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Article

La(OH)₃ and La₂O₂CO₃ nanorod catalysts for Claisen-Schmidt condensation

Fei Wang, Na Ta, Yong Li, Wenjie Shen*

State Key Laboratory of Catalysis, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, Liaoning, China

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ABSTRACT

La(OH)₃ nanorods of 15 nm diameter and up to 700 nm long were synthesized using different pH values of the solution used in the hydrothermal synthesis. A more alkaline solution favored the formation of tiny La(OH)₃ nuclei, which grew along the *c*-axis due to their anisotropic nature and led to the formation of rod-shaped crystals. Calcination of the La(OH)₃ nanorods at 773 K gave La₂O₂CO₃ nanorods. Their basic properties were correlated with their size. As the aspect ratio increased from 2 to 20, the basic sites increased from 0.08 to 0.24 mmol/g, which was due to a higher exposure of (110) planes. In the catalysis of the condensation reaction of benzaldehyde with acetophenone, the reaction rate was correlated with the number of La³⁺–O^{2–} pairs on the exposed (110) facets of the La₂O₂CO₃ nanorods.

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1. Introduction

Metal oxides are widely used in heterogeneous catalysis either as a support to disperse and stabilize metal nanoparticles or as an essential component in the reaction. Recent studies have demonstrated that the shape of oxide particles at the nanometer level affected the preferential exposure of reactive facets, which in turn promoted catalytic performance [1–4]. For example, CeO₂ nanorods that mainly exposed the (100) and (110) planes were more active for CO oxidation than polyhedral CeO₂ nanoparticles that were enclosed by the (111) planes [5,6]. Co₃O₄ nanorods that exposed the more reactive (110) planes more efficiently catalyzed CO oxidation [7], methane combustion [8], and selective reduction of NO by ammonia [9] than conventional spherical particles that mainly exposed the (111) facets. This morphology-dependent phenomenon has been observed with metal oxides with acid-base properties as

well. For example, MgO hexagonal platelets that exposed the (100) facets were more active for the benzoylation of aromatics than cubic and square particles [10]. MgO nanosheets that mainly exposed the (111) planes showed much higher activity in the condensation reaction of benzaldehyde with acetophenone than cubic MgO crystals enclosed by the (100) facets [11,12].

Lanthanum oxides are used as promoters or supports in heterogeneous catalysis [13,14]. The basicity of La₂O₃ caused the easy adsorption of water and CO₂ to form La₂O₂CO₃ that are the catalytic species in most La₂O₃-catalyzed reactions [15,16]. For example, La₂O₃ plates that mainly exposed the (001) planes favored the formation of La₂O₂CO₃ species that were more active and selective in oxidative coupling of methane to ethylene [14]. Rod-shaped La₂O₂CO₃ gave a selective deposition of copper particles on the (110) planes, and the resulting catalyst was highly efficient for the dehydrogenation of primary aliphatic

* Corresponding author. Tel: +86-411-84379085; Fax: +86-411-84694447; E-mail: shen98@dicp.ac.cn

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alcohols [17]. $\text{La}_2\text{O}_2\text{CO}_3$ is the key intermediate in the thermal transformation of $\text{La}(\text{OH})_3$ to La_2O_3 , and its nanostructure is often determined by that of the $\text{La}(\text{OH})_3$ precursor [17,18]. In the synthesis strategies for synthesizing $\text{La}(\text{OH})_3$ nanorods in the liquid phase, the diameter and length of the nanorods depended on the pH value of the synthesis solution [18–22]. Using hydrazine as the precipitation agent provided nanorods with a diameter of 10–15 nm and a length of 30–50 nm [19]. Organic bases such as butylamine and triethylamine produced $\text{La}(\text{OH})_3$ nanorods with diameters of 8–15 nm and lengths of 100–600 nm [20,21]. Precipitation in aqueous ammonia solution favored the growth of the nanorods where the diameter was 15 nm and the length increased to 120–200 nm [18]. Hydrothermal synthesis in aqueous ammonia solution yielded $\text{La}(\text{OH})_3$ nanorods with diameters of 40–60 nm and lengths of 300–1000 nm [22]. It appeared that the alkalinity of the synthesis solution played a decisive role in determining the aspect ratio of the $\text{La}(\text{OH})_3$ nanorods. However, detailed information on the growth mechanism of the nanorods is still limited.

