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Novel WO_3/SO_4^2 -Zr O_2 -Ti O_2 double bridge coordination catalyst hfor oxidation of cyclohexene



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ABSTRACT

A solid super acid WO₃/SO₄²-ZrO₂–TiO₂ catalyst was prepared with adjustable acidity *via* double bridge connection strategy for oxidation of cyclohexene (CHE) to adipic acid (AA). XRD, SEM and N₂ adsorption-desorption isotherm indicated that WO₃ was successfully decorated and was highly dispersed on SO₄²⁻ZrO₂–TiO₂ surface. An obvious stretching vibration peak (1125-1055 cm⁻¹) in FT-IR illustrated that connection effect between SO₄²⁻ and ZrO₂–TiO₂ was double bridge connection. NH₃-TPD profile appeared a strong acid center peak (516 °C), while this center of solid super acid catalyst could reduce decomposition rate of H₂O₂ directly, and increase reaction time between CHE and H₂O₂ meanwhile. The marked catalytic performance was attributed to the synergistic effect between WO₃ and SO₄²-ZrO₂–TiO₂. DFT calculation was employed to further analyze reaction process and system energy.

1. Introduction

Adipic acid (AA) had been widely used in plastic packaging, medical and chemical preparation fields, as a vital aliphatic dicarboxylic acid [1, 2]. In previous work, AA was successfully synthesized by oxidizing of cyclohexene, cyclohexanone or cyclohexanol with nitric acid. However, there were still many problems and challenges, *e.g.*, nitric acid served as oxygen source could release nitric oxide, waste acid and so on. In addition, the system acidity couldn't be effectively controlled as well [3,4]. Therefore, it's necessary to develop a novel preparation strategy to achieve the green synthesis of AA.

It's reported that employing O_2 or H_2O_2 as green oxygen sources was a desirable candidate instead of nitric acid for CHE oxidation [5]. Partial hydrogenation of benzene was a well-known reaction, which had been studied for many years. The first industrial production of cyclohexene was manufactured by Asahi in 1990 in Japan [6]. Up to 2015, China became the second country to achieve industrialize CHE [7]. Therefore, the price of CHE had appeared decrease in recent years. Generally, H_2O_2 served as oxygen source had the characteristics of moderate conditions, low toxicity, high yield and short process route advantages [8–10]. Maintaining an ideal acid condition was extremely important for CHE

oxidation because it could decrease H_2O_2 decomposition rate and enhance reaction time between CHE and H_2O_2 . In the traditional AA synthesis process, PH value was adjusted by introducing inorganic acid (*e.g.*, H_2SO_4) or organic acids (*e.g.*, AA) [11,12]. For example, Jin et al. discussed the effect of acidity environment for AA yield, proving that adding H_2SO_4 could significantly improve CHE conversion rate [13]. However, this strategy had not been applied in industrialization due to some subsistent problems (such as corrode equipment and waste acid treatment) [14–16]. Up to now, a lot of efforts had been devoted to solve this problem. From recent researches, it was found that metal oxides with mechanical stability and easier separation could be employed in the catalysts for preparation of AA [17,18]. Moreover, metal oxides showed the unique ability for fixing acids as well, which could combined with SO_4^2 to structure SO_4^2 / M_xO_y solid super acid [19].

In this paper, a novel WO₃/SO²₄-ZrO₂-TiO₂ solid super acid catalyst had been established successfully *via* impregnation precipitation method for AA preparation. The main advantages involved: (i) Designing a solid super acid catalyst could regulate acidity. (ii) Comparing to traditional technology process, the introduction of the other acidic chemicals was avoided and a simplified the experiment pathway was also realized. The synthesis process of catalyst was shown in Scheme 1. This study provided

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Scheme 1. The preparation process diagram of WO_3/SO_4^2 -Zr O_2 -Ti O_2 .

a new strategy for green preparation of AA by $\mathrm{H}_2\mathrm{O}_2$ oxidation of CHE without any other reagents.

