Size dependence of photocatalytic oxidation reactions of Rh nanoparticles dispersed on (Ga1-xZnx)(N1-xOx) support

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Size dependence of photocatalytic oxidation reactions of Rh nanoparticles dispersed on \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) support

Yi Zhang, D. A. J. Michel Ligthart, Peng Liu, Lu Gao, Tiny M. W. G. M. Verhoeven, Emiel J. M. Hensen *

Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, P.O. Box 513, 5600 MB, Eindhoven, The Netherlands

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ABSTRACT
Mixed Ga–Zn oxynitrides were synthesized using coprecipitation, wet-precipitation, and solid-solution methods. The oxynitrides were used as supports for Rh nanoparticle catalysts in photocatalytic water splitting, CO oxidation, and H2 oxidation. Mixed Ga–Zn oxynitrides produced by wet precipitation and nitridation had good visible-light-absorption properties and high surface areas, so they were used to support uniformly sized poly(vinylpyrrolidone)-stabilized Rh nanoparticles. The nanoparticle size range was 2–9 nm. These catalysts had negligible activity in photocatalytic H2 production by water splitting with methanol as a sacrificial agent. Other mixed Ga–Zn oxynitrides were also inactive. A reference sample provided by Domen also showed very low activity. The influence of particle size on Rh-catalyzed oxidation of CO and H2 was investigated. For CO oxidation, the activities of small particles were higher for particles with higher Rh oxidation degrees. The opposite holds for H2 oxidation.

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1. Introduction
Among the many systems explored for photocatalytic water splitting, mixed Ga–Zn oxynitrides \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) modified with Cr2O3-encapsulated noble metal cocatalysts constitute a promising and attractive catalyst system [1–3]. Maeda et al. [1–3] were the first to report the good performance of \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) solid solutions as light-harvesting semiconductors for water splitting under visible-light irradiation. \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) samples were synthesized by mixing Ga2O3 and ZnO powders, followed by heating in NH3 (nitridation) [1]. The resulting solid solution has a narrow band gap (2.4–2.8 eV) compared with those of GaN (3.4 eV) and ZnO (3.2 eV) reference materials. The same authors later performed a series of investigations into the influence of the starting materials, nitridation conditions, and post-calcination treatment on the photocatalytic activity. The crystallinity and composition of \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) are important factors for achieving good catalytic performance [2,4–10]. However, the solid-state reaction is laborious and results in a low surface area (<10 m2/g), bulk defects, and a low ZnO content [11–13]. Moriya et al. [14] suggested that the Zn content of \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) could not exceed \(x = 0.4\) because Zn2+ is easily reduced to Zn metal, which evaporates at high temperatures in reducing atmospheres. This limits the visible-light absorption of the prepared solids. Consistent with this, an increase in the Zn content of the crystalline structure results in a shift of the absorption edge to higher wavelengths [15–18]. Han et al. [16] used a sol-gel method to synthesize \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) \((x = 0.482)\) with the absorption edge at 560 nm. Lee et al. [17] synthesized \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) by nitridation of a mixture of ZnGa2O4 and ZnO nanocrystals to tune the Zn content from \(x = 0.30\) to 0.87, giving absorption-edge values ranging from 460 to 565 nm. Li et al. [19] also prepared \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) by the method used by Lee et al. [17], but used ZnGa2O4 and ZnO nanofibers to obtain nanostructured \((\text{Ga}_{1-x}\text{Zn}_x)(\text{N}_{1-x}\text{O}_x)\) with a high surface area and

* Corresponding author. Tel: +31-40-2475178; E-mail: e.j.m.hensen@tue.nl
high Zn ratio (x = 0.5) by nitriding at 650 °C. It is therefore desirable to develop novel and more facile methods for low-temperature synthesis of (Ga1-xZnx)(N1-xOx) materials with improved photocatalytic activities.

Recently, soft chemical methods for preparing (Ga1-xZnx)(N1-xOx) from layered double hydroxide (LDH) precursors have been explored [20,21]. Materials derived from LDHs have large surface areas (100–300 m²/g) [20]. Zou et al. [13] reported the synthesis of (Ga1-xZnx)(N1-xOx) from a ZnGa2O4 precursor by nitridation to obtain products with higher Zn and lower N contents, and larger surface areas than those of the original materials reported by the Domen group. Such ZnGa2O4 phosphors with spinel structures were obtained by calcining single-phase Zn2Ga-based LDHs of relatively small size. However, this route is less facile because it requires two calcination steps from LDHs to (Ga1-xZnx)(N1-xOx). Wang et al. [21] used a simple method based on direct nitridation of LDHs containing Zn2+, Ga3+, and CO32−. Compared with the conventional solid-solution method involving nitridation for 15 h, this synthetic method requires a shorter nitridation time (0.5 h). Zn-rich (Ga1-xZnx)(N1-xOx) can be obtained because Zn is stabilized in the interlayer region of the LDH precursors [20]. Mapa et al. [22] reported a simple synthesis of (Ga1-xZnx)(N1-xOx) by fast combustion of aqueous solutions of Ga(NO3)3 and Zn(NO3)2 with urea in a furnace at 500 °C.

(Ga1-xZnx)(N1-xOx) materials do not show photocatalytic activities without cocatalysts. It was found that Rh/Cr2O3 core–shell structures are the best cocatalysts for H2 production. The Domen group investigated the effect of the size of Rh particles supported on (Ga1-xZnx)(N1-xOx); they compared photodeposition, impregnation, and adsorption as methods for introducing Rh and also explored the promoting effect of Cr2O3. Rh nanoparticle (NP) dispersion was found to be important for the rate of H2 production; this was attributed to the need for a high Rh surface area [23]. Ikeda et al. [24] reported that poly(vinylpyrrolidone) (PVP)-stabilized Rh NPs can act as highly dispersed cocatalysts on semiconductors. Our recent work shows that the Rh NP density is more important than the particle size because a high rate of removal of charge carriers from the semiconductor is important [27]. It is worth mentioning that smaller supported Rh particles are more prone to oxidation than larger ones [25,26].