In this work, we prepared $\text{La}(\text{OH})_3$ nanorods with tunable aspect ratios in the range of 2–45 by precisely controlling the pH value of the synthesis solution and examined the growth mechanism of the nanorods. The $\text{La}(\text{OH})_3$ nanorods were transformed into $\text{La}_2\text{O}_2\text{CO}_3$ nanorods by calcination at 773 K in air. The basic properties of these rod-shaped oxides were correlated with their catalytic performance in the condensation reaction of benzaldehyde with acetophenone.

2. Experimental

2.1. Materials Preparation

$\text{La}(\text{OH})_3$ nanorods were synthesized using a hydrothermal method. 0.8 g of commercial La_2O_3 powder was dissolved in 120 mL of 10% nitric acid. Aqueous KOH solution (9.0 mol/L) was added at room temperature to adjust the pH value of the mixture to the 7–13 range. The slurry was divided into four and transferred into four autoclaves (100 mL), which were gradually heated to 453 K and kept at that temperature for 12 h. The solid was filtrated, washed with water, and dried at 323 K overnight under vacuum to yield the $\text{La}(\text{OH})_{3-x}$ samples, where x denotes the pH value of the initial slurry. Calcination of these lanthanum hydroxides at 773 K for 4 h in air produced $\text{La}_2\text{O}_2\text{CO}_3$ samples.

2.2. Structural Analysis

Nitrogen adsorption isotherms at 77 K were recorded with a Micrometrics ASAP 2010 instrument. Before the measurement, the sample was degassed at 573 K for 3 h. The surface area was calculated using a multipoint BET analysis of the adsorption isotherm. X-ray powder diffraction (XRD) patterns were recorded on a D/MAX 2500/PC powder diffractometer (Rigaku) using a $\text{Cu K}\alpha$ radiation source operated at 40 kV and 200 mA. Raman spectra were obtained with a Jobin-Yvon T64000 triple stage spectrometer with a laser source at 325 nm and a spectral resolution of 2 cm^{-1} . Transmission electron microscopy

(TEM) images were recorded on a Hitachi 7700 operated at 120 kV. High resolution TEM (HRTEM) images were obtained with a FEI Tecnai G² F30 S-Twin microscope operated at 300 kV. The specimen was prepared by ultrasonically dispersing the sample powder in ethanol and drops of the suspension were deposited on a clean carbon-coated copper grid and dried in air.

Temperature programmed desorption (TPD) of CO_2 on the $\text{La}_2\text{O}_2\text{CO}_3$ samples was conducted with a U-shape quartz tubular reactor connected to a mass spectrometer (OmniStar 200). The samples (50 mg) were heated to 773 K at a rate of 10 K/min under He flow (30 mL/min) and kept at that temperature for 2 h to remove surface impurities. The sample was then exposed to a mixture of 30% CO_2/He (20 $\text{mL}\cdot\text{min}^{-1}$) at 473 K for 1 h, and purged with He (30 mL/min) at 473 K for 3 h. After cooling down to room temperature, the sample was heated to 1073 K at a rate of 10 K/min under He flow (30 mL/min). Desorption of CO_2 was monitored by the mass spectrometer.

2.3. Catalytic Tests

The Claisen-Schmidt condensation reaction of benzaldehyde with acetophenone was conducted in a 50 mL round bottomed flask under nitrogen atmosphere and magnetic stirring. In a typical test, 3 mmol acetophenone, 2.5 mmol benzaldehyde, 100–300 mg catalyst (activated at 373 K for 2 h prior to the test) and 10 mL toluene were added into the flask and the reaction was performed at 383 K for a fixed period. The product was analyzed using an offline gas chromatograph (Agilent GC-7890A, HP-5 capillary column). The reaction rate was measured by adjusting the conversion of benzaldehyde to be less than 15% by changing the mass of the catalyst and reaction time.

3. Results and discussion

3.1. Structure and morphology of $\text{La}(\text{OH})_3$ nanorods

The influence of the pH value of the synthesis solution on the size of the $\text{La}(\text{OH})_3$ nanorods was first examined by changing the amount of aqueous KOH solution (9.0 mol/L). As shown in Fig. 1, the diffraction lines of the samples can be indexed to hexagonal $\text{La}(\text{OH})_3$ (JCPDS No. 36-1481). The crystalline size, estimated from the (100) line by the Scherrer equation, depended on the pH value of the synthesis solution. The size was 32.5 nm with a pH of 7.0 and it gradually decreased to 13.1 nm with a pH of 13.0. The corresponding $I_{(101)}/I_{(100)}$ ratio decreased from 1.8 to 1.4, which implied an anisotropic growth along the (100) orientation with increasing alkalinity of the synthesis solution.

