Synthesis of $SrTiO^3$ nanoparticles for photocatalytic applications

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Abstract. Due to the heightened emphasis on environmental protection and the escalating demand for renewable energy sources, the potential applications of strontium titanate ($SrTiO_3$) nanoparticles in photocatalysis have shown remarkable promise. With rapid advancements in technological capabilities, the standards for $SrTiO_3$ photocatalytic materials have soared. Researchers have relentlessly delved into and innovated techniques for preparing strontium titanate powders, striving to yield nanocrystalline $SrTiO_3$ that exhibits specific morphologies, high purity, superior dispersibility, and exceptional photocatalytic efficiency, while continually refining the properties of these powders. The paper encapsulates the advancements in preparation methodologies and photocatalytic attributes of perovskite $SrTiO_3$ nanoparticles, encompassing diverse synthetic routes such as hydrothermal synthesis, sol-gel process, chemical precipitation, solid-state reaction, sonochemical technique, and composite modification strategies. The characteristics, merits, demerits, and prevailing challenges associated with each synthesis technique are thoroughly and analyzed. Ultimately, this review serves as a valuable reference and foundation for the synthesis, modification, and application of $SrTiO_3$ nanoparticle photocatalysts, fostering their development and practical implementation in environmental remediation and renewable energy technologies.

Keywords: $SrTiO_3$ nanoparticles, synthesis, photocatalytic applications, hydro-thermal method, solid-state method, modification.

1. Introduction

Amidst heightened environmental protection awareness and pressing renewable energy demands, the research and development of solar energy has shown good potential and broad prospects. In this wave, photocatalytic technology has sprung up, which not only provides new ideas for the efficient use of solar energy, but also becomes a powerful tool for solving the current serious problems of environmental pollution and energy shortage [1-2]. Strontium titanate is widely used as a functional material in electronic, mechanical and ceramic industries. Full light domain polyhedral strontium titanate photocatalytic materials are mainly used in organic matter degradation, photovoltaic power generation, photolysis of water to produce hydrogen, light-proof multifunctional coatings and other fields, the application prospect is broad. $SrTiO_3$ has excellent physical and chemical properties, such as: high dielectric constant, low dielectric loss, high forbidden band width, good photocatalytic activity, high withstand voltage strength, and so on, and therefore is widely used to come to the manufacture of oxygen-sensitive components, crystal boundary layer capacitors, photocatalytic electrode materials, etc [3].

The structure as well as the crystalline properties of strontium titanate have an important influence on its overall performance. In order to meet these requirements, it is necessary to prepare strontium titanate powders with uniformity, high purity, specific morphology and crystalline surface, and to thoroughly investigate their photocatalytic properties [4] the focus is on reducing energy losses, improving photocatalytic efficiency and simultaneously reducing costs to achieve higher economic efficiency and performance. Strontium titanate with good photoelectron-catalytic properties should be nanoscale, morphologically controllable, highly pure, well dispersed, and with much exposure of the dominant crystal surface.

At present, there are numerous methods for the preparation of nano-$SrTiO_3$ powders, which are mainly divided into liquid-phase and solid-phase methods. The liquid-phase methods, distinguished by their minimal pollution, high raw material utilization, and yield of high-purity powders with large specific surface areas and uniform particle size distributions, encompass hydrothermal synthesis[5], sol-gel method [6], co-precipitation method [7-8], among others. Conversely, the solid-state reaction method [9-10] is a simple process, mature technology, the reaction material is ground and then calcined. This article delves into a comprehensive review and analytical assessment of recent advancements by domestic and international scholars in the preparation methodologies of chalcogenide-type $SrTiO_3$ nanopowders and their associated photocatalytic properties.

2. Preparation methods

2.1. Hydrothermal synthesis

The hydrothermal method is usually carried out at high temperatures (100 to 1000°C) and high pressures (1 to 100 MPa), which is especially suitable for the production of inorganic materials such as oxides, nano-materials, ceramics and glass [11] Although hydrothermal methods require specific pressure-resistant equipment and high requirements for experimental conditions, their unique synthesis environment and controllability [12] make them important in the field of nanomaterial preparation. Hydrothermal method is useful in the preparation of nanocomposites to enhance the photocatalytic performance [13-14], and the combination of other methods with it such as bio-template method [15], can integrate the advantages of multiple methods.

In the studies of Huang [16] and Shen [17], it was found that higher hydrothermal synthesis temperature causes aggregation and irregular growth of nanoparticles, which in turn leads to non-homogeneous microstructure. The increase in hydrothermal synthesis temperature can lead to the enlargement of $SrTiO_3$ particle size, and the higher the temperature, the more prone to agglomeration. It is concluded that the morphology of $SrTiO_3$ is the best when the hydrothermal temperature is 130°C. Meanwhile, the synthesis time also affects the size of $SrTiO_3$ nanoparticles. At the initial stage of the reaction, $SrTiO_3$ nucleates and forms smaller particles. With the extension of reaction time, $SrTiO_3$ first nucleates, then forms particles, and the size increases.

Zhang Na and colleagues [18] made SrTiO3 nanoparticles, with uniform size and regular morphology, via hydrothermal synthesis. They used TiO_2 and $Sr(OH)_2{\cdot}8H_2O$ as precursor for titanium and strontium, respectively. The reaction was conducted in a stainless-steel autoclave lined with PTFE, utilizing NaOH solution as the alkaline medium and oleic acid as the dispersing agent to help reaction along. They carried out a comprehensive experiment to find out how different factors like the length of the reaction, the molar ratio of reactants (Sr/Ti), and the amount of oleic acid affected the properties of the nanoparticles, especially their size, purity, and shape. The optimal synthesis conditions were identified as follows: an oleic acid concentration of 3%, a reaction duration of 30 hours, and a molar ratio of Sr/Ti equal to 0.75.Under these conditions, they managed to make pure $SrTiO_3$ nanoparticles. These particles were tiny, had a big surface area, didn't clump together much, and worked great as photocatalysts.