2. Experimental

2.1. Catalysts preparation

2.1.1. Preparation of SO₄²⁻-ZrO₂-TiO₂ support

The SO₄²-ZrO₂-TiO₂ was manufactured by the impregnation precipitation method [20]. Firstly, 1.2 mol TiCl₄ and 1.2 mol ZrOCl₂·8H₂O were diluted by 200 ml deionized water. PH of the mixture was controlled at around 9–10 with NH₃·H₂O and then stirred for 1 h. Then the solution was placed at room temperature for 10 h, and the filter cake was repeatedly washed until all Cl⁻ were washed away (detected with 0.1 mol L⁻¹ AgNO₃). Subsequently, the dried precipitate solid was immersed in 0.5 mol L⁻¹ H₂SO₄ aqueous solution (proportion of 15 ml g⁻¹) for 12 h. Finally, the dried filter cake was calcined in a muffle furnace at 550 °C for 4 h and the resulting product was named SO₄²-ZrO₂-TiO₂. A similar method for preparing CuO-TiO₂, La₂O₃-TiO₂, ZrO₂-TiO₂ by replacing ZrOCl₂·8H₂O with Cu(NO₃)₂·H₂O and La₂(NO₃)₃·6H₂O.

2.1.2. Synthesis of WO_3/SO_4^2 -ZrO₂-TiO₂ sample

The synthesis of the WO₃/SO²₄-ZrO₂-TiO₂ sample was prepared *via* the complexation method. First of all, 3.75 g (NH₄)₁₀W₁₂O₄₁~*x*H₂O was dissolved in an aqueous solution containing 0.5 g C₂H₂O₄·2H₂O and was stirred for 4 h at 25 °C. Subsequently, 8.01 g SO²₄-ZrO₂-TiO₂ was added to above solution. And then the resulting mixed solution (A) was heated to 85 °C. They were maintaining reaction temperature until all water evaporated. In the end, the dried solid was calcined and treated in muffle furnace at 450 °C for 4 h. The product obtained was named X WO₃/SO²₄-ZrO₂-TiO₂ (X was the mass fraction of WO₃ in the catalyst). WO₃/CuO-TiO₂, WO₃/La₂O₃-TiO₂ and WO₃/ZrO₂-TiO₂ were also prepared in the same way, except to replace SO²₄-ZrO₂-TiO₂ with CuO-TiO₂, La₂O₃-TiO₂ and ZrO₂-TiO₂, respectively.

2.2. Preparation of WO_3/SO_4^2 -Zr O_2 -Ti O_2 -H sample

Solution A was aged 24 h at room temperature, then it was maintained at 110 °C for 24 h in hydrothermal synthesis reactor. After filtering and drying, the precipitate was calcined in muffle furnace at 450 °C for 4 h, named WO_3/SO_4^2 -ZrO₂-TiO₂-H.

2.3. Characterization of catalyst

The X-ray diffraction (XRD) patterns were recorded on a RINT2000 vertical goniometer X-ray diffractometer (using CuK α radiation ($\lambda = 0.15418$ nm) in the range of 10–80°, at a speed of 5°·min⁻¹). N₂ adsorption-desorption isotherm was carried out on ASAP 2020V4.01 sorptometer at –196 °C. All samples were outgassed at 100 °C for 8 h before the measurement. NH₃-TPD was used to reflect NH₃ adsorption on the catalyst surface. It was fully automated by Zhejiang Pantai Instrument FINESORB-3010 Temperature-rising chemisorption to test. The test sample was 70 mg, the particle size was 40–60 mesh, and the TPD process was pretreated at 200 °C for 1h. At room temperature of 25 °C, NH₃ was adsorbed for 1 h and N₂ was purged for 15 min. The temperature was

programmed to rise to 600 °C at a rate of 10 °C·min⁻¹. The electrical signal was detected by the TCD thermal conductivity detector. In order to test the thermal stability of the tungsten multiphase catalyst, TGA-DTG measurements were performed on a METTLER TGA/DSC1. The temperature was increased from 30 to 800 °C with heating rate of 10 °C·min⁻¹ under nitrogen atmosphere. FT-IR spectra were carried out on HGCS spectrometer from 500 to 4000 cm⁻¹ using material diluted with KBr. SEM pictures were obtained by JEM-2100 electron microscope.

2.4. Catalysts test

110 mmol H₂O₂ (50%) and 0.28 g catalyst were placed in a threemouth flask with an isobaric drop funnel and reflux unit of the thermometer. When reaction temperature reached 75 °C, 25 mmol CHE was added until no reflux occurred in the reaction system, and the reaction temperature was finally raised to 95 °C for 6 h. The quantitative and qualitative analysis of products was respectively carried out using gas chromatography (GC, SE-30 Capillary column) and gas chromatographmass spectrometer (GC-MS) under hot conditions (FID detector temperature: 280 °C; Injection temperature: 280 °C; Heating procedure: 40–280 °C with a heating rate of 10 °C and stayed at 120 °C for 5min).