TEM observations (Fig. 2) showed that the aspect ratio of the $\text{La}(\text{OH})_3$ nanorods increased remarkably with the basicity of the synthesis solution. At pH = 7.0, short $\text{La}(\text{OH})_3$ nanorods with a diameter (D) of 40 nm and a length (L) of 75 nm were produced. With a slight increase in the pH value to 9.0, the diameter decreased to 35 nm while the length increased to 140 nm. At pH = 11.0, the diameter further decreased to 20 nm

Fig. 1. XRD patterns of the $\text{La}(\text{OH})_3$ nanorods prepared with a pH value of 7.0 (1), 9.0 (2), 11.0 (3), and 13.0 (4).

Fig. 2. TEM images of the $\text{La}(\text{OH})_3$ nanorods prepared with a pH value of 7.0 (a), 9.0 (b), 11.0 (c), and 13.0 (d).

while the length increased to 280 nm. At pH = 13.0, the diameter slightly decreased to 15 nm but the length was sharply extended to 700 nm. Table 1 summarizes the surface areas and aspect ratios of the $\text{La}(\text{OH})_3$ nanorods. It is obvious that the aspect ratio increased with increasing pH value. The surface area decreased, which was mainly due to the increase in the length of the nanorods. These results indicated that the higher

Table 1

Physical and chemical properties of the $\text{La}(\text{OH})_3$ nanorods.

Sample	Size ^a		Aspect ratio (L/D)	Crystal size ^b (nm)	Surface area (m^2/g)
	L/nm	D/nm			
$\text{La}(\text{OH})_3\text{-7}$	75	40	2	32.5	104
$\text{La}(\text{OH})_3\text{-9}$	140	35	4	21.9	94
$\text{La}(\text{OH})_3\text{-11}$	280	20	14	15.0	78
$\text{La}(\text{OH})_3\text{-13}$	700	15	45	13.1	62

^a Determined by TEM measurements.

^b Estimated from the Scherrer equation.

alkalinity of the synthesis solution provided sufficient OH^- species to give rapid nucleation of $\text{La}(\text{OH})_3$ with smaller sizes and also induced a preferential growth along the axial direction, resulting in a much larger aspect ratio.

The sizes of the products at different time during the hydrothermal synthesis at the pH value of 13.0 were investigated by XRD (Fig. 3) and TEM (Fig. 4). Precipitation of lanthanum nitrate with aqueous KOH solution immediately yielded $\text{La}(\text{OH})_3$ nanoparticles (about 15 nm) with poor crystallinity and irregular shape. After hydrothermal synthesis for 4 h, short nanorods with a diameter of 12 nm and lengths of 50–70 nm were produced. At 8 h, the diameter of the nanorods remained almost unchanged but the length continuously increased to 500 nm. On further extending the synthesis time to 12 h, the diameter was only slightly enlarged to 15 nm while the length was significantly increased to 700 nm. This result indicated Ostwald ripening of the nanorods occurred under the hydrothermal conditions. The XRD patterns also confirmed the preferential growth of the $\text{La}(\text{OH})_3$ nanorods. The intensity of the diffraction

Fig. 3. XRD patterns of the $\text{La}(\text{OH})_3\text{-13}$ samples at different synthesis time. (1) 0 h; (2) 4 h; (3) 8 h; (4) 12 h.

Fig. 4. TEM images of $\text{La}(\text{OH})_3\text{-13}$ samples at different synthesis time. (1) 0 h; (2) 4 h; (3) 8 h; (4) 12 h.

lines of hexagonal $\text{La}(\text{OH})_3$ was much enhanced with time, showing better crystallinity. In particular, the intensity of the (110) line increased and separated into the (110) and (101) lines. The intensity ratio between the (101) and (100) lines was 2.1 at 4 h, and it gradually decreased to 1.6 at 8 h and 1.4 at 12 h, implying that the growth rate of the (101) plane was much higher than that of the (100) and (110) facets.