In the present study, we considered that it would be valuable to study the relation between the preparation methods, structures, and catalytic activities of (Ga1-xZnx)(N1-xOx) materials systematically. Based on our earlier work [27], we were also interested in investigating the influence of the Rh cocatalyst NP size on the oxidation states of Rh NPs, using extended X-ray absorption fine-structure (EXAFS) and X-ray absorption near-edge structure (XANES) methods, and the rate of photocatalytic H2 production by water splitting. We also evaluated these catalysts for the oxidation of CO and H2 to understand the influence of NP size and oxidation state on these elementary reactions.

2. Experimental

2.1. Synthesis of (Ga1-xZnx)(N1-xOx)

Mixed zinc oxide/gallium nitrides were synthesized using the methods reported in the literature [11,13,21]. For coprecipitation (samples denoted by “C”), Zn(NO3)2·6H2O (≥99.9%, Sigma-Aldrich; 11.9 g) and Ga(NO3)3·xH2O (99.9%, Alfa Aesar; 6.6 g) were dissolved in deionized water (60 mL; solution A), NaOH (≥97%, Merck; 4.8 g) in deionized water (60 mL; 2 mol/L NaOH, solution B), and Na2CO3 (anhydrous, Merck; 3.2 g) in deionized water (60 mL; 0.03 mol/L Na2CO3, solution C). Solutions A and B were added dropwise to solution C while controlling the pH at 10. The mixture was stirred and aged for 20 h at 65 °C in a water bath. The suspension was filtered, and the obtained powder was dried at 110 °C for 12 h and calcined in a 20% O2/He flow at 900 °C (5 °C/min) for 6 h. The calcined material was transferred to a 10 mol/L NaOH solution and stirred at 65 °C for 20 h, followed by filtering and washing with deionized water. It was then dried overnight to form ZnGa2O4 spinel. The ZnGa2O4 spinel powder was heated at temperatures in the range 500–900 °C in a pure NH3 flow (200 mL/min) for 10 h.

The wet-precipitation method (samples denoted by “W”) involved dissolution of Zn(NO3)2·6H2O (35.7 g) and Ga(NO3)3·xH2O (21.8 g) in deionized water (100 mL; solution D), NaOH (14.4 g) in deionized water (100 mL; 0.6 mol/L NaOH, solution E), and Na2CO3 (6.36 g) in deionized water (100 mL; 3.8 mol/L Na2CO3, solution F). Solutions D and E were added dropwise to solution F while maintaining the pH at 8. The mixture was stirred and aged for 20 h at 90 °C using an oil bath. The suspension was filtered, and the obtained solid was washed with deionized water and dried at 110 °C overnight to form the LDH precursor. This material was sieved into a fraction of 125–250 μm and then loaded into a quartz-tube reactor between quartz-wool plugs. The material was exposed to pure NH3 flow (200 mL/min) for nitridation and heated from room temperature to 800 °C (5 °C/min) for 1 h.

The solid-solution method (samples denoted by “S”, used by the Domen group) is described in the literature and involves mixing stoichiometric amounts of ZnO (99.9%, Kanto Chemicals) and Ga2O3 (99.9%, High Purity Chemicals) under an NH3 flow at 800 °C for 5–20 h [1,2,4]. In the present study, we used similar materials but from different suppliers, i.e., ZnO (99.5%, AnalR Normapur) and Ga2O3 (≥99.99%, Aldrich). The raw materials were mixed and placed in a quartz tube at a Zn:Ga molar ratio of ca. 1. The mixed powder was heated at 800 °C for 15 h in NH3 (200 mL/min), resulting in a yellow powder. After nitridation for 15 h, the sample was cooled to room temperature in the NH3 flow [4]. Typically, 1.08 g of Ga2O3 and 0.94 g of ZnO provided approximately 1 g of (Ga1-xZnx)(N1-xOx). (Ga1-xZnx)(N1-xOx) prepared as described in reference [23] was kindly provided by the Domen group [23] for Rh loading, Cr2O3 modification, and photocatalytic evaluation.

The resulting (Ga1-xZnx)(N1-xOx) materials are denoted by ZGN(x,y), where x is the synthetic method (“C”, “W”, or “S”), and y is the nitridation temperature (°C); for example, ZGN(W-800) is (Ga1-xZnx)(N1-xOx) synthesized by wet-precipitation and heated in NH3 at 800 °C.
2.2. Synthesis of Rh NPs and photocatalysts

Uniformly sized PVP-stabilized Rh NPs were prepared according to the literature procedure [28]. A Rh precursor salt was reduced in the presence of PVP at different temperatures in an appropriate solvent. Small NPs were obtained by dissolving RhCl₃·nH₂O (Aldrich; 10 mg) and PVP (Mn = 10 000, Sigma-Aldrich; 0.11 g) in water (2 mL) and 1,4-butanediol (Sigma-Aldrich; 3 mL). The mixture was then added to 1,4-butanediol (17 mL), which was preheated to 120 or 160 °C. To obtain larger NPs, Rh(acac)₃ (acac = acetylacetonate; Aldrich; 20 mg) and PVP (0.11 g) were dissolved in tetrahydrofuran (THF; Sigma-Aldrich; 2 mL) and 1,4-butanediol (3 mL), which was preheated to 160 or 220 °C. Each mixture was refluxed under a N₂ flow for 6 h and cooled to room temperature. A modified method was used to obtain very small (≤3.5 nm) Rh particles. A solution consisting of RhCl₃·nH₂O (10 mg), PVP (0.11 g), water (2 mL), and 1,4-butanediol (3 mL) was added to a suspension of ZGN (0.25 g) in preheated 1,4-butanediol (17 mL). The mixture was heated to 120 °C, refluxed under a N₂ flow for 6 h, and then cooled to room temperature. The loading of the support materials was carried out by dropwise addition of the Rh NP suspension to a suspension of ZGN (0.25 g) in glycerol (≥99%, Aldrich; 10 mL). The slurry was filtered, and the resulting powder was dried at 110 °C overnight. The catalysts are denoted by Rh(PVP)/ZGN(x-y)-z, where z is the average Rh NP size.