In Zhang Y [19] research, titanium dioxide and strontium hydroxide octahydrate powders were used as the titanium and strontium sources, respectively. $SrTiO_3$ cubic phase was synthesized by controlling the current conditions. And in the study of the basal heterostructure, its photocatalytic performance was significantly improved by different synthesis and modification methods. The potential of $SrTiO_3$ for photocatalytic applications was further exploited by these methods, including hierarchical assembly, complexation with noble metals, co-doping, and Nb doping. In addition, efficient hydrogen production, which provides a new idea for the development of energy field, has been achieved by visible-light-driven Cr-doped $SrTiO_3$ synthesized by sol-gel hydrothermal method.

Researchers [20] systematically examined the influence of thermal solvents on the hydrothermal synthesis of strontium titanate, utilizing $Sr(NO_3)_2$ and $(C_3H_7O)_4Ti$ as the respective precursors, and ethylene glycol and deionized water as the thermal solvents. Furthermore, they delved into the correlations between the resultant structural features and the optical, adsorptive, and CO_2 reduction capabilities of the synthesized $SrTiO_3$. Utilizing X-ray diffraction (XRD), scanning electron microscopy (SEM), Brunauer-Emmett-Teller (BET) analysis, and other advanced characterization techniques, the study revealed that the elevated viscosity of ethylene glycol compared to water facilitated the synthesis of $SrTiO_3$ nanoparticles with finer particle sizes and well-defined crystallinity. The as-prepared $SrTiO_3$ exhibited a porous architecture, characterized by a significant specific surface area and an abundance of adsorption sites. Notably, the prevalence of TiO_2 terminations on the surface of the particles enhanced the CO_2 adsorption capacity, ultimately contributing to an improved catalytic performance. Additionally, $SrTiO_3$ synthesized in ethylene glycol displayed the highest photocurrent, which serves as a proxy for the efficient separation of photogenerated electrons and holes. This observation underscores the minimal recombination rate of photogenerated charge carriers, coupled with the potential for energy storage within the material.

Sikam et al [21] using SrO_6N_2, TiO_2-P25 and Co $(NO_3)_2 \cdot 6H_2O$ solution as raw materials, prepared undoped and doped $SrTiO_3$ powder samples by hydrothermal synthesis method. In case of undoped samples, the $SrTiO_3$ was prepared the same route to the doped samples but the Co $(NO_3)_2 \cdot 6H_2O$ was not added. Utilizing a hydrothermal technique, the Perovskite structure of $SrTiO_3$ and Co-doped $SrTiO_3$ was successfully synthesized. The incorporation of Co into the $SrTiO_3$ lattice led to the formation of nanoparticles that exhibited a reduced energy gap, an increased specific surface area, and enhanced magnetization properties. This strategic placement of Co atoms is expected to introduce magnetic characteristics and novel physical states, thereby broadening the material's potential applications. These include advanced spintronic devices, exceptional photocatalytic activity, remarkable thermoelectric performance, and superior solar cell efficiency. Alternatively, Co-doped STOS annealed in air are considered promising candidates for photocatalyst applications due to their extremely high specific surface area and narrowest band gap.

Qibo Jia [5] prepared regular polyhedral single crystal $SrTiO_3$ particles with three crystal faces {100}, {110} and {111} by a one-step hydrothermal method. The morphology, shape, comparison of crystal surface area, photocatalytic activity and crystal growth process of titanium trioxide were studied. It is found that the regular shape and crystal face type of single crystal $SrTiO_3$ can be controlled by different acids and alcohols. The research paves the way for the development of the next generation of high-efficiency photocatalytic materials based on $SrTiO_3$, which are dominated by the overall water decomposition or degradation of organic matter.

Hydrothermal method is a green and environmentally friendly way to prepare high-quality nano-strontium titanate powder, featuring complete grain development, high sintering activity, low raw material cost, and simple process flow. However, it requires specific pressure-resistant equipment, imposes high demands on experimental conditions, and takes a relatively long reaction time.

2.2. Sol-gel method

The sol-gel method is a commonly used process widely applied in the synthesis of nanomaterials, effectively controlling the morphology, particle size, and structure of the products. It is suitable for synthesizing photocatalytic materials with regular morphology, small particle size, and nanostructure under normal pressure and lower temperatures [22].

Wang Yanhong[23], Zhou[24], and Wang Jiawei[25] all doped metal ions in the preparation process to obtain perovskite-type nano-strontium titanate powders with better performance. Among them, Wang Yanhong also prepared SrTiO3 (STO): Rh photocatalyst using the sol-gel method to enhance the photocatalytic hydrogen production activity, investigating the effects of doping amount and synthesis temperature on photocatalytic activity. After Rh doping, SrTiO3 not only exhibits high crystallinity but also possesses smaller particle sizes (corresponding to a larger specific surface area), thereby resulting in higher photocatalytic activity. Within the experimental range, when the Rh loading is 2% (mass fraction) and the calcination temperature is 900℃, the nano-strontium titanate composite photocatalytic material exhibits the highest activity. Zhou successfully prepared $SrTiO_3$ and $SrTiO_3:Er^{3+}$ nanoparticles. It was found that the incorporation of Er^{3+} did not change the cubic phase structure of $SrTiO_3$, but significantly improved its photocatalytic hydrogen production activity under simulated sunlight. $SrTiO_3:Er^{3+}$ nanoparticles exhibit green and red luminescence characteristics under the excitation of 980 nm, and the edge of the absorption band moves in the direction of longer wave, which enhances the absorption capacity in the visible band. These results show that $SrTiO_3$ is a good carrier of Er^{3+} ions, and the incorporation of Er^{3+} is an effective way to improve the photocatalytic performance of $SrTiO_3$, which provides a new strategy for the preparation of high-performance photocatalytic materials. Wang Jiawei prepared La-doped $SrTiO_3$ samples, explored the influence of pH value and citric acid dosage on the purity of $SrTiO_3$ powder, and characterized and analyzed the products using XRD. The experimental results indicated that the photocatalytic effect of $SrTiO_3$ reached its optimum when the pH value of the reaction system was 4 and the molar ratio of citric acid to metal ions (n (CA): n (M)) exceeded 1.3:1.0.

