, when hydrothermally treated in an aqueous medium in the presence of polyvinylpyrrolidone, the rod-like crystal which results exhibits a novel exposed crystal face (001). It is noted that the hydrophilic polymer acts as a steric stabilizer or capping agent to thereby prevent aggregation of the rod-like crystals of rutile titanium dioxide.

[0005] The need exists for improved methods for producing novel types of rutile titanium dioxide (TiO_2) nanoparticles which have high surface areas, e.g., in the range of from $120 \text{ m}^2/\text{g}$ to $160 \text{ m}^2/\text{g}$, and high refractive indices for improved UV blocking capability and which demonstrate high performance levels in catalysis, e.g., biomass conversion, and in electronic applications, such as lithium ion batteries and fuel cells.

SUMMARY OF THE INVENTION

[0006] The described and claimed inventive concepts(s) comprise in one embodiment a method for preparing a novel form of rutile TiO_2 nanoparticles which are ordered acicular aggregates of elongated TiO_2 crystallites. The elongated TiO_2 crystallites are rod-like, e.g., slender and/or needle-like, having a thickness of from 3 nm to 5 nm and a length which can vary from 20 nm up to 50 nm, although longer and shorter lengths may also be present. However, the elongated TiO_2 crystallites assemble together during the process in a manner which results in ordered acicular aggregates that resemble nano-sized flower bouquets or triangular funnels. The largest dimension of the funnel-shaped nano-particles is about 100 nm.

[0007] The method comprises:

- (a) forming an aqueous solution of a soluble titanium compound at a titanium concentration of from 0.1 to 1.5 moles per liter, although a concentration range of from 0.5 to 1.0 moles per liter is preferred, optionally in the presence of a mineral acid;
- (b) introducing a morphology controlling agent, or a mixture thereof, selected from an α -hydroxy carboxylic acid of the formula R-CH(OH)COOH , an α -hydroxy carboxamide of the formula R-CH(OH)CONH_2 , or an α -amino acid of the formula $\text{R-CH(NH}_2\text{)COOH}$, wherein R is an alkane, alkene, alkyne, arene, or cycloalkane group having 6 or more carbon atoms, into the solution at an acid- or carboxamide-to-titanium molar ratio of from 0.02 to 0.2 while simultaneously heating the solution to a temperature in the range of from 60°C to 80°C with constant stirring;
- (d) introducing TiO_2 seeds into the stirred solution at a seed-to- TiO_2 molar ratio of from 0.0005 to 0.0015 and maintaining the stirred solution at a temperature in the range of from 60°C to 80°C for a period of from one to 3 hours;

- (e) elevating the temperature of the stirred solution to a value of from 100°C to the refluxing temperature and maintaining said temperature for a period of from 2 hours to 4 hours to form a reaction product;
- (f) cooling the reaction mixture from step (e) to room or ambient temperature;
- (g) optionally neutralizing the reaction mixture; and
- (h) separating and drying the reaction product.

[0008] The reaction product can then be calcined. Calcining, which can be adjusted over a wide range for time and temperature, operates to enhance the properties of the resulting nanoparticles by expanding or opening the pore structure and/or increasing the refractive index.

[0009] Soluble titanium compounds useful according to the described method include, but are not limited to, titanium oxychloride (TiOCl_2), titanium oxybromide (TiOBr_2), titanium oxyiodide (TiOI_2), titanium oxynitrate ($\text{TiO}(\text{NO}_3)_2$), titanium trichloride (TiCl_3), titanium tribromide (TiBr_3), titanium oxalate ($\text{Ti}_2(\text{C}_2\text{O}_4)_3$), potassium hexafluorotitanate (K_2TiF_6), ammonium hexafluorotitanate ($(\text{NH}_4)_2\text{TiF}_6$), potassium titanyloxolate ($\text{K}_2\text{TiO}(\text{C}_2\text{O}_4)_2$), ammonium titanyloxolate ($(\text{NH}_4)_2\text{TiO}(\text{C}_2\text{O}_4)_2$), titanium bis(ammonium lactate) dihydroxide ($[\text{CH}_3\text{CH}(\text{O})\text{COONH}_4]_2\text{Ti}(\text{OH})_2$), and mixtures thereof.