A portion of the catalyst was exposed to ultraviolet–ozone (UVO) to remove the organic capping agent. It was recently reported that such treatment removes PVP from the Rh NPs [29]. For this purpose, the sample (0.5 g) was dispersed on Al foil in a UVO chamber (PR 100, Ultra Violet Products, Inc.) and exposed to UV light and ozonated air at room temperature for 20 h [27]. The catalysts are denoted by Rh(PVP-UVO)/ZGN(x-y)-z.

A Cr₂O₃ shell was deposited on the Rh NPs [23,24,30]. Typically, Rh(PVP-UVO)/ZGN (0.15 g) was dispersed in an aqueous 0.2 mmol/L K₂CrO₄ solution (80 mL) in a double-walled glass vessel (held at 10 °C) with a quartz window on top. The reaction vessel was connected to a closed glass system to collect the produced H₂. Prior to photodeposition, the air in the vessel was completely removed by evacuation using a turbo drag pump. After evacuation, the solution was irradiated with visible light (λ = 420–630 nm) to reduce CrO₄²⁻ to Cr₂O₃. The irradiation was performed for 8 h. The final product was washed with deionized water and dried overnight at 110 °C. These samples are denoted by Cr-Rh(PVP-UVO)/ZGN(x-y)-z, where Cr indicates Cr₂O₃ addition.

For comparison, reference samples were prepared using RhCl₃·nH₂O and K₂CrO₄ as precursors according to the photodeposition method used by the Domen group and others [31–33]. Typically, ZGN (0.25 g) was added to an aqueous solution (36 mL) containing RhCl₃·nH₂O (13 mg) under stirring. Methanol (4 mL) was then added as a sacrificial reagent. The mixture was transferred to a glass vessel, and the air in the vessel was removed. After evacuation for 1.5 h, the suspension was irradiated with visible light (420–630 nm) for 4 h. The evolution of H₂ with time was followed. The material was isolated from the solution by filtration. After drying overnight at 110 °C, it was dispersed in a K₂CrO₄ solution (0.2 mmol/L, 80 mL) for Cr₂O₃ photodeposition, following the same procedure as used for Cr-Rh(PVP-UVO)/ZGN. These catalysts are denoted by Cr-Rh/ZGN(S). The same Cr₂O₃ and Rh loading procedures were applied to the (Ga salmon)N₁(O₂) sample provided by the Domen group; the resulting catalysts are denoted by Cr-Rh/ZGN(D).

2.3. Catalyst characterization

The metal was determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) using a Goffin Meyvis SpectroCirus CCD apparatus. The sample was dissolved under stirring and heating in a melt of K₂SO₄ in H₂SO₄ until a clear solution was obtained. The surface area of the support material was determined using a Micromeretics TriStar 3000 apparatus by N₂ physisorption at liquid N₂ temperature after outgassing the sample at 150 °C for 3 h. UV-Vis absorption spectra were obtained using a Shimadzu UV-2401 PC spectrometer in diffusion-reflectance mode with BaSO₄ as a reference. X-Ray diffractometry (XRD) patterns were recorded using a D4 Endeavor diffractometer (Bruker) at a scan speed of 0.36°/min to determine the support structure. The morphologies of the support materials were studied by scanning electron microscopy (SEM) using an FEI Quanta 3D FEG instrument in high-vacuum mode at a low voltage (typically 10 mPa and 10 kV). Energy-dispersive X-ray spectroscopy (EDX) was performed using an EDAX instrument (AMETEK) with Genesis 700 software. Transmission electron microscopy (TEM) was performed using an FEI Tecnai 20 transmission electron microscope. Typically, a ground sample was dispersed in pure ethanol, sonicated, and dispersed over a conventional carbon-coated Cu grid. The average particle size and particle size distribution were determined by measuring at least 150 metal particles.

X-ray photoelectron spectroscopy (XPS) was performed using a Thermo Scientific spectrometer, with an Al Kα monochromatic source. The spectra were recorded at an emission background pressure of 1 × 10⁻³ mPa. All the binding energies were referenced to the C 1s peak at 284.5 eV, related to surface adventitious carbon. Analysis and quantification of the measurements were performed using Casa-XPS software and Wagner's sensitivity factors.