Peng Fuchang's research [26] delved into the effects of Zn doping on the photocatalytic performance of $SrTiO_3$, as well as the influence of preparation conditions such as heat treatment temperature, through various characterization techniques and performance evaluation methods. The recombination probability of photogenerated electrons and holes can be reduced by proper Zn doping, so as to improve the photocatalytic performance. Samples prepared at a suitable heat treatment temperature exhibited complete crystal forms, high purity, and an ordered porous and loose surface morphology. Notably, when the doping ratio of Zn to Sr was 1.5:100 and the heat treatment was conducted at 900°C, the prepared samples exhibited exceptional photocatalytic activity and stability, with a photocatalytic activity as high as 95.5%, significantly outperforming undoped $SrTiO_3$ (58.5%).

Some researchers [27] employed the complex sol-gel method to prepare perovskite strontium titanate nanopowders using strontium nitrate and tetrabutyl titanate as raw materials, with hydrogen peroxide as an auxiliary oxidant. They investigated the effects of reactant concentration, reaction time, and initial concentration of basic fuchsin under ultrasonic conditions on the degradation rate of basic fuchsin wastewater and the reusability of strontium titanate nanopowders. The obtained strontium titanate nanopowders exhibited a perovskite structure with a particle size of 100 nm and regular morphology, albeit with some agglomeration. For basic fuchsin wastewater with a mass concentration of 40 mg/L, a degradation rate of 97.7% was achieved within 10 minutes when the addition of strontium titanate was 1 g/L and hydrogen peroxide was 5 mL/L, demonstrating good reusability.

Zhang Wenkui [6] prepared perovskite-type nano-$SrTiO_3$ using strontium nitrate and tetrabutyl titanate as raw materials via the sol-gel method. Various factors influencing the sol-gel process were studied. Ethanol, glacial acetic acid, water, glycerol, temperature, and pH value all significantly impacted the sol-gel process, with reaction temperature having the most pronounced effect on gel formation time and gel quality. Increasing the reaction temperature during the sol-gel process significantly reduced the gelation time. The structure and properties of the products were characterized using infrared spectroscopy, differential thermal analysis, X-ray diffraction, scanning electron microscopy, and UV-visible spectroscopy absorption. Perovskite-type $SrTiO_3$ crystals were formed at 650°C, with uniform particle size distribution. As the heat treatment temperature increased, the phase composition of the powders changed, resulting in more complete crystal forms, increased particle size and lattice constant, and a corresponding red shift in the maximum UV absorption position.

The sol-gel method is a common approach for preparing nano-strontium titanate powders, offering high product purity, strong controllability, simplicity of operation, and low heat treatment temperatures. However, this method also has notable drawbacks, including high costs, particularly due to the use of organic precursors and solvents, which increases costs and environmental pollution. The calcination process may affect photocatalytic activity, and the reaction process is sensitive to experimental conditions, requiring strict parameter control, which limits its application to some extent.

2.3. Chemical coprecipitation method

The chemical coprecipitation method primarily relies on specific chemical reactions to coprecipitate metal ions with a precipitant, specifically generating strontium titanate precipitates from titanium and strontium salts under the action of a precipitant. Subsequently, various heat treatment methods such as drying and calcination can be employed to produce target products with high purity, small particle sizes, and uniform distribution [15].

In the experiments conducted by Wang Guiyun [28], tetrabutyl titanate and strontium nitrate were used as raw materials, and the influence of various process conditions on product quality was investigated through orthogonal experiments. It was found that within a certain range, as the amount of alkali, solvent (anhydrous ethanol), and water increased, the dripping rate of the alkali solution and strontium nitrate solution decreased, leading to improved product quality. Under the experimental conditions of 75 ml ethanol addition, slow stirring, and 150 ml of 4% sodium hydroxide, a product with a main content of 99.71% and a strontium-to-titanium ratio of 1.002 was obtained. X-ray diffraction analysis and scanning electron microscopy revealed that the product consisted of spherical strontium titanate particles with a particle size of approximately 60 nm.

Wang Kaiming [8] mixed strontium chloride and titanium tetrachloride-ethanol solution, added ammonium bicarbonate, ammonia water, and ethanol as precipitants, and achieved rapid mixing under high-intensity mechanical mixing conditions. By adjusting various process conditions such as concentration, pH, high mechanical mixing intensity, and aging time, a highly dispersed and filterable nanopowder precursor consisting of a mixture of strontium carbonate and amorphous titanium oxyhydroxide was obtained. The resulting slurry with a pH ≥ 10 and an aging time of 10-40 minutes allowed for the preparation of a well-dispersed and filterable strontium titanate nanopowder precursor with a particle size of 34 nm. Further calcination at 920℃ yielded cubic-phase strontium titanate nanopowder with good dispersion, good crystallinity, and an average particle size of 56 nm.

Researchers [29] used strontium chloride and titanium tetrachloride solutions as raw materials, selecting sodium carbonate and sodium hydroxide as precipitants. They focused on studying the conditions for synthesizing strontium titanate via coprecipitation, including the strontium-to-titanium ratio of reactants, final pH, washing of solid-liquid separates, and calcination temperature. Analysis and testing revealed that a final pH above 9 was necessary for complete precipitation of strontium ions and smaller product particle sizes. As the raw material strontium-to-titanium ratio increased, so did the product's strontium-to-titanium ratio. Optimal results were achieved when the raw material strontium-to-titanium ratio was controlled between 1.00 and 1.02, yielding products with good strontium-to-titanium ratios and purity. The preferred calcination temperature ranged from 880 to 950℃, with a calcination time of 4 to 6 hours.