[0010] Morphology controlling agents as described above with R groups having 6 or more carbon atoms include, but are not limited to, mandelic acid ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{COOH}$), 4-hydroxymandelic acid ($\text{C}_6\text{H}_4(\text{OH})\text{CH}(\text{OH})\text{COOH}$), benzilic acid ($(\text{C}_6\text{H}_5)_2\text{C}(\text{OH})\text{COOH}$), 2-hydroxy-4-phenylbutyric acid ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}_2\text{CH}(\text{OH})\text{COOH}$), 2-hydroxy-2-phenylpropionic acid ($(\text{C}_6\text{H}_5)(\text{CH}_3)\text{C}(\text{OH})\text{COOH}$), 2-hydroxyoctanoic acid ($\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}(\text{OH})\text{COOH}$), mandelamide ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{CONH}_2$), phenylalanine ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$), tyrosine ($\text{C}_6\text{H}_4(\text{OH})\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$), and combinations and mixtures thereof. In addition, ammonium (NH_4^+), sodium (Na^+) and potassium (K^+) salts of the above-listed α -hydroxy carboxylic acids ($\text{R}-\text{CH}(\text{OH})\text{COOH}$) may also be used with satisfactory results.

[0011] The described and claimed inventive concepts(s) embrace, in a second embodiment, novel rutile TiO_2 nanoparticles which are produced by the described method. The rutile TiO_2 nanoparticles, i.e., the reaction product, are ordered acicular aggregates of elongated, i.e., rod-like, TiO_2 crystallites. The individual crystallites have a thickness in the range of from 3 nm to 5 nm, and one end of each of the rod-

like crystallites are joined, i.e., assembled, into a cluster such that the opposite ends of each of the crystallites extend, or fan, outwardly in the general shape of a nano-sized flower bouquet or a funnel. The funnel-shaped structures have a diameter in the range of 50 nm and a height in the range of from 50 nm to 100 nm.

[0012] Novel rutile TiO_2 nanoparticles obtainable according to the inventive concept(s) described and claimed herein can be deployed in a wide variety of applications, including, but not limited to, UV blocking, catalysis, photocatalysis, and in electronic, photovoltaic and photonic applications.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Fig. 1 is an SEM (Scanning Electron Microscopy) image of funnel-shaped rutile TiO_2 nanoparticles according to the invention.

[0014] Fig. 2 is an enlarged SEM image which illustrates in more detail ordered acicular aggregates of elongated TiO_2 crystallites according to the invention.

[0015] Fig. 3 is a TEM (Transmission Electron Microscopy) image of funnel-shaped rutile TiO_2 nanoparticles according to the invention.

[0016] Fig. 4 is an enlarged TEM image of funnel-shaped rutile TiO_2 nanoparticles according to the invention.

[0017] Fig. 5 is an X-ray diffraction (XRD) pattern of the funnel-shaped rutile TiO_2 nanoparticles produced according to Example 1 and shown in Fig. 1.

[0018] Fig. 6 is an SEM image of the shaped rutile TiO_2 nanoparticles shown in Fig. 1 after calcining at 550°C for 6 hours.

[0019] Fig. 7 is an enlarged SEM image of the shaped rutile TiO_2 nanoparticles shown in Fig. 6.

[0020] Fig. 8 is an X-ray diffraction (XRD) pattern of the calcined rutile TiO_2 nanoparticles shown in Fig. 6 which confirms that the rutile phase is present.

DETAILED DESCRIPTION OF THE INVENTION

[0021] The novel rutile TiO_2 nanoparticles, meaning the ordered acicular aggregates, are prepared by thermally hydrolyzing a soluble TiO_2 precursor compound, or a mixture of such compounds, in aqueous solution in the presence of a morphology controlling agent, or a mixture of morphology controlling agents, under specific conditions. The term “acicular” as used herein refers to a crystal habit

composed of a radiating mass of slender, needle-like crystals, and the term "novel rutile TiO₂ nanoparticles" as used herein is intended to mean the ordered acicular aggregates of the needle-like TiO₂ crystallites.