X-ray absorption spectroscopy (XAS) was performed at the Dutch-Belgian beamline (Dubble) at the European Synchrotron Radiation Facility, Grenoble, France (storage ring 6.0 GeV, ring current 200 mA). Data were collected at the Rh K-edge in fluorescence mode with a solid-state detector. Energy selection was performed using a double crystal Si(111) monochromator. Background removal was carried out using standard procedures. EXAFS analysis was then performed with EXCURVE931 on k³-weighted unfiltered raw data using the curved wave theory. Phase shifts were derived from ab initio calculations using Hedin-Lundqvist exchange potentials and Von Barth ground states. Energy calibration was carried out with Rh foil. The amplitude reduction factor, S₀₂, associated with central atom...
shake-up and shake-off effects was set at 1.0 by calibration of the first- and second-shell Rh–Rh coordination numbers to 12 and 6, respectively, for the K\(^{\pm}\)-weighted EXAFS fitting of the Rh foil [25]. The structure of the Rh metal foil and the first two shells of the Fourier-transform (FT) EXAFS spectrum of Rh\(_2\)O\(_3\) corresponded well to the literature data [34]. The near-edge regions of the absorption spectra of these reference compounds were used to fit the near-edge regions of the catalysts. Spectra at the Rh K-edge were recorded in a stainless-steel controlled-atmosphere cell. Typically, the sample (80 mg) was pressed in a holder and placed in the cell. Carbon foils were held between two high-purity carbon spacers. High-purity gases (He and O\(_2\)) were delivered by thermal mass flow controllers. The total gas flow was kept at 50 mL/min [26]. After recording two EXAFS spectra of the sample at room temperature under a He flow, the sample was heated in a 3% O\(_2\)/He flow to a final temperature of 300 °C, while recording the XANES spectra.

### 2.4. Catalytic activity measurements

#### 2.4.1. Photocatalytic \(\text{H}_2\) production

Photocatalytic \(\text{H}_2\) production by water splitting was performed using the setup described in detail elsewhere [27]. Typically, the catalyst (0.1 g) was added to a closed reactor vessel containing deionized water (36 mL) and methanol (4 mL; sacrificial electron donor) under stirring. After complete removal of the air from the vessel by evacuation for 30 min, a light source (Xe Arc Lamp, Oriel) was switched on, and the suspension was irradiated with visible light (420–630 nm, 320 mW/cm\(^2\)) for at least 4 h. Tests were repeated at least three times. The setup performance was regularly checked using a 0.3 wt% Pt/TiO\(_2\) reference photocatalyst. \(\text{H}_2\) gas evolved from water splitting was analyzed using an online gas chromatograph (GC; ATI UNICAM GC-610, Shincarbon, thermal conductivity detector).

#### 2.4.2. Oxidation reactions

The catalytic activities in the oxidation of CO and \(\text{H}_2\) with molecular O\(_2\) were determined in a parallel ten-flow microreactor system equipped with thermal mass flow controllers and an online GC (Interscience, Porapak Q, Molecular sieve 5A, thermal conductivity detector). Typically, the SiC-diluted catalysts were loaded into quartz reactor tubes [25]. Prior to the activity measurements, the samples were dried in a He flow (10 °C/min) from room temperature to 110 °C for 1 h. The reactor was cooled in He to the reaction temperature. At each reaction temperature, rates were determined for 1.5 h, during which no deactivation was observed. For CO (\(\text{H}_2\)) oxidation, the feed contained 2 vol% CO (\(\text{H}_2\)) and \(\text{O}_2\) with \(\text{O}_2/\text{CO} = 1\) (\(\text{O}_2/\text{H}_2 = 1\)), balanced by He, at gas hourly space velocities between \(7 \times 10^4\) and \(1 \times 10^5\) h\(^{-1}\) in the temperature range 40–210 °C (30–230 °C). The activation energy was determined on the basis of measurements in which the conversion was below 20%.

### 3. Results and discussion

#### 3.1. Catalyst synthesis and characterization

##### 3.1.1. Support materials

The basic characterization results for the precursor and ZGON(C) samples are shown in Fig. 1. XRD shows that the precursor mainly consists of crystalline ZnGa\(_2\)O\(_4\) spinel. It is con-

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**Fig. 1.** XRD patterns (a) (Z = ZGON, S = spinel), UV-Vis spectra (b), and SEM images (c, d) of spinel precursor and ZGON(C) at different nitridation temperatures.
converted to the ZGON phase by nitridation. Nitridation takes place above 600 °C, and the XRD patterns of the spinel precursor and the ZGON materials agree with the literature data [13,19]. The UV-Vis spectra show increased visible-light absorption by the nitrided samples. When the ZGON phase has been fully formed, the absorption edge decreases with increasing nitridation temperature. Treatment at 700 °C shows the highest visible-light response with an absorption edge at ca. 600 nm. These results are consistent with those reported by Ward et al. [18].

The synthetic conditions and sample compositions are listed in Table 1. The starting solid solution and the ZnGa₂O₄ spinel both have a Zn/Ga ratio of 2.7. No Zn was lost during spinel formation by this method. The Zn/Ga ratio decreases with increasing nitridation temperature as a result of Zn loss by evaporation. The N content of the spinel precursor is very low and remains almost constant following nitridation at 500 and 600 °C. At higher temperatures, it increases substantially up to almost 29 at% at 900 °C. The surface areas of the ZnGa-LDHs, ZnGa₂O₄ spinel precursors, and nitrided ZGON materials are 42, 13, and 12–14 m²/g, respectively. The surface area therefore decreases during thermal conversion of the LDH precursor to the ZnGa₂O₄ spinel, but nitridation has little effect. This is consistent with the SEM results.

Figure 2 shows the basic characterization results for the ZGON(S-800) and ZGON(W-800) samples. The XRD patterns of these samples are very similar to that recorded for ZGON(C-800). The UV-Vis absorption edge at 470 nm for ZGON(S-800) is lower than that, located at ca. 590 nm, for ZGON(W-800). ZGON(C-800) has an absorption edge at ca. 520 nm. The SEM images show that ZGON(S) consists of long rods with irregular surfaces, whereas ZGON(W-800) mainly contains hexagonal nanoplates of similar morphology to those described by Wang et al. [21]. The surface area of ZGON(S) is 10 m²/g, similar to that of ZGON(C-800). ZGON(W-800) has a slightly higher surface area (19 m²/g), which originates from the higher surface area of the LDH precursor (83 m²/g). The Zn/Ga and N/Ga ratios of 0.13 and 0.79, respectively, for ZGON(S) are consistent with the values reported by Maeda et al. [1,2]. These ratios are slightly higher than that for ZGON(C-800). Both are substantially lower than the Zn/Ga ratio of 2.0 for ZGON(W-800). The reasons for the high Zn content of the latter sample are the short nitridation time and the different synthetic procedure, which does not include calcination and washing steps.