In the study by researcher Zhang Hao [7], purified industrial-grade metatitanic acid and analytical-grade strontium nitrate were used as the main raw materials to synthesize strontium titanate nanopowder with an average particle size of approximately 60 nm via chemical coprecipitation. ICP, XRD, and TEM were employed to investigate the effects of raw material purity, synthesis conditions, and raw material titanium-to-strontium molar ratios on product purity, phase composition, and microscopic morphology. The optimal synthesis conditions within the experimental range were determined to be a molar ratio of metatitanic acid, hydrogen peroxide, and ammonia water of 1.0:6.5:2.5, a raw material titanium-to-strontium molar ratio of 1.10:1.00, and a calcination temperature of 600℃. Using inexpensive metatitanic acid as the main raw material helped reduce the production cost of strontium titanate nanopowder. The nanopowder prepared by this method has potential applications in electronic ceramics, optoelectronic devices, and other fields.

Liu Huanhuan's [3] research successfully synthesized strontium titanate nanoparticles using SrCl2·6H2O and TiCl4 as raw materials and NaOH as a precipitant via a low-temperature direct precipitation method. Through FTIR, SEM, XRD, and particle size characterization analyses of the products, it was found that as the reaction time increased, the higher the reaction temperature and the lower the initial feed concentration, the larger the particle size of the resultant strontium titanate powder. The optimal preparation conditions within the experimental range were: pH = 13, temperature 75℃, time 4 hours, initial feed concentration ($SrCl_2$, 2 mol/L, $TiCl_4$, 2 mol/L), and the addition of 0.5% of PEG4000 as a dispersant to the reaction system. This yielded low-agglomeration, nanoscale perovskite-type strontium titanate powder with an average particle size of 50-70 nm. By controlling the reaction temperature and conditions, this method effectively avoided agglomeration that might occur at high temperatures, providing a new low-temperature synthesis route for the preparation of strontium titanate nanoparticles.

Hu Xiong's [30] study focused on the direct precipitation method for the preparation of nano-strontium titanate powder and its surface modification process. Emphasis was placed on investigating the influence of the surfactant sodium dodecylbenzene sulfonate (SDBS) on the properties of nano-strontium titanate powder during synthesis. The microstructure was characterized using XRD, TEM, SEM, and BET. Within the experimental range, the optimal concentration of SDBS surfactant added was 0.15 mol/L. The SDBS-modified nano-strontium titanate powder retained its crystal structure, with spherical particles having an average particle size of approximately 25 nm, a narrow particle size distribution, and significantly improved agglomeration. The results indicated that the surface-modified nano-strontium titanate powder exhibited excellent photocatalytic and electrical properties.

Researchers have also explored the application of strontium titanate powder prepared by the coprecipitation method in catalyzing the degradation of wastewater. Jiang Yuanru's[31] study used a precipitation method to prepare strontium titanate powder. The catalytic activity of the strontium titanate powder towards malachite green wastewater was investigated, exploring the effects of catalyst dosage and time on the catalytic performance. Experiments showed that the $SrTiO_3$ powder had a diameter of 0.5-2 μm, good dispersion, and a smooth surface. Within the experimental range, a degradation rate of 97.8% for 100 mL of 30 mg/L malachite green wastewater was achieved using 0.1 g of $SrTiO_3$ and 0.5 mL of hydrogen peroxide oxidant under ultrasonic treatment for 10 minutes. Guo Yanqin [32] prepared perovskite $SrTiO_3$ powder by precipitation and characterized its crystal structure and morphology using XRD and SEM. The decolorization performance of the sample towards methyl orange solution was also studied. Results indicated that a decolorization rate of 97.4% could be achieved for a methyl orange solution with a pH of 4.0, using 0.1 g of $SrTiO_3$ under light exposure for 90 minutes. These two studies demonstrate that strontium titanate powder is an effective catalyst for treating wastewater containing organic dyes, offering a new solution for environmental protection.

The coprecipitation method employs inexpensive and readily available raw materials, with a simple process, mild conditions, and strong controllability. By adjusting process parameters such as solution pH, reaction temperature, and precipitant properties, diverse control over product morphology, particle size, and purity can be achieved. These advantages indicate the potential for large-scale industrial application of the coprecipitation method. However, it also has some drawbacks, such as the use of certain precipitants, subsequent complex impurity removal processes, and harmful by-products that can cause environmental pollution issues, necessitating the promotion of green chemistry and sustainable development.

2.4. Solid-state method

The solid-state method involves subjecting raw materials to rigorous mechanical grinding and thorough mixing, followed by calcination of the mixture within a specific temperature range. After a designated period of chemical reaction, the desired product is obtained.[1] By modulating process parameters such as raw material ratios, reaction temperature, and reaction time, the structure and properties of the product can be tailored to better suit diverse application requirements.

Numerous researchers both domestically and internationally have employed the high-temperature solid-state method for synthesizing nanocrystalline perovskite-type strontium titanate powder materials. Wu Ying [9] prepared cubic $SrTiO_3$ with a particle size of approximately 500nm by first uniformly mixing SrCO3 and TiO2, then grinding the mixture in an agate mortar for 2 hours, and finally reacting it in a high-temperature tube furnace for an additional 2 hours. Xin Gang [33], on the other hand, weighed $SrCO_3$ and TiO_2 in a molar ratio of 1:1, thoroughly ground the mixture in a mortar, transferred it to an alumina crucible for calcination over 10 hours, and allowed it to cool naturally to room temperature. The resulting product exhibited uniform particle sizes ranging from 0.5 to 0.7μm, with some minor particle adhesion observed, indicating an increase in particle size compared to the raw materials. In Berbenni’s study [34], $SrTiO_3$ and Sr_2TiO_4 can be prepared by annealing at 800–850°C for about 12h high energy milled mixtures of $SrCO_3$ and rutile. However, the $SrTiO_3$ nanoparticles obtained are large and uneven in size.