Figure 5 shows the HRTEM images of the $\text{La}(\text{OH})_3$ -13 sample. When viewed along the [010] orientation, the interplanar spacings of 0.56 and 0.32 nm corresponded to the (100) and (101) planes, respectively. On imaging along the [110] direction, (101) and (002) facets at an angle of 90° were clearly observed. The hexagonal cross-section viewed along the [001] orientation was enclosed by six planes with an angle of 120° between the two neighboring planes. Therefore, it can be inferred that the $\text{La}(\text{OH})_3$ nanorod exposed (100), (010) and (110) side facets and (001) end facets. Among these, the polar (001) plane in the hexagonal structure has a higher surface energy than the non-polar planes [23,24], which would induce preferential growth along the [001] direction. These results demonstrated that the growth of the $\text{La}(\text{OH})_3$ nanorods was mainly governed by the pH value of the synthesis solution and the crystallographic structure. It is likely that the growth process involves two mechanisms: oriented attachment in the initial stage and Ostwald ripening during the growing stage [25,26]. In the initial stage, tiny $\text{La}(\text{OH})_3$ nanoparticles were formed in a homogeneous nucleation process. Under the hydrothermal conditions at 453 K, these small $\text{La}(\text{OH})_3$ nanoparticles agglomerated into a rod-shape structure by an oriented attachment mechanism. With increased synthesis time, the short $\text{La}(\text{OH})_3$ nanorods grew longer, during which the diameter increased slightly but the length increased significantly, probably by the Ostwald ripening mechanism. It was the anisotropic crystal structure of the hexagonal $\text{La}(\text{OH})_3$ that induced the nucleation and growth along the axial direction. Therefore, the morphological evolution from nanoparticles to nanorods was through a nucleation-dissolution-recrystallization growth mechanism, and the crystal structure of the seeds played an important role in the formation of the nanorods [27,28]. Hex-

Fig. 5. HRTEM images of the $\text{La}(\text{OH})_3$ -13 nanorods viewed along: (a) [010] orientation, (b) [110] orientation; (c) a hexagonal cross-section viewed near the [001] orientation; (d) illustration of the actual shape of the $\text{La}(\text{OH})_3$ -13 nanorod.

agonal $\text{La}(\text{OH})_3$ can be described as infinite linear chains of lanthanum and oxygen atoms that extend along the c -axis. Since the atomic interactions along the a - and b -directions are much weaker than that along the c -axis, the growth direction was confined to the [001] direction along the c -axis [29]. The $\text{La}(\text{OH})_3$ nanoparticles were incorporated along the c -axis due to this anisotropic feature, which led to the formation of the rod-shaped structure. Ostwald ripening with time caused a remarkable increase in the length but with only marginal growth in the diameter, resulting in a much higher aspect ratio of the nanorods.

3.2. Structure and morphology of $\text{La}_2\text{O}_2\text{CO}_3$ nanorods

Upon calcination at 773 K in air, the $\text{La}(\text{OH})_3$ nanorods were transformed into $\text{La}_2\text{O}_2\text{CO}_3$ nanorods. The diffraction lines of the samples were assigned to hexagonal $\text{La}_2\text{O}_2\text{CO}_3$ -II (JCPDS 84-1963) (Fig. 6(a)). Raman spectra (Fig. 6(b)) further con-

Fig. 6. XRD patterns (a) and Raman spectra (b) of the $\text{La}_2\text{O}_2\text{CO}_3$ -7 (1), $\text{La}_2\text{O}_2\text{CO}_3$ -9 (2), $\text{La}_2\text{O}_2\text{CO}_3$ -11 (3), and $\text{La}_2\text{O}_2\text{CO}_3$ -13 (4) nanorods.

Fig. 7. TEM images of the $\text{La}_2\text{O}_2\text{CO}_3$ -7 (a), $\text{La}_2\text{O}_2\text{CO}_3$ -9 (b), $\text{La}_2\text{O}_2\text{CO}_3$ -11 (c), and $\text{La}_2\text{O}_2\text{CO}_3$ -13 (d) nanorods.

firmed the formation of $\text{La}_2\text{O}_2\text{CO}_3$. The bands at 358, 384, and 747 cm^{-1} were assigned to the stretching and bending modes of the La–O bond [30]. Their intensity slowly decreased with increasing aspect ratio. The intense band at 1086 cm^{-1} was assigned to the vibration of CO_3^{2-} group [30]. The intensity of this band increased and broadened gradually with increasing aspect ratio.