---

**Table 1**

<table>
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<tr>
<th>Synthesis method</th>
<th>Nitridation</th>
<th>Surface area (m²/g)</th>
<th>Surface atomic ratio</th>
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<td>C</td>
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<td>500 10 14 0.93 0.14 5.8</td>
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<tr>
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<tr>
<td>ZnGa₂O₄ spinel</td>
<td>900 10 12 0.02 0.55 28.5</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>W</td>
<td>LDH precursor</td>
<td>83 2.1 0.58 13.2</td>
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<td></td>
</tr>
<tr>
<td>S</td>
<td>800 1 19 2.0 1.00 12.5</td>
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<tr>
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<td>800 1 19 2.0 1.00 12.5</td>
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</table>

*Determined by EDX.*

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**Fig. 2.** XRD patterns (a), UV-Vis spectra (b), and SEM images (c, d) of ZGON(S-800) and ZGON(W-800).
3.1.2. PVP-stabilized Rh NPs

The synthetic conditions for the PVP-stabilized Rh NPs are listed in Table 2. The average particle size and distribution of the unsupported systems are similar to those reported earlier [27,35]. ZGN(W-800) was used to support these Rh(PVP) NPs because of its favorable absorption edge and relatively high surface area. No noticeable changes in the Rh NP shapes and sizes were observed by TEM for the supported systems (Fig. 3).

3.1.3. UVO treatment and Cr2O3 photodeposition

Instead of calcination, which may negatively affect the size distribution and the semiconductor N content, UVO treatment was performed on a portion of each catalyst to remove PVP from the Rh NPs [36]. After this treatment, the Rh NPs were coated with Cr2O3 by photodeposition. Typically, such low-

Table 2
Details of Rh NP synthesis and properties of ZGN(W-800)-supported Rh catalysts.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Rh NPs synthesis conditions</th>
<th>ZGN-supported catalysts</th>
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<tbody>
<tr>
<td>Precursor</td>
<td>Solvent</td>
<td>T_reduction (°C)</td>
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<tr>
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<td>RhCl₃/CH₃OH</td>
<td>H₂O</td>
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<tr>
<td>Rh(PVP)/ZGN(W-800)-3.7</td>
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<td>THF</td>
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<tr>
<td>Cr-Rh(PVP-UVO)/ZGN(W-800)-7.5</td>
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</tbody>
</table>

* Determined by ICP-AES. * Estimated average Rh NP size from TEM. * RhCl₃ solution was reduced in the presence of ZGN.

3.2. Surface compositions of ZGN-based catalysts derived from XPS Ga 2p₃/₂, Zn 2p₃/₂, O 1s, N 1s, and Rh 3d peak areas.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Surface atomic ratio Rh⁺/Ga, O/Ga, N/Ga (at%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZGN(D)</td>
<td>1.01 1.6 2.6 — 49.0</td>
</tr>
<tr>
<td>ZGN(S)</td>
<td>0.07 2.8 2.8 — 41.5</td>
</tr>
<tr>
<td>ZGN(W-800)</td>
<td>2.0 4.9 2.5 — 24.0</td>
</tr>
<tr>
<td>Rh(PVP-UVO)/ZGN(W-800)-2.3</td>
<td>1.8 6.1 2.5 1.1 21.8</td>
</tr>
<tr>
<td>Rh(PVP-UVO)/ZGN(W-800)-7.5</td>
<td>1.5 4.0 2.4 0.4 26.6</td>
</tr>
<tr>
<td>Cr-Rh(PVP-UVO)/ZGN(W-800)-7.5</td>
<td>1.5 5.0 2.5 0.5 24.7</td>
</tr>
</tbody>
</table>

**Fig. 3.** Representative TEM images and particle size distributions of Rh(PVP)/ZGN(W-800) with 2.3 (a), 3.7 (b), 5.4 (c), 7.5 (d), and 9.3 nm (e) Rh NPs.
Figure 4 shows the experimental and fitted FT EXAFS spectra and $k^3$-weighted $\chi(k)$ EXAFS functions of fresh (in pure He at room temperature) Rh(PVP)/ZGON(W-800) (a, b) and Rh(PVP-UVO)/ZGON(W-800) (c, d) with 2.3 (1), 5.4 (2), and 9.3 nm (3) Rh NPs.