Compared to the high-temperature solid-state method, the low-temperature solid-state reaction approach [35] is more energy-efficient and environmentally friendly, achieving partial atomic economy in the process, aligning with the principles of green chemistry. Ding Shiwen [36] pioneered the use of a low-temperature solid-state reaction method to synthesize strontium titanate nanopowders, employing TiCl4 and Sr (OH)2·8H2O as raw materials. The study investigated the effects of grinding time, reaction time, and reaction temperature on the phase structure of the strontium titanate nanopowders. After 1 hour of mixing and grinding, followed by a 5-hour solid-state reaction at 40℃, pure cubic-phase strontium titanate nanopowders with small particle sizes and good dispersion were successfully prepared. This method offers a simple and effective route for the preparation of nanoscale strontium titanate materials. Characterization of the powders using XRD and TEM revealed that the optimal grinding time, reaction temperature, and reaction time for the synthesis of strontium titanate nanopowders were 1 hour, 40℃, and 5 hours, respectively. Under these conditions, the resulting strontium titanate nanopowders exhibited a pure cubic-phase $SrTiO_3$ crystal structure, with uniformly square-shaped particles, good dispersion, and an average particle size of approximately 40 nm.

Liu Guya[10] successfully prepared 125 nm cubic-phase $SrTiO_3$ via the solid-state method, achieving uniformly sized strontium titanate powders through precise control of reaction conditions. This chemical process is characterized by simplicity, short reaction times, high product purity, low energy consumption, and the absence of solvents, thereby minimizing environmental pollution. Experimental results indicated that the XRD pattern of $SrTiO_3$ obtained after heating at 600℃ for 10 hours and subsequent washing with 1 mol/L HNO3 showed strong and sharp X-ray diffraction peaks, indicative of excellent crystallinity. Furthermore, the absence of any additional infrared spectral peaks in the infrared spectrum confirmed the purity of the product, consistent with the XRD characterization.

In order to meet the needs of modern technology development, efficient, simple, low-cost and high-quality preparation of $SrTiO_3$ electronic ceramic powder, in Zhu Qi-An's study[37], $SrTiO_3$ nanoparticles were prepared by solid-phase grinding and low-temperature calcination with strontium hydroxide and tetrabtyl titanate as raw materials. The cubic phase $SrTiO_3$ nanoparticles with an average particle size of 15-35 nm were synthesized by calcination at a lower temperature (400 ~ 600℃), with uniform spherical morphology and narrow particle size distribution. With the increase of calcination temperature, the grain size and crystallinity of the sample increase. The synthesized samples were characterized by XRD, FT-IR, SEM and TEM, and the formation process of the products was characterized by TG-DTA. The method not only overcomes the problem that liquid phase method is easy to introduce aqueous impurities and low production efficiency, but also reduces the roasting temperature by 600-800℃ compared with traditional solid phase method. The product was characterized by XRD, SEM, TEM and FT-IR, and the process of precursor roasting reaction was analyzed by TG-DTA.

The preparation of perovskite-type strontium titanate nanomaterials through the high-temperature solid-state method is associated with considerable energy consumption during the reaction process. In contrast, the low-temperature solid-state reaction method offers advantages such as lower energy consumption, simpler processing, and minimal environmental pollution, aligning more closely with the principles of green chemistry.

2.5. Sonochemistry method

The mechanism underlying the application of sonochemistry in nanomaterials synthesis stems from the acoustic cavitation effect. Acoustic cavitation refers to the formation, growth, and collapse of microbubbles in liquids, along with the resultant physical and chemical effects [38-39] Sonochemical treatment has proven to be a useful technique in synthesizing novel materials with unique properties.

In the experiments conducted by Liu Hong [40], titanium tetrachloride (TiCl4) was used as the titanium source, strontium chloride hexahydrate (SrCl2·6H2O) as the strontium source, and sodium hydroxide (NaOH) as the mineralizer. Employing the sonochemical method, well-crystallized starshaped, square, and spherical $SrTiO_3$ nanopowders were synthesized at relatively low temperatures. The effects of sonication time, initial Sr/Ti molar ratio, pH value, and initial reactant ion concentration on the morphology of the synthesized products were investigated. With increased sonication time promoting the generation of $SrTiO_3$ with more regular shapes, uniform sizes, and improved crystallinity. Variations in the initial Sr/Ti molar ratio directly impacted the supersaturation of the solution, affecting the morphology, size, and purity of $SrTiO_3$. The pH value influenced both the synthesis of $SrTiO_3$ and the particle morphology, an increase in pH led to faster nucleation rates and ion aggregation into precipitates, favoring the formation of crystalline precipitates. Therefore, a moderate increase in pH was conducive to powder synthesis. Different $SrTiO_3$ nanoparticle morphologies were obtained under varying ion concentrations and pH values. Under the experimental conditions with a reaction time of 40 minutes, a reaction temperature of 70℃, and a Sr/Ti molar ratio of 1.0, the resulting $SrTiO_3$ particles exhibited high crystallinity, uniform sizes, and high purity.

In Xu Ming's study [41], mono-sized $SrTiO_3$ particles with tailored morphology were successfully synthesized by using $SrCl_2$ and $TiCl_4$ as raw materials, adding NaOH as precipitant. Then, the mixture solution was exposed to high-intensity ultrasound irradiation under ambient air for a given time. At the end of the reaction, the precipitate was separated, washed and dried. Mono-sized strontium titanate ($SrTiO_3$) particles with tailored morphology can be obtained by controlling the parameters such as reactant concentration, sonication time and sonication power. The size of particles could be tailored from sub-micrometer to nanosize by increasing the reactant concentration. When the sonication power increases, the sonication time required to obtain mono-size spherical $SrTiO_3$ particles decreases, but excessive sonication power would reduce the mono-sized of the particle. As the sonication time increases, the $SrTiO_3$ particles take on a mono-size cubic morphology. Within the experimental range, mono-size spherical $SrTiO_3$ was sonicated for about 40min or less, with sonication power ranging from 400-1600W. From the fact that the products from the control group, which was not irradiated with ultrasound, had spherical, cubic $SrTiO_3$ particles, it can be concluded that the stellar $SrTiO_3$ particles should be attributed to the acoustic environment.