[0022] The process is a wet chemical hydrolysis method in which the structure of the ordered acicular aggregates is controlled using a morphology controlling agent selected from (i) an α -hydroxy carboxylic acid of the formula R-CH(OH)COOH, (ii) an α -hydroxy carboxamide of the formula R-CH(OH)CONH₂, or (iii) an α -amino acid of the formula R-CH(NH₂)COOH, wherein R is an alkane, alkene, alkyne, arene, or cycloalkane group having 6 or more carbon atoms.

[0023] The process begins by forming an aqueous solution of a soluble titanium compound at a titanium concentration of from 0.1 to 1.5 moles per liter, but preferably 0.5 to 1.0 moles per liter, optionally in the presence of a mineral acid. Distilled or deionized water can be used to form the aqueous solution, and a mineral acid, e.g., hydrochloric acid (HCl), can be introduced as needed for controlling the rate of hydrolysis.

[0024] The morphology controlling agent, or a mixture thereof, is introduced into the solution at an acid- or carboxamide-to-titanium molar ratio of from 0.02 to 0.4, although best results have been observed when the ratio is from 0.02 to 0.2. The solution is simultaneously heated to a temperature in the range of from 60°C to 80°C with constant stirring. Thereafter, TiO₂ seeds are introduced into the stirred solution at a seed-to-TiO₂ molar ratio of from 0.0005 to 0.0015, and the stirred solution is maintained at a temperature in the range of from 60°C to 80°C for a period of from one to 3 hours. The TiO₂ seeds can conveniently comprise a slurry of TiO₂ in the anatase phase (available from Millennium Inorganic Chemicals), but other TiO₂ nucleating agents can also be used with satisfactory results.

[0025] The temperature of the stirred solution is next elevated to a value of from 100°C to the refluxing temperature and maintained at that level for a period of from 2 hours to 4 hours during which time a reaction product is formed. The solution, i.e., reaction mixture which results, is then cooled to room or ambient temperature, and, optionally, it can be neutralized, e.g., pH of from 5 to 8, with introduction of a base, such as an ammonia solution or a sodium hydroxide solution. The reaction product is then separated by filtration and washed with deionized water to remove salts generated during hydrolysis. The resulting filter cake can be dried in an oven or re-slurried with water and spray dried.

[0026] As noted above, the reaction product can then be calcined as desired over a wide range of time and temperature to enhance the properties of the resulting nanoparticles, such as by expanding or opening the pore structure and/or increasing the refractive index.

[0027] For best results the soluble titanium precursor compound is selected from titanium oxychloride (TiOCl_2), titanium oxybromide (TiOBr_2), titanium oxyiodide (TiOI_2), titanium oxynitrate ($\text{TiO}(\text{NO}_3)_2$), titanium trichloride (TiCl_3), titanium tribromide (TiBr_3), titanium oxalate ($\text{Ti}_2(\text{C}_2\text{O}_4)_3$), potassium hexafluorotitanate (K_2TiF_6), ammonium hexafluorotitanate ($(\text{NH}_4)_2\text{TiF}_6$), potassium titanyloxolate ($\text{K}_2\text{TiO}(\text{C}_2\text{O}_4)_2$), ammonium titanyloxolate ($(\text{NH}_4)_2\text{TiO}(\text{C}_2\text{O}_4)_2$), and titanium bis(ammonium lactate) dihydroxide ($[\text{CH}_3\text{CH}(\text{O})\text{COONH}_4]_2\text{Ti}(\text{OH})_2$). Other commercially available soluble titanium precursor compounds can be deployed in the process and produce satisfactory results and, although not specifically named herein, they are embraced within the described and claimed inventive concept(s).