3. Results and discussion

3.1. Characterization of the catalyst

SEM images of ZrO₂–TiO₂, SO₄²-ZrO₂–TiO₂ and WO₃/SO₄²-ZrO₂–TiO₂ catalysts were presented in Fig. 1. The ZrO₂–TiO₂ exhibited irregular lumps structures in Fig. 1a–c. However, when SO₄^{2–} was introduced, the sulfated ZrO₂–TiO₂ (SO₄^{2–}ZrO₂–TiO₂) showed a smooth surface. Furthermore, the ZrO₂–TiO₂ sample size also became relatively uniform due to the existence of SO₄^{2–} (Fig. 1d–f). After loading with WO₃, the WO₃/SO₄^{2–}ZrO₂–TiO₂ catalyst exhibited a rough surface (Fig. 1g–i), which demonstrated that the WO₃ had been successfully decorated on SO₄^{2–}ZrO₂–TiO₂ surface.

The crystal structure of pure WO₃ and a series of composite samples were characterized by X-ray diffraction analysis (XRD) in Fig. 2b. It could be clearly seen that the SO₄²-ZrO₂–TiO₂ presented similar curves [21,22], compared to the pristine ZrO₂–TiO₂. Furthermore, the characteristic peak appeared at *ca*. 54° completely disappeared, and the other peak at 31° showed a significant shift (31 to 22°) [23,24]. This phenomenon illustrated that the synergistic effect between ZrO₂–TiO₂ and SO₄^{2–} could lightly eliminate the crystal structure of the ZrO₂–TiO₂ sample and reduce the influence caused by various crystal types. Interestingly, the diffraction peaks located at 23, 33 and *ca*.50° were identified over the complexation WO₃/SO₄^{2–}ZrO₂–TiO₂ in Fig. 2a. With the increase of WO₃, the flat peaks were gradually strengthened to be sharp peaks, and peak position was almost unchanged. It indicated the WO₃/SO₄^{2–}ZrO₂–TiO₂ was successfully synthesized.

FT-IR spectra was employed to further study on the chemical construction of ZrO_2 -TiO₂ and SO_4^2 -ZrO₂-TiO₂ in Fig. 3a. The absorption bands at around 3444 and 1630 cm⁻¹ were attributed to the characteristic peaks of water (O–H). Similarly, compared to the pristine ZrO_2 -TiO₂, for SO_4^2 -ZrO₂-TiO₂ and WO_3/SO_4^2 -ZrO₂-TiO₂, the absorption peaks between 1055 and 1125 cm⁻¹ were belonged to the characteristic peaks of S=O and S–O, which was well indexed to the double



Fig. 1. SEM images of the TiO₂-ZrO₂ (a-c), SO₄²⁻ZrO₂-TiO₂ (d-f) and WO₃/SO₄²⁻ZrO₂-TiO₂ (g-i)



Fig. 2. XRD patterns of pure WO₃ and X WO₃/SO₄²⁻-ZrO₂-TiO₂ (a) and SO₄²⁻-ZrO₂-TiO₂ and ZrO₂-TiO₂ (b).

bridge connection type of solid super acid [25]. This results illustrated that SO_4^{2-} had been successfully loaded on ZrO_2-TiO_2 . Furthermore, the peaks at near 810 cm⁻¹ was the vibration absorption peaks of W–O, corresponding to the characteristic peaks of WO₃, demonstrating that WO₃ was resoundingly decorated on the surface of SO_4^2 - ZrO_2-TiO_2 [26, 27].

Fig. 3b showed the NH₃-TPD profiles of WO₃/SO₄²-ZrO₂-TiO₂ and WO₃/ZrO₂-TiO₂. Curve of the WO₃/ZrO₂-TiO₂ was observed over a wide temperature range, suggesting that there were two types acid sites. For WO₃/ZrO₂-TiO₂, the broad desorption peaks appeared at 113 °C was weak acid sites, while the NH₃ desorption peaks at 370 °C could be

ascribed to NH₃ species desorbed at medium-strong acid sites [28]. As presented in Fig. 3b, two distinct desorption peaks were observed over WO₃/SO₄²-ZrO₂-TiO₂ catalyst in the entire temperature range. The desorption peaks at 103 °C could be attributed to the NH₃ desorbed at the weak acid sites. However, the desorption peaks were exhibited at 516 °C, which confirmed that induction of SO₄²⁻ brought about the strong acidity for WO₃/SO₄²-ZrO₂-TiO₂ [29]. FT-IR spectra and NH₃-TPD of catalysts illustrated the successful construction of solid super acid.