The $SrTiO_3$ coating shifts the conduction band of the nanoporous TiO_2 electrode in the negative direction due to the surface dipoles generated at the $SrTiO_3/TiO_2$ interface. For the first time this paper [42] described a convenient sonochemical method for the synthesis of nanocrystalline $SrTiO_3/TiO_2$ composites with tunable crystal sizes at ambient pressure and at temperatures as low as 50℃. The characterization of products that the XRD patterns showed the presence of pure phase cubic $SrTiO_3$ in the samples prepared under ultrasonic irradiation, whereas without ultrasonic irradiation only amorphous samples were obtained. The TEM images clearly showed the nanoporous structure of the samples. The TEM images showed that small particles of several nanometers form larger agglomerates. The assembly of small particles between the agglomerates formed pores. The average crystal size of $SrTiO_3$ can be adjusted between 6.0 and 28.8 nm by simply changing the volume ratio of water and ethanol, and it decreases with increasing ethanol content. The researchers experimentally concluded that ultrasonic irradiation brought about three beneficial effects: to accelerate dissolution of amorphous titanium oxide particles, to accelerated crystallization of $SrTiO_3$ nanoparticles, and to enhance diffusion of Sr^{2+} and OH^- ions into the internal amorphous titanium oxide particles.

Jiang Chuanxia [43] explored the unconventional synthetic route of sonochemical methodology for the preparation of porous perovskite-type strontium titanate nanomaterials. This study delved into the influence of sonication duration and pH values on the morphology and crystallinity of strontium titanate crystals, as well as their electrorheological properties. Within the experimental scope, when the reaction time was set at 100 minutes and the pH reached 10, chrysanthemum-like strontium titanate particles were formed. As the pH increased from 10 to 12, the particle morphology transformed from chrysanthemum-like to nearly spherical, accompanied by a transition in crystallinity from amorphous to polycrystalline and eventually to single-crystalline. The strontium titanate nanomaterials synthesized via sonochemical methodology exhibited high purity, uniform particle size distribution, and pronounced porosity. This porous structure not only enhanced the material's specific surface area but also offered more active sites, facilitating mass transport and reactions, potentially amplifying its performance capabilities. Research indicated that the porous strontium titanate nanomaterials demonstrated robust electrorheological responses under electric fields, where their rheological properties (e.g., viscosity, shear modulus) underwent notable variations with changes in electric field intensity, thereby opening avenues for applications in electrorheological fluids, smart fluids, and related fields.

In comparison to traditional methods, the sonochemical approach holds unique advantages. The sonication-induced cavitation exerts shearing effects on agglomerates, increasing particle collisions, eliminating local concentration inhomogeneities within the reaction system, and accelerating the reaction process. Consequently, sonochemical synthesis boasts rapid and efficient reactions under mild conditions, yielding uniform and highly pure products with effective control over morphology, particle size, and purity. While demonstrating remarkable performance at the laboratory scale, industrial applications of sonochemical methods face challenges due to the high cost of ultrasonic equipment, leading to increased production costs. Furthermore, during industrial scale-up, issues such as reduced reaction efficiency and inconsistent product quality may arise, complicating industrial implementation.

2.6. Composite and Modification

$SrTiO_3$ suffers from low solar light utilization efficiency, and its intrinsic photocatalytic activity is constrained by factors like photogenerated carrier separation efficiency, hindering its practical application advancements (Jin Xingzhi et al.). In recent years, researchers have employed various modification strategies to enhance the photocatalytic performance of $SrTiO_3$.

Among them, the doping is a kind of important means of modification. Yuhan Wang [44] developed an electrochemically assisted ultra-fast synthesis method for the preparation of high-performance Ti^{3+} self-doped $SrTiO_3$, which is a highly efficient photocatalyst. At a high potential of 1.8V, the production presented regular cuboid particles with a size between 30-100 nm, oxygen vacancy defect ratio of 21.31%, specific surface area of 21.3826 m^2/g, band gap of 3.03 eV, and had strong absorption of light in the wavelength range of 400~800 nm. The material has a degradation rate of up to 96.85% for Rhodamine B (RhB) and has demonstrated excellent performance in stability tests over five cycles. The researchers [45] utilized a planetary ball mill to synthesize nitrogen-doped strontium titanate via the mechanochemical reaction of strontium carbonate, titanium dioxide, and hexamethylenetetramine. The photocatalytic activity of nitrogen-doped strontium titanate can be further enhanced through co-doping with high-valence metal ions or coupling with semiconductors and precious metals. La3+ was co-doped with N3- in the strontium titanate, resulting in the formation of LaxSr1-x TiO_3-yNy through mechanical and non-chemical reactions, with La3+ predominantly doped on the surface of the product as indicated by XPS analysis.

By integrating $SrTiO_3$ with other semiconductor materials, its photoresponse range was broadened, and its photocatalytic performance was further enhanced. Wu Ying [9] achieved this enhancement by combining strontium titanate with other photocatalysts, resulting in improved photocatalytic capabilities of the composite materials. Notably, La-WO_3/$SrTiO_3$-50% exhibited the most prominent effect, achieving complete degradation of methyl orange within 60 minutes under visible light irradiation. This marked improvement in visible light absorption and photocatalytic efficacy surpassed that of Bi_2O_3, La-WO_3, and $SrTiO_3$ individually, with La-WO_3/STO-50% demonstrating the optimal performance.

In summary, through doping, compositing, and other multifaceted modification methods, researchers have notably elevated the performance of strontium titanate photocatalysts. Nevertheless, for large-scale practical applications, further investigations on stability and efficiency under long-term usage conditions are imperative, representing key research directions for the future.