[0028] As noted above, morphology controlling agents, or mixtures thereof, for carrying out the inventive concept(s) include (i) α -hydroxy carboxylic acids of the formula $\text{R-CH}(\text{OH})\text{COOH}$, (ii) α -hydroxy carboxamides of the formula $\text{R-CH}(\text{OH})\text{CONH}_2$, and (iii) α -amino acids of the formula $\text{R-CH}(\text{NH}_2)\text{COOH}$, wherein R is an alkane, alkene, alkyne, arene, or cycloalkane group having 6 or more carbon atoms. Examples of such morphology controlling agents include, but are not limited to, mandelic acid ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{COOH}$); 4-hydroxymandelic acid ($\text{C}_6\text{H}_4(\text{OH})\text{CH}(\text{OH})\text{COOH}$); benzilic acid ($(\text{C}_6\text{H}_5)_2\text{C}(\text{OH})\text{COOH}$); 2-hydroxy-4-phenylbutyric acid ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}_2\text{CH}(\text{OH})\text{COOH}$); 2-hydroxy-2-phenylpropionic acid ($(\text{C}_6\text{H}_5)(\text{CH}_3)\text{C}(\text{OH})\text{COOH}$); 2-hydroxyoctanoic acid ($\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}(\text{OH})\text{COOH}$); mandelamide ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{CONH}_2$); phenylalanine ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$); and tyrosine ($\text{C}_6\text{H}_4(\text{OH})\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$). In addition, the ammonium (NH_4^+), sodium (Na^+) and potassium (K^+) salts of such acids and carboxamides can also be used.

[0029] In a preferred embodiment of the invention, the morphology controlling agent is mandelic acid ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{COOH}$), and the soluble titanium compound is titanium oxychloride (TiOCl_2).

[0030] The process of the invention produces novel rutile TiO_2 nanoparticles, i.e., the reaction product comprises ordered acicular aggregates of elongated, i.e., rod-like, TiO_2 crystallites. The individual crystallites have a thickness in the range of

from 3 nm to 5 nm, and one end of each of the rod-like crystallites are joined, i.e., assembled, into a cluster such that the opposite ends of each of the crystallites extend, or fan, outwardly in the general shape of a nano-sized flower bouquet or a funnel. The funnel-shaped structures have a diameter in the range of 50 nm and a height in the range of from 50 nm to 100 nm. The rutile TiO₂ nanoparticles in powder form show a desirably high specific surface area and pore volume. It is preferred that specific surface area be in the range from 120 m²/g to 160 m²/g and that pore volume be in the range from 0.3 cm³/g to 0.5 cm³/g or higher.

EXAMPLES

[0031] The present invention will be illustrated in further detail with reference to the working examples which follow and Figs. 1-8. It should be noted, however, that these examples should not be construed to limit the scope of the described and claimed inventive concept(s).

Example 1 - Preparation of funnel-shaped nanoparticles using carboxylic acids

[0032] 1,255 g of deionized water, 9.5 g of mandelic acid (from Alfa Aesar), 97 g HCl solution (37% from Fisher Scientific), and 397g of titanium oxychloride solution (25.2% in TiO₂, from Millennium Inorganic Chemicals) were mixed together in a heated reactor equipped with a glass condenser and an overhead stirrer. While being constantly stirred, the mixture was heated to 65°C. A TiO₂ seed slurry containing 0.2g TiO₂ in anatase phase (from Millennium Inorganic Chemicals) was added, and the hydrolysis reaction was maintained at 65°C for 2 hours. During this period, TiO₂ particles were formed and crystallized through hydrolysis of the titanium oxychloride precursor compound. The reaction temperature was then increased to 103°C, and that temperature was maintained for 4 hours. The hydrolysis was essentially complete at this stage.

[0033] The resulting reaction mixture was then cooled to room temperature and transferred to a different container where the particles formed were allowed to settle for a few hours. After essentially all of the particles were observed to have settled to the bottom of the container, the mother liquor, i.e., liquid reaction medium, was removed and about the same volume of fresh deionized water was added to the container. The reaction mixture was then stirred to re-slurry the particles, and then the pH of the slurry was increased to a value of about 7 by slow addition of an

ammonia solution (~29%, Fisher Scientific). The particles comprising the reaction product were then separated from the liquid reaction mixture using a Buchner filter and washed with deionized water until the conductivity of the filtrate was lowered to about 500 $\mu\text{S}/\text{cm}$. The wet filter cake sample was then stored as a slurry by re-slurring the filter cake with a small amount of deionized water. The powder form of the sample was obtained by drying the slurry sample in an oven overnight at 90°C. X-ray Diffraction (XRD) measurement on the powder sample, shown in Fig. 5, indicates that the sample contains 100% rutile with crystallite size about 8 nm. BET measurement on the powder sample shows that the powder has a specific surface area of 140 m^2/g and a pore volume of 0.34 cm^3/g .