Figure 7 shows the TEM images of the $\text{La}_2\text{O}_2\text{CO}_3$ samples. Compared with their hydroxide precursors, the diameters were only slightly decreased but the lengths were shortened remarkably. HRTEM analysis of the typical $\text{La}_2\text{O}_2\text{CO}_3$ -13 sample indentified that the nanorod had straight sides and regular ends (Fig. 8). The dominant exposure of the (001) plane was clearly seen in the images viewed along the [010] and [110] orientations. Figure 8(c) shows an image of a single $\text{La}_2\text{O}_2\text{CO}_3$ nanorod viewed along the [001] orientation. The nanorod grew along the [110] direction and was enclosed by (110), (100) and (010) planes. When viewed along the growing direction of [110], the nanorod had a rectangular cross-section with (110) and (001) side planes. Taking all these observations into account, the actual shape of the $\text{La}_2\text{O}_2\text{CO}_3$ nanorod was a square block that was terminated by two (001) flat planes, two (110) side planes and two (110) end planes. The width of the flat (001) plane was

Fig. 8. HRTEM images of the $\text{La}_2\text{O}_2\text{CO}_3$ -13 nanorods viewed along: (a) [010] orientation, (b) [001] orientation, (c) [110] orientation; (d) a rectangular cross-section ($10\text{ nm} \times 15\text{ nm}$) of a single nanorod viewed near the [110] orientation; (e) illustration of the actual shape of the $\text{La}_2\text{O}_2\text{CO}_3$ nanorod.

15 nm while that of the side (110) plane was 10 nm. The area of the (110) planes increased with increasing aspect ratio of the $\text{La}_2\text{O}_2\text{CO}_3$ -x nanorods, as summarized in Table 2. The atomic configurations of both (110) and (110) planes were composed of La and O atoms while the flat (001) surface was terminated by C and O atoms [17].

Figure 9 shows the CO_2 -TPD profiles of the $\text{La}_2\text{O}_2\text{CO}_3$ nanorods. The basicity of lanthanum oxides usually follows the order of low coordination oxygen anions $> \text{La}^{3+}\text{-O}^{2-}$ pairs $>$ hydroxyl groups [31–33]. The temperature of CO_2 desorption allows the basicity to be roughly categorized into three types: weak basicity (below 433 K), medium basicity (433–600 K) and strong basicity (above 600 K) [33]. The $\text{La}_2\text{O}_2\text{CO}_3$ nanorods showed only one intense CO_2 desorption peak at 490–560 K, which represented the basic sites with medium-strength due to surface $\text{La}^{3+}\text{-O}^{2-}$ pairs. The amounts of these basic sites increased with increasing aspect ratio of the $\text{La}_2\text{O}_2\text{CO}_3$ nanorods (Table 2), and was in good agreement with the increasing surface area of the (110) planes.

3.3. Claisen-Schmidt condensation reaction

The $\text{La}_2\text{O}_2\text{CO}_3$ nanorods were used to catalyze the Claisen-Schmidt condensation of benzaldehyde with aceto-

Table 2

Claisen-Schmidt condensation of benzaldehyde with acetophenone on the $\text{La}_2\text{O}_2\text{CO}_3$ nanorods.

Sample	Size ^a		Aspect ratio (L/D)	Surface area (m^2/g)	Area of the (110) planes (m^2/g)	Amount of the basic sites ^b (mmol/g)	Reaction rate ^c (mol/(g·s))	TOF ^d (10^{-3} s^{-1})
	L/nm	D/nm						
$\text{La}_2\text{O}_2\text{CO}_3$ -7	80	38	2	85	14.6	0.08	4.46×10^{-7}	5.6
$\text{La}_2\text{O}_2\text{CO}_3$ -9	140	30	5	77	15.1	0.11	6.05×10^{-7}	5.5
$\text{La}_2\text{O}_2\text{CO}_3$ -11	230	15	15	67	22.3	0.20	1.18×10^{-6}	5.9
$\text{La}_2\text{O}_2\text{CO}_3$ -13	310	15	20	60	26.1	0.24	1.39×10^{-6}	5.8

^a Determined by TEM measurements.

^b Estimated from the CO_2 -TPD profiles in Fig. 9.

^c Conversion of benzaldehyde kept less than 15% by varying the mass of the catalyst and reaction time. The selectivity of the product was $> 99\%$.

^d Obtained by dividing the reaction rate by the amount of basic sites.