 N_2 adsorption-desorption isotherm and pore size distribution of catalysts were shown in Fig. 4a. It displayed IV-type curves with the H_1 hysteresis loops [3], which indicated that mesoporous materials had the



Fig. 3. FT-IR spectra of WO₃, ZrO₂-TiO₂, WO₃/SO₄²-ZrO₂-TiO₂ and SO₄²-ZrO₂-TiO₂ catalysts (a) NH₃-TPD profiles of WO₃/SO₄²-ZrO₂-TiO₂ and WO₃/ZrO₂-TiO₂ (b).



Fig. 4. N₂ adsorption-desorption isotherm and pore size distribution (Inset) of heterogeneous catalysts (a) TG spectra of SO₄²-ZrO₂-TiO₂ and ZrO₂-TiO₂ (b).

characteristic of typical uniform pore structure [30]. As displayed in Fig. 4a and Table 1, it showed large specific surface area of *ca.* 299.71 m² g⁻¹ and pore volume of *ca.* 0.18 cm³ g⁻¹. After combining SO₄²⁻ with ZrO₂–TiO₂, the specific surface area and pore volume increased significantly to 347.28 m² g⁻¹ and 0.84 cm³ g⁻¹ respectively. What's more, when WO₃ was introduced, the specific surface area and pore volume of SO₄²⁻ZrO₂–TiO₂ decreased to 201.77 m² g⁻¹ and 0.49 cm³ g⁻¹, which suggested the WO₃ might occupy the part of channel of support. In addition, the pore size distribution of ZrO₂–TiO₂, SO₄²⁻ZrO₂–TiO₂ and WO₃/SO₄²⁻ZrO₂–TiO₂ centered at *ca.* 3.96, 7.15 and 7.15 nm, respectively (the inner of Fig. 4a) further illuminated the excellent synergistic effect between SO₄²⁻ and ZrO₂–TiO₂. Those results proved that SO₄²⁻ was successfully loaded on the surface of ZrO₂–TiO₂.

The thermal stability of WO₃/SO₄²-ZrO₂-TiO₂ and SO₄²-ZrO₂-TiO₂ were shown in Fig. 4b. The sample SO₄²-ZrO₂-TiO₂ weight loss process could be roughly divided into two parts. The first part occurred at 100–200 °C was ascribed to the gradual evaporation of physically adsorbed water from sample. The largest weight loss occurred at about 515 °C and the total weight loss was 20.0%. The appearance of this weightlessness peak could be attributed to decomposition of sulfur components on the sample surface [31]. Interestingly, when WO₃ was introduced into the support SO₄²-ZrO₂-TiO₂, the mass of the catalyst was

Physical properties of heterogeneous catalysts.

Sample	S_{BET} (m ² ·g ⁻¹)	$V_{\rm T}~({\rm cm}^3 \cdot {\rm g}^{-1})$	D _{BJH} (nm)
ZrO ₂ -TiO ₂	299.71	0.18	2.73
SO ₄ ²⁻ ZrO ₂ -TiO ₂	347.28	0.84	8.15
30%WO ₃ /SO ₄ ²⁻ ZrO ₂ -TiO ₂	201.77	0.49	8.14

almost unchanged and the total weight loss about 2.5%.

3.2. Catalytic performance test

3.2.1. Influence of catalyst type

Major difference in CHE conversion between the different catalysts types were observed. Compared to WO₃/CuO–TiO₂ and WO₃/ La₂O₃–TiO₂, catalytic properties of WO₃/ZrO₂–TiO₂ was enhanced dramatically. As shown in Fig. 5a, the activity of WO₃/SO²₄-ZrO₂–TiO₂ in CHE oxidation reaction was 4 times higher than catalyst WO₃/ ZrO₂–TiO₂, which might be ascribed to appropriate acid sites of WO₃/ SO²₄-ZrO₂–TiO₂. Interestingly, the strength of acid sites in WO₃/SO²₄-ZrO₂–TiO₂ might be much greater than WO₃/ZrO₂–TiO₂ (Fig. 3b), which suggested that the catalyst's acidity also played an important role in oxidation reaction of cyclohexene. The stronger acid could inhibit the H₂O₂ decomposition rate, which could enhance the contact time between CHE and H₂O₂. Therefore, reducing the decomposition rate of H₂O₂ could increase oxygen molecule utilization rate, thus enhancing the conversion of CHE.