[0034] SEM images of the slurry sample are shown in Fig. 1 at a magnification of 10,000. Funnel-shaped nanoparticles can be seen more clearly in Fig. 2 at a magnification of 50,000. The TEM image of the slurry sample shown in Fig. 3 illustrates a funnel-shaped particle with a diameter in the range of 50 nm. The TEM image in Fig. 4 illustrates general alignment of individual nano-sized rutile TiO_2 crystallites.

[0035] The funnel-shaped nanoparticles shown in Fig. 2 were calcined at 550°C for 6 hours. SEM images of the calcined nanoparticles can be seen in Fig. 6 (50,000 magnification) and in Fig. 7 (100,000 magnification). Calcining, which can be adjusted for time and temperature, operates to enhance the properties of the resulting nanoparticles by expanding or opening the pore structure and/or increasing the refractive index.

Example 2 - Preparation of funnel-shaped nanoparticles using amino acids

[0036] The same procedure was followed as in Example 1 except that 20.7 g phenylalanine (Alfa Aesar) was used as morphology controlling agent instead of mandelic acid. The SEM/TEM images of the reaction product were similar to those shown in Figs 1-4. XRD measurement on the powder sample indicates that the sample contains 100% rutile with crystallite size of about 9 nm. BET measurement on the powder sample shows that the powder has a specific surface area of 124 m^2/g and a pore volume of 0.37 cm^3/g .

Example 3 - Preparation of funnel-shaped nanoparticles using carboxylic acids

[0037] The same procedure was followed as in Example 1, except that 14.3 g of benzoic acid (Alfa Aesar) was used as the morphology controlling agent instead of mandelic acid. The SEM/TEM images of the reaction product are similar to those shown in Figs 1-4. The XRD measurement of the powder sample was similar to the measurement shown in Fig. 5 for the funnel-shaped nanoparticles produced using mandelic acid and confirms that the sample contains 100% rutile with crystallite size of about 8 nm. BET measurement on the powder sample shows that the powder has a specific surface area of 121 m²/g and a pore volume of 0.53 cm³/g.

What is claimed is:

1. A method for preparing rutile TiO_2 nanoparticles which are aggregates of elongated TiO_2 crystallites comprising:

(a) forming an aqueous solution of a soluble titanium compound at a titanium concentration of from 0.5 to 1.0 moles per liter, optionally in the presence of a mineral acid;

(b) introducing a morphology controlling agent or a mixture thereof selected from (i) an α -hydroxy carboxylic acid of the formula R-CH(OH)COOH , (ii) an α -hydroxy carboxamide of the formula R-CH(OH)CONH_2 or (iii) an α -amino acid of the formula $\text{R-CH(NH}_2\text{)COOH}$, wherein R is an alkane, alkene, alkyne, arene, or cycloalkane group having 6 or more carbon atoms, into the solution at an acid- or carboxamide-to-titanium molar ratio of from 0.02 to 0.2 while simultaneously heating the solution to a temperature in the range of from 60°C to 80°C with constant stirring;

(d) introducing TiO_2 seeds into the stirred solution at a seed-to- TiO_2 molar ratio of from 0.0005 to 0.0015 and maintaining the stirred solution at a temperature in the range of from 60°C to 80°C for a period of from one to 3 hours;

(e) elevating the temperature of the stirred solution to a value of from 100°C to the refluxing temperature and maintaining said temperature for a period of from 2 hours to 4 hours to form a reaction product;

(f) cooling the reaction mixture which results from step (e) to room or ambient temperature;

(g) optionally neutralizing the reaction mixture; and

(h) separating and drying the reaction product.