Table 4

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>SHELL</th>
<th>$R(\AA)$</th>
<th>$N$</th>
<th>$\Delta \sigma^2(\AA^2)$</th>
<th>$E_0$(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh(PVP)/ZGON(W-800)-2.3</td>
<td>Rh–O</td>
<td>2.019</td>
<td>2.33</td>
<td>0.007</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Rh–Rh</td>
<td>2.684</td>
<td>3.81</td>
<td>0.007</td>
<td>0.7</td>
</tr>
<tr>
<td>Rh(PVP)/ZGON(W-800)-5.4</td>
<td>Rh–O</td>
<td>1.992</td>
<td>0.88</td>
<td>0.005</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Rh–Rh</td>
<td>2.690</td>
<td>7.16</td>
<td>0.005</td>
<td>-0.3</td>
</tr>
<tr>
<td>Rh(PVP)/ZGON(W-800)-9.3</td>
<td>Rh–O</td>
<td>2.043</td>
<td>4.14</td>
<td>0.006</td>
<td>-0.1</td>
</tr>
<tr>
<td>Rh(PVP-UVO)/ZGON(W-800)-2.3</td>
<td>Rh–O</td>
<td>2.041</td>
<td>2.89</td>
<td>0.006</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>Rh–Rh</td>
<td>2.695</td>
<td>3.19</td>
<td>0.005</td>
<td>0.05</td>
</tr>
<tr>
<td>Rh(PVP-UVO)/ZGON(W-800)-3.7</td>
<td>Rh–O</td>
<td>2.013</td>
<td>1.89</td>
<td>0.002</td>
<td>0.05</td>
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<tr>
<td>Rh(PVP-UVO)/ZGON(W-800)-5.4</td>
<td>Rh–O</td>
<td>2.002</td>
<td>1.18</td>
<td>0.005</td>
<td>-0.6</td>
</tr>
<tr>
<td>Rh(PVP-UVO)/ZGON(W-800)-7.5</td>
<td>Rh–O</td>
<td>2.690</td>
<td>6.37</td>
<td>0.004</td>
<td>-0.1</td>
</tr>
<tr>
<td>Rh(PVP-UVO)/ZGON(W-800)-9.3</td>
<td>Rh–O</td>
<td>2.014</td>
<td>1.09</td>
<td>0.007</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>Rh–Rh</td>
<td>2.687</td>
<td>7.36</td>
<td>0.005</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

*Only the first Rh–O and Rh–Rh shells were fitted; $\Delta K = 2.5-12$ Å$^{-1}$; estimated error in $R \pm 0.01$ Å, $N \pm 20$, $\Delta \sigma^2 \pm 10$; the R-factor was below 30%.

**Table 4**

Fitted parameters of $k^3$-weighted EXAFS spectra at Rh K-edge of fresh ZGN-based catalysts.
Fig. 5. Rh K-edge XANES spectra recorded during oxidation at 140 °C of Rh(PVP-UVO)/ZGON(W-800) with 2.3 (1), 3.7 (2), 5.4 (3), 7.5 (4), and 9.3 nm (5) Rh NPs. Rh3O+ and Rh foil references are included for comparison. The dots represent the results of XANES fitting by linear combinations of the two references.

Table 5
Rh K-edge XANES spectra fitting results; fractions of oxidic Rh (\(f_{\text{ox}}\)) in ZGON-supported Rh catalysts in fresh state and during oxidation from room temperature to 300 °C.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>(f_{\text{ox}}) (%)</th>
<th>He</th>
<th>T (°C) in O2/He RT</th>
<th>60</th>
<th>110</th>
<th>140</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Rh(PVP)/ZGON(W-800)-2.3]</td>
<td>44</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP)/ZGON(W-800)-5.4]</td>
<td>19</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP)/ZGON(W-800)-9.3]</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-2.3]</td>
<td>89</td>
<td>92</td>
<td>92</td>
<td>92</td>
<td>93</td>
<td>93</td>
<td>95</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-3.7]</td>
<td>60</td>
<td>60</td>
<td>63</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-5.4]</td>
<td>39</td>
<td>40</td>
<td>41</td>
<td>41</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-7.5]</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>—</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-9.3]</td>
<td>24</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

*Estimated error in \(f\) ± 5%.

3.2. Catalyst activity measurements

3.2.1. Photocatalytic H2 production

Photocatalytic H2 production by water splitting was performed using the (Cr-)Rh(PVP-UVO)/ZGON(W-800) materials and reference materials. The setup was regularly tested using a reference catalyst (25 mg of TiO2 (P25) containing 0.3 wt% Pt loaded by photodeposition), which gave H2 production rates of around 2100 µmol h⁻¹ gcat⁻¹, in good agreement with other studies [39,40]. The sample provided by the Domen group, to which 1 wt% Rh was added by photodeposition, gave a H2 production rate of only 0.3 µmol h⁻¹ gcat⁻¹, which is in line with the results reported by Maeda et al. [23]. After photodeposition using a K3CrO4 solution, the Cr-Rh/ZGON(D) activity increased to 3.7 µmol h⁻¹ gcat⁻¹. This confirms that Cr2O3 deposition improves the water-splitting efficiency of the Rh/ZGON sample. However, the activity is almost two orders of magnitude lower than the values reported by Maeda et al. [23]. The reason for this is unclear. Our ZGON(S)- and ZGON(W)-based catalysts, namely Cr-Rh/ZGON(S), Cr-Rh/ZGON(W), and Cr-Rh(PVP-UVO)/ZGON(W), did not show any photocatalytic activity, and these results were reproducible. The absence of Cr2O3 deposition, verified by ICP analysis, is consistent with the absence of photocatalytic activities of the parent ZGON materials. The reason for the absence of photocatalytic activity is unclear. Our synthetic methods were the same as those used by the Domen group [41]. ZGON(S) was prepared in the same way, but the Zn and surface N contents are slightly different. ZGON(W) contains much more Zn than the sample prepared using the solid-state method. Although we cannot draw firm conclusions at present, we speculate that slight differences in the bulk and surface compositions explain the absence of activity for our samples. There have been a large number of literature reports on the use of ZGON-type materials, but only those reported by the Domen group (cited earlier), Hahn et al. [42], Busser et al. [43], and Chorkendorff’s group in collaboration with the Domen group [44] reported good photocatalytic water-splitting activities. This highlights the tight control needed to prepare active ZGON semiconductor materials. In the next section, we explore the oxidation of H2 as a model for reverse water splitting to produce H2. We first evaluated the activities of these samples in CO oxidation, given recent reports on the size and oxidation-state dependences of supported Rh NPs [25].