3.2.2. Effect of the preparation method

Fig. 5b displayed the influence of different preparation methods on catalyst activity. It could be found that $(NH_4)_{10}W_{12}O_{41} \sim xH_2O$ as a tungsten source was conducive to oxidation reaction of CHE. Furthermore, compared to the hydrothermal method, catalyst had predominant performance *via* complexation method. At the moment, AA yield and CHE conversion rate could reach up to 42.5 and 99.6%, respectively.



Fig. 5. Influence of catalyst preparation method. (A-E preparation method in supporting).



Fig. 6. Influence of the molar ratio of cyclohexene to hydrogen peroxide (a), reaction temperature (b), reaction time (c) and catalyst amount (d).

3.2.3. Influence of calcination temperature of the catalyst

As shown in Fig. 5c, when calcination temperature was set as 450 °C, the AA yield reached up to 42.5%. Increasing the calcination temperature would reduce the yield of AA. This phenomenon was mainly attributed to the reduction of catalytic activity, which was due to the decomposition of SO_4^{2-} bonded to metal oxides. In addition, TG (Fig. 4b) test results further proved our conclusion.

3.2.4. Effect of nWO₃: nSO₄²⁻

 nWO_3 : nSO_4^{2-} had an important influence on the activity of difference catalysts. With an increase of nWO_3 : nSO_4^{2-} , the catalytic performance was enhanced gradually (Fig. 5d). When the molar ratio of tungsten trioxide to sulfate reached 1 : 1.88, the AA yield was as high as 42.5%. What's more, with a further increase of nWO_3 : nSO_4^{2-} , the yield of AA increased slightly. Therefore, from an economic point of view, 1:1.88 (30% WO_3/SO_4^2-ZrO_2-TiO_2) was chosen as the best molar ratio.

3.2.5. Influence of the molar ratio of CHE to H_2O_2

As shown in Fig. 6a, AA yield on WO_3/SO_4^2 - ZrO_2 - TiO_2 increased with the mole ratio CHE to H_2O_2 , and then descend. When the molar ratio of CHE to H_2O_2 was changed from 1 : 4 to 1 : 4.4, the AA yield increased from 24.8% to 42.5%. The AA selectivity slightly decreased with the increasing H_2O_2 amount.

3.2.6. Effect of reaction temperature

The effect of reaction temperature on catalyst activity was illustrated in Fig. 6b. The AA selectivity increased steadily with the reaction temperature rising from 80 to 95 °C. However, it would began to decrease as the temperature reached 110 °C. This phenomenon might be attributed to the fact that lower temperatures (<95 °C) were conducive to the H₂O₂ decomposition. Moreover, the reaction system at higher temperature would lead to the rapid decomposition of H₂O₂. These results indicate that the optimal temperature was 95 °C for CHE oxidation.

3.2.7. Influence of reaction time

Fig. 6c presented the influence of reaction time on the oxidation of CHE with H_2O_2 . The yield and selectivity of AA had an approximately double increase from 5 h to 6 h, after that, the AA yield decreased to 47.5% (8 h). This manifested that the CHE oxidation reaction reached to a chemical equilibrium state when the reaction time was maintained for *ca*. 6 h.

3.2.8. Effect of catalyst amount

In Fig. 6d, the dependency of AA yield on the catalyst amount was illustrated. It was found that the amount of catalyst was achieved increased from 0.20 to 0.28 g. At this juncture, the AA yield was the highest (51.2%), which was due to an increase in the number of active sites, leading to higher catalyst activity [32,33]. Nevertheless, AA selectivity significantly decreased with the increase of catalyst amount, which was due to the fact that the excessive amount of catalyst might aggravate the by-product formation. GC-MS analysis showed the yield and selectivity of 1, 2-cyclohexanediol (1, 2-diol) was enhanced with the increase of amount of catalyst from 0.28 to 0.41g (Table 2).