2. The method of claim 1 wherein said elongated TiO_2 crystallites have a thickness of from 3 nm to 5 nm and a length of from 20 nm to 50 nm.

3. The method of claim 2 wherein said rutile TiO_2 nanoparticles are aggregates wherein one set of ends of said elongated TiO_2 crystallites of each aggregate are joined in a cluster and the opposite ends of said crystallites fan outwardly in the general shape of a funnel having a diameter in the range of 50 nm and a height in the range of from 50 nm to 100 nm.

4. The method of claim 1 wherein said morphology controlling agent is selected from mandelic acid ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{COOH}$); 4-hydroxymandelic acid ($\text{C}_6\text{H}_4(\text{OH})\text{CH}(\text{OH})\text{COOH}$); benzilic acid ($(\text{C}_6\text{H}_5)_2\text{C}(\text{OH})\text{COOH}$); 2-hydroxy-4-phenylbutyric acid ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}_2\text{CH}(\text{OH})\text{COOH}$); 2-hydroxy-2-phenylpropionic acid ($(\text{C}_6\text{H}_5)(\text{CH}_3)\text{C}(\text{OH})\text{COOH}$); 2-hydroxyoctanoic acid ($\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}(\text{OH})\text{COOH}$); mandelamide ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{CONH}_2$); phenylalanine ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$); tyrosine ($\text{C}_6\text{H}_4(\text{OH})\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$); and ammonium (NH_4^+), sodium (Na^+) and potassium (K^+) salts thereof and mixtures thereof.

5. The method of claim 1 wherein said soluble titanium compound is selected from titanium oxychloride (TiOCl_2), titanium oxybromide (TiOBr_2), titanium oxyiodide (TiOI_2), titanium oxynitrate ($\text{TiO}(\text{NO}_3)_2$), titanium trichloride (TiCl_3), titanium tribromide (TiBr_3), titanium oxalate ($\text{Ti}_2(\text{C}_2\text{O}_4)_3$), potassium hexafluorotitanate (K_2TiF_6), ammonium hexafluorotitanate ($(\text{NH}_4)_2\text{TiF}_6$), potassium titanyloxolate ($\text{K}_2\text{TiO}(\text{C}_2\text{O}_4)_2$), ammonium titanyloxolate ($(\text{NH}_4)_2\text{TiO}(\text{C}_2\text{O}_4)_2$), titanium bis(ammonium lactate) dihydroxide ($[\text{CH}_3\text{CH}(\text{O})\text{COONH}_4]_2\text{Ti}(\text{OH})_2$) and mixtures thereof.

6. The method of claim 4 wherein said soluble titanium compound is selected from titanium oxychloride (TiOCl_2), titanium oxybromide (TiOBr_2), titanium oxyiodide (TiOI_2), titanium oxynitrate ($\text{TiO}(\text{NO}_3)_2$), titanium trichloride (TiCl_3), titanium tribromide (TiBr_3), titanium oxalate ($\text{Ti}_2(\text{C}_2\text{O}_4)_3$), potassium hexafluorotitanate (K_2TiF_6), ammonium hexafluorotitanate ($(\text{NH}_4)_2\text{TiF}_6$), potassium titanyloxolate ($\text{K}_2\text{TiO}(\text{C}_2\text{O}_4)_2$), ammonium titanyloxolate ($(\text{NH}_4)_2\text{TiO}(\text{C}_2\text{O}_4)_2$), titanium bis(ammonium lactate) dihydroxide ($[\text{CH}_3\text{CH}(\text{O})\text{COONH}_4]_2\text{Ti}(\text{OH})_2$) and mixtures thereof.

7. The method of claim 6 wherein said morphology controlling agent is mandelic acid ($\text{C}_6\text{H}_5\text{CH}(\text{OH})\text{COOH}$), said soluble titanium compound is titanium oxychloride (TiOCl_2), and said TiO_2 seeds comprise a slurry containing 0.2g TiO_2 in anatase phase.

8. The method of claim 7 wherein said morphology controlling agent is phenylalanine ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}(\text{NH}_2)\text{COOH}$).