Fig. 9. CO₂-TPD profiles of the La₂O₂CO₃-7 (1), La₂O₂CO₃-9 (2), La₂O₂CO₃-11 (3), and La₂O₂CO₃-13 (4) nanorods.

phenone. As shown in Fig. 10, the conversion of benzaldehyde increased with increasing aspect ratio, and the La₂O₂CO₃-13 sample showing a much higher conversion of benzaldehyde. Kinetic measurements at 383 K revealed that the reaction rate was directly associated with the amount of basic sites (La³⁺–O^{2–} pairs) on the nanorods, suggesting that the surface La³⁺–O^{2–} pairs acted as the active sites. The reaction rate was 4.46×10^{-7} mol/(g·s) on the La₂O₂CO₃-7 sample and approached 1.39×10^{-6} mol/(g·s) on the La₂O₂CO₃-13 sample (Table 2). By correlating the reaction rate with the number of the surface basic sites, very close turnover frequency (TOF), 5.5×10^{-3} – 5.9×10^{-3} s^{–1}, were obtained for all samples suggesting that the active sites on the La₂O₂CO₃ nanorods were the same, and most likely were the La³⁺–O^{2–} pairs, discussed above, the (110) planes that were predominantly exposed on the La₂O₂CO₃ nanorod were composed of La and O atoms, which favored the existence of active La³⁺–O^{2–} species. An increase in the aspect ratio of the nanorods enhanced the surface areas of the (110) planes, which in turn increased the number of basic sites. The high activity of the La₂O₂CO₃-13 sample was closely associated with the large amount of surface basic sites shown in the CO₂-TPD measurement. Previous studies have shown that alkaline earth oxides, especially MgO, efficiently catalyzed aldol condensation reactions [34–36]. The active sites were typically

Fig. 10. Benzaldehyde conversion over the La₂O₂CO₃ nanorods. Reaction conditions: acetophenone 3 mmol, benzaldehyde 2.5 mmol, toluene 10 mL, La₂O₂CO₃ 300 mg, 383 K.

assigned to the Mg²⁺–O^{2–} pairs, with the O^{2–} acting as a Lewis basic site and the adjacent Mg²⁺ acting as a weak Lewis acid site. Considering the chemical similarity of La³⁺–O^{2–} and Mg²⁺–O^{2–}, it is likely that the La³⁺–O^{2–} sites on the La₂O₂CO₃ nanorods accounted for the catalytic activity in Claisen-Schmidt condensation.

4. Conclusions

La(OH)₃ nanorods with different aspect ratios were synthesized using hydrothermal synthesis by using different pH values of the synthesis solution. Calcination of these La(OH)₃ precursors at 773 K in air yielded La₂O₃CO₃ nanorods. The amount of basic sites on the main exposed (110) face increased from 0.08 to 0.24 mmol/g with increasing aspect ratio from 2 to 20. The reaction rate in the condensation reaction of benzaldehyde with acetophenone was well correlated with the number of the active La³⁺–O^{2–} sites on the (110) facets.

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Graphical Abstract

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La(OH)₃ and La₂O₂CO₃ nanorod catalysts for Claisen-Schmidt condensation

Fei Wang, Na Ta, Yong Li, Wenjie Shen*

Dalian Institute of Chemical Physics, Chinese Academy of Sciences

The basicity of La₂O₂CO₃ nanorods increased with increasing aspect ratio, and their catalytic activity for Claisen-Schmidt condensation was associated with the La³⁺–O^{2–} sites on the (110) facets.

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La(OH)₃和La₂O₂CO₃纳米棒的合成及其催化Claisen-Schmidt缩合反应性能

王 非, 塔 娜, 李 勇, 申文杰*

中国科学院大连化学物理研究所催化基础国家重点实验室, 辽宁大连116023

摘要: 通过调节溶液的pH值, 在水热条件下合成出长径比为2–45的La(OH)₃纳米棒。对水热合成过程中间体的结构演变分析, 发现高碱度有利于小尺寸晶核的形成, La(OH)₃晶体结构的各向异性导致这些晶种沿着C轴方向生长, 进而形成纳米棒结构。将La(OH)₃纳米棒前驱体于773 K焙烧可以得到长径比为2–20的La₂O₂CO₃纳米棒。随着长径比的增加, La₂O₂CO₃纳米棒暴露的(110)晶面逐渐增加, La³⁺–O^{2–}碱性位的数目也从0.08增加到0.24 mmol/g。因此, 在Claisen-Schmidt缩合反应中, La₂O₂CO₃纳米棒催化剂上的反应速率随着长径比的增加而逐渐增大。

关键词: 氢氧化镧; 碳酸氧镧; 纳米棒; 晶面; 碱性; Claisen-Schmidt缩合反应

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*通讯联系人. 电话: (0411)84379085; 传真: (0411)84694447; 电子信箱: shen98@dicp.ac.cn

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