3.3. Reusability of the catalyst

The catalytic performance and stability of the WO₃/SO₄²-ZrO₂-TiO₂ were evaluated under the optimal conditions. The WO₃/SO₄²-ZrO₂-TiO₂ catalyst could be recycled by filtration and washing with ethanol. After testing five times, it could be found that the activity and selectivity of the catalyst decreased only slightly in Fig. 7. This proved that WO₃/SO₄²-ZrO₂-TiO₂ zrO₂-TiO₂ catalyst had superior activity and stability.

3.4. Analog computation and catalytic mechanism analysis

As presented in Scheme 2, the solid super acids of SO_4^{2-}/M_xO_y type

 Table 2

 Oxidation of CHE to AA catalyzed by optimal conditions.

Catalyst amount (g)	Conversion (%)	Yield (%)			Selectivity (%)		
-	CHE	AA	1, 2- diol	others	AA	1, 2- diol	Others
0.28	92.5	51.2	37.2	4.6	55.3	40.2	4.9
0.41	85.7	16.7	52.8	12.3	19.5	61.6	14.4



Fig. 7. The stability test results of WO₃/SO₄²⁻-ZrO₂-TiO₂.

could be roughly divided into three categories according to the methods of the connection. A large number of studies by researchers had found that FT-IR spectrum was an effective way to identify the three binding types (Scheme 2a-c). The anti-symmetric stretching vibration absorption peak of the highest S=O bond appearing below 1200 cm⁻¹ belonged to the bridge double coordination [34]. In other words, the connection mode between SO_4^{2-} and the metal oxide was a bridge double coordination connection. In this experiment, bridge double coordination (Scheme 2b) solid super acid was successfully fabricated. It could be clearly seen in Scheme 2d that, when SO_4^{2-} coordinated and adsorbed on the metal oxide surface, the electron cloud on the metal-oxygen bond underwent an obvious electron shift and then formed two acid centers (Brønsted acid and Lewis acid) [35]. Subsequently, the resulting acidic centers attracted electrons from surrounding water molecules to restore neutrality. Meanwhile, a large amount of H⁺ would float around in reaction system, which could further inhibit the H₂O₂ decomposition rate and improve a suitable acidic environment for hydrolysis reaction.

Hydrolysis and oxidation reaction were involved in the conversion of cyclohexene to adipic acid (Scheme 3a). Generally, tungsten base catalyst was beneficial to the ring opening of 1, 2-epoxycyclohexane (2). The acidic condition was believed to be required in the two hydrolysis steps [19]. The acidic condition could be provided by SO_4^{2-}/M_xO_y catalyst (Scheme 2d). What's more, DFT calculation was used to further examine the reaction mechanism by the energy change and the energy of each substance (Scheme 3b).

4. Conclusions

In summary, composite WO_3/SO_4^2 -ZrO₂-TiO₂ solid super acid catalyst was fabricated successfully by fixing acid strategy and was firstly applied in production of adipic acid. The bridge double coordination occurred between ZrO_2 -TiO₂ and SO_4^{2-} with the introduction of SO_4^{2-} . Building solid super acid might restrict the decomposition rate of H_2O_2 and might simplify the reaction pathway. Under optimal reaction



Scheme 2. Single coordination (a) bridge double coordination (b) chelating double (c) Coordination exhibited the acid center structure of SO_4^{2-}/M_xO_y solid super acid catalyst (d).



Scheme 3. Reaction flow simulation calculation.

conditions (95 °C, *n*CHE: $nH_2O_2 = 1 : 4.4, 30\% WO_3/SO_4^2$ -ZrO₂-TiO₂ and 6 h), the CHE conversion was as high as 92.5%, and the selectivity of AA was up to 55.3%. DFT calculation presented the optimal model structure and energy of each product, the final product (AA) had an energy of -2866.21 eV.

CRediT authorship contribution statement

Xiangxue Liu: Experimental Design; Experimental Operation, Writing – original draft. Ke Wang: Software, Data curation. Baoquan Liu: BET Test, Investigation. Zhenmei Guo: Validation, Resources. Chao Zhang: Validation, Resources, Writing – original draft. Zhiguo Lv: Project administration, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://do i.org/10.1016/j.jssc.2021.122239.

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