9. Rutile TiO_2 nanoparticles which are ordered acicular aggregates of elongated TiO_2 crystallites having a thickness in the range of from 3 nm to 5 nm in which one end of each of said elongated TiO_2 crystallites are joined into a cluster such that the opposite ends of each of said elongated TiO_2 crystallites extend outwardly in the shape of a nano-sized funnel structure having a diameter in the range of 50 nm and a height in the range of from 50 nm to 100 nm.

10. The rutile TiO_2 nanoparticles of claim 9 which are produced by the process of:

(a) forming an aqueous solution of a soluble titanium compound at a titanium concentration of from 0.5 to 1.0 moles per liter;

(b) introducing a morphology controlling agent or a mixture thereof selected from (i) an α -hydroxy carboxylic acid of the formula R-CH(OH)COOH , (ii) an α -hydroxy carboxamide of the formula R-CH(OH)CONH_2 or (iii) an α -amino acid of the formula $\text{R-CH(NH}_2\text{)COOH}$, wherein R is an alkane, alkene, alkyne, arene, or cycloalkane group having 6 or more carbon atoms, into the solution at an acid- or carboxamide-to-titanium molar ratio of from 0.02 to 0.2 while simultaneously heating the solution to a temperature in the range of from 60°C to 80°C with constant stirring;

(d) introducing TiO_2 seeds into the stirred solution at a seed to TiO_2 molar ratio of from 0.0005 to 0.0015 while maintaining the solution at a temperature in the range of from 60°C to 80°C for a period of from one to 3 hours;

(e) elevating the temperature of the stirred solution to a value of from 100°C to the refluxing temperature and maintaining said temperature for a period of from 2 hours to 4 hours to form a reaction product;

(f) cooling the reaction mixture which results from step (e) to room or ambient temperature;

(g) optionally neutralizing the reaction mixture; and

(h) separating and drying the reaction product.

11. The rutile TiO_2 nanoparticles of claim 10 wherein:

(a) said morphology controlling agent is selected from mandelic acid ($\text{C}_6\text{H}_5\text{CH(OH)COOH}$); 4-hydroxymandelic acid ($\text{C}_6\text{H}_4(\text{OH})\text{CH(OH)COOH}$); benzilic acid ($(\text{C}_6\text{H}_5)_2\text{C(OH)COOH}$); 2-hydroxy-4-phenylbutyric acid ($\text{C}_6\text{H}_5\text{CH}_2\text{CH}_2\text{CH(OH)COOH}$); 2-hydroxy-2-phenylpropionic acid

((C₆H₅)(CH₃)C(OH)COOH); 2-hydroxyoctanoic acid (CH₃CH₂CH₂CH₂CH₂CH₂CH(OH)COOH); mandelamide (C₆H₅CH(OH)CONH₂); phenylalanine (C₆H₅CH₂CH(NH₂)COOH); tyrosine (C₆H₄(OH)CH₂CH(NH₂)COOH); and ammonium (NH₄⁺), sodium (Na⁺) and potassium (K⁺) salts thereof and mixtures thereof, and

(b) said soluble titanium compound is selected from titanium oxychloride (TiOCl₂), titanium oxybromide (TiOBr₂), titanium oxyiodide (TiOI₂), titanium oxynitrate (TiO(NO₃)₂), titanium trichloride (TiCl₃), titanium tribromide (TiBr₃), titanium oxalate (Ti₂(C₂O₄)₃), potassium hexafluorotitanate (K₂TiF₆), ammonium hexafluorotitanate ((NH₄)₂TiF₆), potassium titanyloxolate (K₂TiO(C₂O₄)₂), ammonium titanyloxolate ((NH₄)₂TiO(C₂O₄)₂), titanium bis(ammonium lactate) dihydroxide ([CH₃CH(O)COONH₄]₂Ti(OH)₂) and mixtures thereof.

12. The rutile TiO₂ nanoparticles of claim 10 wherein:

(a) said morphology controlling agent is selected from phenylalanine (C₆H₅CH₂CH(NH₂)COOH) and mandelic acid (C₆H₅CH(OH)COOH) or a mixture thereof; and

(b) said soluble titanium compound is titanium oxychloride (TiOCl₂).