3.2.2. CO oxidation

CO oxidation was carried out using the Rh(PVP-UVO)/ZGON(W-800) catalysts (Table 6). The reaction rate strongly decreases with increasing particle size. When corrected for dispersion, the turnover frequencies (TOFs) are much less dependent on the particle size, although the two catalysts with the largest average particle size are significantly less active than the ones containing smaller particles. The activity of Rh(PVP)/ZGON(W-800)-2.3 before UVO treatment is higher than that after UVO treatment. The particle size dependence for the present Rh/ZGON set is less prominent than the dependences observed for Rh/Co2O3 catalysts [25]. Song et al. [45] have shown that the rate of CO oxidation for a surface rhodium oxide film on CeO2 is much higher than that of Rh metal NPs. The reaction involves the Ce2O3 support, which oxidizes partly reduced rhodium oxide clusters. In the present study, the support is probably not involved in the catalytic CO oxidation reaction because ZnO does not reduce at relatively low reaction temperatures. Grass et al. [28] also concluded that the active phase for CO oxidation of unsupported RH NPs is the surface rhodium.

Table 6
CO oxidation activity and activation energies for selected set of ZGON-based catalysts (O2/CO ratio = 1; T = 160 °C).

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>(r) (mol mol\text{Rh}⁻¹ h⁻¹)</th>
<th>TOF (h⁻¹)</th>
<th>(E_{\text{app}}) (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Rh(PVP)/ZGON(W-800)-2.3]</td>
<td>292</td>
<td>611</td>
<td>93</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-2.3]</td>
<td>151</td>
<td>315</td>
<td>90</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-3.7]</td>
<td>85</td>
<td>287</td>
<td>77</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-5.4]</td>
<td>67</td>
<td>329</td>
<td>81</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-7.5]</td>
<td>32</td>
<td>217</td>
<td>80</td>
</tr>
<tr>
<td>[Rh(PVP-UVO)/ZGON(W-800)-9.3]</td>
<td>26</td>
<td>218</td>
<td>82</td>
</tr>
</tbody>
</table>
oxide. Smaller particles are more prone to form a surface oxide under the reaction conditions used than larger particles are. Assuming that the ZGON support is not involved in the CO oxidation reaction, the decreasing TOF with increasing Rh particle size for the Rh/ZGON set is in line with these results [25,28]. This is also consistent with the higher oxidation degree of smaller particles, shown by XAS. The activation energy for CO oxidation decreases with increasing particle size. The activities of the present catalysts are lower than those for dried Rh(PVP)/SBA-15 catalysts [46]. Consistent with our analysis, little influence of the particle size on the activation energy has been observed [46,47]. The activity of the Rh(PVP-UVO)/ZGON(W-800)-2.3 sample is about two times lower than that before the UVO treatment. This is in contrast to the activity enhancement achieved by UVO treatment of Pt NP systems stabilized with various organic molecules [48]. The difference is probably that Pt oxidation is less important than Rh oxidation, so capping agents decrease the performance of Pt more than that of Rh.

3.2.3. H2 oxidation

We then investigated the catalytic activities of these Rh NP samples in the oxidation of H2 (Fig. 6). The Rh(PVP-UVO) samples with smaller Rh particles have lower reaction rates than catalysts containing larger Rh particles. At low temperature, the Rh(PVP) catalysts display higher catalytic activities than the Rh(PVP-UVO) ones, but the differences become smaller with increasing temperature. For instance, the activities of the catalysts of average particle size 2.3 nm before and after UVO treatment are similar at temperatures higher than 165 °C. The lower activities of the UVO-treated samples are probably the result of more extensive oxidation of the NPs (Table 5). All catalysts with an average Rh size smaller than ca. 7 nm attained similar high reaction rates at temperatures above 165 °C. For Rh NPs larger than 7 nm, the rate increased with increasing particle size. It is therefore concluded that the preferred active phase of these catalysts in H2 oxidation is the metallic phase.

This explains the higher activities of the larger Rh NPs. The strong increase in the activities of small particles during oxidation above 165 °C results from the reduction of the rhodium oxide phase. It is reasonable to assume that metal NPs would also be active sites in H2 generation during photocatalytic water splitting. Shimura et al. [49,50] have investigated the effects of the oxidation states of Rh NPs supported on Sr2TiO4 in the photocatalytic water-splitting reaction, and found that Rh metal catalyzes photocatalytic H2 production better than rhodium oxide does. Our earlier research on Rh particles supported on g-C3N4 also demonstrated that Rh metal particles are preferable for the H2 production reaction [27]. To summarize, for H2 oxidation and its reverse reaction, the Rh metal phase is more active than the rhodium oxide phase in NPs.