3. Conclusion

There are many methods for synthesizing $SrTiO_3$ nanoparticles for photocatalytic applications. A comprehensive review and analysis of research progress both domestically and internationally are as follows.

The hydrothermal method produces fully developed crystals with low raw material costs, being environmentally friendly, but requiring specific pressure-resistant equipment.

The sol-gel method yields products with high purity but results in environmental pollution due to the use of organic precursors and solvents, requiring strict parameter control and limiting its application.

The coprecipitation method, with its inexpensive and readily available raw materials, mild conditions, and strong manipulability, holds promise for large-scale industrialization. However, the use of precipitants and subsequent complex purification processes may lead to environmental pollution.

The low-temperature solid-state method is a promising green chemistry process with low energy consumption and little environmental impact.

Ultrasonic chemistry boasts rapid and efficient reactions under mild conditions, producing uniform and high-purity products, yet the industrial application of ultrasonic devices poses challenges.

Researchers have also significantly improved the comprehensive photocatalytic performance of strontium titanate nanomaterials through compositing, doping, and modification, not only opening new avenues for their application in energy and environmental fields but also providing fresh insights into the research and preparation of other nanomaterial.

References

[1] Li Pengwei, Cui Junhao, Ge Yanfeng, et al. Research progress on barium titanate photocatalytic material [J]. Journal of Functional Materials, 2020, 51(1): 1049-1054.

[2] Jiang Lei. Study on Photocatalytic Activity of Strontium Titanate[D]. Harbin University of Commerce, 2020

[3] Liu Huanhuan, Shang Shaoming, Hou Hua. Study on the preparation of nano strontium titanate powder by direct precipitation method at low temperature [J]. Applied Chemical Industry, 2016, 45(4): 687-690, 695.

[4] Liu Xudong, Yan Huiyun, Bi Xiaoguo, et al. Progress of Preparation Method of Strontium Titanate Powder [J]. Journal of Shenyang Institute of Engineering (Natural Science), 2020, 16(03): 86-90.

[5] Jia Qibo, Liu, Jian, Zhong Li, Li Yan, Duan Dongping. Preparation of the regular polyhedral single-crystalline $SrTiO_3$ particles with exposing different crystal facets [J]. Materials Letters, 2021, 288(Apr.1): 129338.1-129338.3.

[6] Zhang W K, Tong X L, Huang H, et al. Preparation of perovskite-type nano-$SrTiO_3$ by sol-gel process [J]. The Chinese Journal of Nonferrous Metals, 2005, 15(4): 643-649.

[7] Zhang Hao, Chang Zhuguo, Cui Bin. Preparation of strontium titanate nanopowder by chemical coprecipitation method with new technique [J]. Electronic Components and Material, 2009, 28(6): 12-15.

[8] Wang Kaiming, Wen Chuangeng, Zhou Yingyan, et al. Preparation of Nanometer $SrTiO_3$ Powders by the Special Liquid-phase Precipitation Methods[J]. Electronic Components and Material, 2005, 24(4): 9-12.

[9] Wu Yin. Study on Perovskite Type Photocatalytic Materials with Wide Spectral Response [D]. Huaqiao University, 2018.

[10] Liu Guya. Solid phase synthesis and characterization of $SrTiO_3$ [J]. SCIENCE & TECHNOLOGY INFORMATION, 2017, 15(21): 219+221.

[11] Liu Huiping, Yang Yi, Li Yunpeng, et al. Hydrothermal Preparation of Nitrogen-doped Reduced Graphene Oxide and Its Properties as a Function of Doping Time[J]. Journal of Wuhan University of Technology, 2024, 46(02): 13-20+27.

[12] Hu Xuemei, Qiao Junqiang. Photocatalytic Performance of Copper Zinc Tin Sulfide via Hydrothermal Synthesis [J]. Journal of the Chinese Ceramic Society, 2022, 50(07): 1936-1944.

[13] Zu Li, Xia Yangwen, He Lili, et al. Preparation of Silver Modified Mixed Crystal TiO2 by Hydrothermal Method and Its Photocatalytic Performance [J]. Journal of Synthetic Crystals, 2022, 51(04): 673-678+686.

[14] Xie Junquan. Preparation of Biomimetic TiO2 by hydrothermal method and its photocatalytic [J]. New Chemical Materials, 2023, 51(S1): 69-75.

[15] Liang Ping, Xia Ziwen, Feng Yang, et al. Preparation methods and application prospects of different nanomaterials [J/OL]. New Chemical Materials, 2024, DOI: 10.19817/j.cnki.issn1006-3536.2024.08.046.

[16] Huang S T, Lee W W, Chang J L, et al. Hydrothermal synthesis of $SrTiO_3$ nanocubes: Characterization, photocatalytic activities, and degradation pathway[J]. Journal of the Taiwan Institute of Chemical Engineers, 2014, 45(4):1927-1936.

[17] Shen H, Lu Y, Wang Y, et al. Low temperature hydrothermal synthesis of $SrTiO_3$ nanoparticles without alkali and their effective photocatalytic activity [J]. Journal of Advanced Ceramics, 2016, 5(4): 1-10.

[18] Zhang Na, Zhong Li, Duan Dongping. Regulation of properties and characterization of strontium titanate nanoparticles synthesis by oleic acid-assisted hydrothermal process [J]. The Chinese Journal of Process Engineering, 2019, 19(6): 1212-1219.

[19] Zhang Y, Zhong L, Duan D. Single-step hydrothermal synthesis of strontium titanate nanoparticles from crystalline anatase titanium dioxide [J]. Ceramics International, 2015, 41(10): 13516-13524.

[20] Zhang Y, Zhong L, Duan D. A single-step direct hydrothermal synthesis of $SrTiO_3$ nanoparticles from crystalline P25 TiO_2 powders [J]. Journal of Materials Science, 2016, 51(2): 1142-1152.

[21] Sikam P , Moontragoon P , Sararat C ,et al. DFT calculation and experimental study on structural, optical and magnetic properties of Co-doped $SrTiO_3$[J].Applied Surface Science, 2018, 446(JUL.15): 92-113.

[22] Ming Q, Zu W, Zhu L, et al. Sol-gel assisted chemical activation for nitrogen doped porous carbon [J]. Microporous and Mesoporous Materials. 2019. 15(286): 18-24.

[23] Wang Yanhong, Liu Shuang, and Chen Wei, et al. Sol-gel synthesis of Sr Ti O3: Rh photocatalysts for hydrogen evolutionby water splitting under visible light [J]. Chemical Research, 2017, 28(5): 593-597.

[24] D. Zhou, P. Zhai, G. Hu, J. Yang. Up conversion luminescence and enhanced photocatalytic hydrogen production for Er^{3+} doped $SrTiO_3$ nanopaeticles [J]. Chemical Physics Letters, 2018, 711: 77-80

[25] Wang Jiawei. Sol-gel method to synthesis LST ($La_{0.2}Sr_{0.7}TiO_3$) powder and its characterization [J].Shanxi Chemical Industry, 2015, 35(6): 18-21.

[26] Peng Fuchang, Lai Qi. Study on Preparation and Properties of $SrTiO_3$ Photocatalyst Doped Zn [J]. Materials Reports, 2016, 30(S2): 276-279.

[27] Hou Qinqin, Jiang Yuanru, Wang Wei, et al. Study on Preparation of Strontium Titanate Nanopowders and Ultrasonic Degradati on Effect toward Basic Fuchsin Wastewater [J]. Materials Reports, 2014, 28(20): 38-40, 61.

[28] Wang Guiyun, Wang Yanji, Xu Yongquan, et al. Synthesis Highly Pure Ultrafine $SrTiO_3$ by Chemical precipitation [J]. Journal of Material Science & Engineering, 2003, 21(4): 562-564.

[29] Lu Hongxia, Jing Hui, Zhang Lingling, et al. Strontium Titanate Powder of Co-precipitation Method Preparation Research [J]. Hunan Nonferrous Metals, 2017, 33(6): 49-51, 80.

[30] Hu Xiong, Ding Yigang, Wu Yuanxin, et al. Preparation of nano-sized strontium titanate powder and research on its surface modification process [J]. Inorganic Chemicals Industry, 2007, 39(10): 19-20.

[31] Jiang Yuanru, Li Zhao, Wang Lijing, et al. Study on Preparation of Strontium Titanate Powder Catalyst and Degradation of Malachite Green Wastewater [J]. Chemical World, 2012, 53(8): 467-470.

[32] Guo Yanqin. Synthesis and decolorization of $SrTiO_3$ powders for methyl orange [J]. Ordnance Material Science and Engineering, 2014(6): 94-96.

[33] Xin Gang, Guo Wei, Ma Yanli. Study of $SrTiO_3$ prepared by molten salt synthesis process for water splitting [J]. Journal of Dalian University of Technology, 2011, 51(1): 20-24.

[34] Berbenni V, Marini A, Bruni G. Effect of mechanical activation on the preparation of $SrTiO_3$ and Sr2TiO4 ceramics from the solid-state system SrCO3-TiO2 [J]. Journal of Alloys and Compounds, 2001, 329(1-2):230-238.

[35] Lian Hongfang. Advances in Studying on Synthesis of Nanometer Powders by Solid State Reaction under Low Temperature [J]. Guangdong Chemical Industry, 2006, 33(7): 8-9, 63.

[36] Ding Shiwen, Zhang Yuanyuan, Zhang Hongjun. Synthesis of $SrTiO_3$ nanopowder by solid-state reaction at low temperature [J]. Electronic Components and Material, 2009, 2 8(10): 28-30.

[37] ZHU Q A, XU J G, XIANG S, et al. Preparation of $SrTiO_3$ nanoparticles by the combination of solid phase grinding and low temperature calcining[J]. Materials Letters, 2011, 65(5): 873-875.

[38] He Shoujie, Ha Jing, Wang Yunming, et al. Applications of Sonochemistry in Preparing Nanosized Materials [J]. Chemistry Bulletin, 2008, 71(11): 846-851.

[39] Xu Ke. Application of Sonochemistry in Nanomaterials Synthesis [J]. Journal of West Anhui University, 2007, 23(5): 71-74.

[40] Liu Hong. Synthesis of TiO_2 and $SrTiO_3$ nanoparticles by ultrasonic chemical method [D]. Nanjing Tech University, 2008.

[41] Xu M, Lu Y N, Liu Y F, et al. Synthesis of monosized strontium titanate particles with tailored morphologies [J]. Journal of the American Ceramic Society, 2010, 89(12): 3631-3634.

[42] Jimmy C. Yu, Lizhi Zhang, Quan Li, Kwan Wai Kwong, An-Wu Xu, and Jun Lin. Sonochemical Preparation of Nanoporous Composites of Titanium Oxide and Size-Tunable Strontium Titanate Crystals[J]. Langmuir, 2003, 19(18): 7673-7675

[43] Jiang Chuanxia. Preparation and electrorheological properties of porous perovskite nanomaterials [D]. University of Science and Technology of China, 2010.

[44] Yuhan Wang, Xinyue Liu, Kai Yu, Zhiqiang Ning, Qiushi Song, Hongwei Xie, and Ultra-fast synthesis of the high performance photocatalytic Ti3+ self-doped strontium titanate by an electrochemical assist in molten salt: effect of electrochemical potential Check for updates [J]. Journal of Materials Chemistry A, 2024, 12, 6087

[45] TSUGIO SATO, PEILIN ZHANG, SHU YIN, High performance visible light responsive photocatalysts for environmental cleanup via solution processing [J]. Progress in Crystal Growth and Characterization of Materials, 2012, 58(2/3): 92-105.