3.3. General discussion

We synthesized ZGON(W) catalysts with higher surface areas and Zn/Ga ratios than those reported by the Domen group. Despite their favorable light-absorbing properties shown by UV-Vis spectroscopy, ZGON(W-800) and ZGON(S) loaded with Rh NPs via the PVP method and photodeposition of Rh, respectively, are not active in photocatalytic H2 production under visible-light irradiation. The most likely reason is the differences in the bulk and surface compositions of the final ZGON materials. For ZGON(W-800), we obtained a similar crystalline structure (Fig. 2(a)), UV-Vis absorption spectrum (Fig. 2(b)), Zn/Ga ratio, and N surface content (Table 1) as Wang et al. [21] who did not report photocatalytic activity measurements for their samples. For ZGON(S), we found that the structure, surface area, and Zn/Ga and N/Ga ratios are close to those of the materials reported by the Domen group. A notable difference in the XPS spectra (not shown) was a slight shift of the Ga and Zn 2p3/2 peaks of the sample provided by the Domen group, ZGON(D), to lower binding energies compared with ZGON(S). This is consistent with slightly different bulk and surface compositions. Although ZGON(S) did not show any photocatalytic activity, the Domen's sample produced a small amount of H2 after loading with Rh, and H2 production was further enhanced after Cr2O3 photodeposition. Nonetheless, its activity is much lower than that reported by the Domen group. From the absence of Cr2O3 deposition on Rh/ZGON(W-800) and the other ZGON(S)-based samples, we infer that the photogenerated electron–holes are not able to reduce the chromate. This is consistent with the absence of photocatalytic H2 production before Cr2O3 deposition, and points to a problem with electron transfer from the ZGON light absorber to the cocatalyst. In our study, we used PVP-stabilized Rh NPs. Although the use of PVP might cause the absence of electron transfer from the support to the cocatalyst, we found that conventional photodeposition of Rh on the semiconductor did not produce active photocatalysts either. In the studies by groups other than the Domen group that achieved photocatalytic H2 production by water splitting using these materials, the synthetic procedures and/or photocatalytic performance were different from those reported by the Domen group. For instance, Maeda et al. [1,2] used pure NH3 and Busser et al. [43] used 10% NH3/He for nitridation,
and their products are also photocatalytic. Hahn et al. [42] used the same procedures as Maeda et al. [12] and obtained a photocatalytic H2 production of ca. 13 µmol h⁻¹ gcat⁻¹, which is only slightly higher than the activity of our Cr-Rh/ZGN(D) (3.7 µmol h⁻¹ gcat⁻¹). The activity reported by Hahn et al. [42] is also two orders of magnitude lower than the activity reported by the Domen group [23]. Maeda et al. [41] suggested that the pressure during nitridation and structures of the starting materials can influence the photocatalytic performance of the ZGN product. We therefore speculate that tight control of ZGN synthesis is crucial to obtain photocactive materials that can be used for photocatalytic water splitting. From the above analysis, we infer that it is probable that small differences in the surface composition sometimes inhibit the photocatalytic performance. In addition to the exact ZGN composition, the contact with the Rh NPs may also affect the final performance.

The CO oxidation results demonstrate that smaller Rh particles are more easily oxidized than larger ones. The catalytic activity increases with increasing oxidation degree of the Rh phase, in accordance with previous results [25,28]. This confirms that the rhodium oxide phase is more active for CO oxidation than Rh NPs are [25,28,46]. The difference compared with the study by Lighthart et al. [25] is that ZGN is not reducible. This results in a less pronounced dependence of the reaction rate on the Rh particle size. For H2 oxidation, we observe the opposite trend. Rh metal particles are more active than oxodic ones. Small particles, which are oxidic, therefore show low reaction rates, and larger ones with at most a thin oxide layer, which can be easily removed, have high H2 reaction rates. This is consistent with the common notion that metal NPs catalyze H2 combustion best. Nilekar et al. [51] suggested that removal of adsorbed O from the surface was a significant step in the reaction mechanism: O⁺ + H⁺ → OH⁺ + * or O₂H⁺ + * → O⁺ + OH⁺, followed by OH⁺ + H⁺ → H₂O + 2*. Among these elementary reactions, hydrogenation of OH (OH⁺ + H⁺ → H₂O + 2*) is expected to be facile. Also, dissociation of H₂ and O₂ on Rh metal surfaces should be easy. O⁺ hydrogenation (O⁺ + H⁺ → OH⁺ + *) is difficult on Rh metal. The Rh-O bond in rhodium oxide is stronger than the Rh-O bond of an O adatom on Rh metal, consistent with the higher activity of Rh metal NPs in H2 combustion. Clearly, above ca. 165 °C, the activity of the smaller particles strongly increases because the particles become metallic, in line with the typical reduction temperatures of rhodium oxide, at around this temperature [26]. Although H2 formation also occurs in photocatalytic water splitting, some differences should be noted. The photogenerated electrons reduce protons at the NP metal surfaces. Shimura et al. [49,50] and Maeda et al. [37] suggested that electron extraction from the conduction band of ZGN by rhodium oxide is less efficient than that achieved by Rh metal. This suggests that rhodium oxide cocatalyst reduction is necessary for obtaining active photocatalysts.

4. Conclusions

Mixed [Ga1-xZnx](N1-xOx) materials were synthesized by co-precipitation, wet-precipitation, and solid-solution methods. The textural and light-absorption properties and chemical compositions of these materials were compared. PVP-stabilized Rh NPs with sizes in the 2–9 nm range were loaded onto wet-precipitated [Ga1-xZnx](N1-xOx). Small Rh NPs were more prone to oxidation than larger ones. UVO treatment was used to remove PVP and enhanced oxidation. All the samples were inactive for photocatalytic H2 production. The lower activity than a reference sample provided by the Domen group is explained for some samples by subtle differences in the bulk and surface compositions, stressing the need for tight control of the synthesis of [Ga1-xZnx](N1-xOx). Small, more oxidic Rh NPs are more active in CO oxidation than larger metal ones, whereas the reverse holds for the H2 oxidation reaction. Under H2 oxidation conditions, smaller particles become very active at elevated temperatures when the surface is reduced.

Acknowledgments

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References

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**Graphical Abstract**


Size dependence of photocatalytic oxidation reactions of Rh nanoparticles dispersed on (Ga1-xZnx)(N1-xOx) support

Yi Zhang, D. A. J. Michel Ligthart, Peng Liu, Lu Gao, Tiny M. W. G. M. Verhoeven, Emiel J. M. Hensen*  
Eindhoven University of Technology, The Netherlands

The influence of Rh particle size on (the photo)catalytic performance of ZnO/GaN-supported Rh was investigated. Small oxidic particles were most active in CO oxidation, and large metal ones were most active in H2 oxidation.

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[References]


[41] Maeda K. personal communication


