

CrossMark  
click for updatesCite this: *Chem. Sci.*, 2017, 8, 2574

# Visible light-induced water splitting in an aqueous suspension of a plasmonic Au/TiO<sub>2</sub> photocatalyst with metal co-catalysts†

A. Tanaka,<sup>\*a</sup> K. Teramura,<sup>ab</sup> S. Hosokawa,<sup>ab</sup> H. Kominami<sup>c</sup> and T. Tanaka<sup>ab</sup>

We found that plasmonic Au particles on titanium(IV) oxide (TiO<sub>2</sub>) act as a visible-light-driven photocatalyst for overall water splitting free from any additives. This is the first report showing that surface plasmon resonance (SPR) in a suspension system effectively induces overall water splitting. Modification with various types of metal nanoparticles as co-catalysts enhanced the evolution of H<sub>2</sub> and O<sub>2</sub>. Among these, Ni-modified Au/TiO<sub>2</sub> exhibited 5-times higher rates of H<sub>2</sub> and O<sub>2</sub> evolution than those of Ni-free Au/TiO<sub>2</sub>. We succeeded in designing a novel solar energy conversion system including three elemental technologies, charge separation with light harvest and an active site for O<sub>2</sub> evolution (plasmonic Au particles), charge transfer from Au to the active site for H<sub>2</sub> production (TiO<sub>2</sub>), and an active site for H<sub>2</sub> production (Ni cocatalyst), by taking advantage of a technique for fabricating size-controlled Au and Ni nanoparticles. Water splitting occurred in aqueous suspensions of Ni-modified Au/TiO<sub>2</sub> even under irradiation of light through an R-62 filter.

Received 22nd November 2016

Accepted 29th December 2016

DOI: 10.1039/c6sc05135a

www.rsc.org/chemicalscience

Although hydrogen (H<sub>2</sub>) is primarily used in the chemical industry, it will become an important fuel in the near future. Production of H<sub>2</sub> from water by a semiconductor photocatalyst under photoirradiation of solar light has attracted significant attention because it offers a promising way to produce a clean, low-cost and environmentally friendly energy source.<sup>1</sup> Metal oxides as photocatalysts have been reported to be active for overall water splitting, but most of them require ultraviolet (UV) light ( $\lambda < 400$  nm) because of the large bandgaps of semiconductor materials. However, UV light accounts for only about 5% of the total solar energy, whereas visible light accounts for about 50% of the total solar energy. The development of photocatalysts using visible light is an important topic from a practical point of view. Various visible light-responding photocatalysts, such as a solid solution of GaN and ZnO (Ga<sub>0.5</sub>N<sub>0.5</sub>)<sup>2</sup> and Z-type systems based on Pt/WO<sub>3</sub>–Pt/ZrO/TaON<sup>3</sup> and BiVO<sub>4</sub>–Ru/SrTiO<sub>3</sub>:Rh,<sup>4</sup> have been reported for overall water splitting. To efficiently utilize solar energy, photocatalysts responding to longer wavelengths are required, and the design of photocatalysts working under green light (*ca.* 550 nm) and

red light (*ca.* 620 nm) is a challenge. In addition, simple and additive-free water splitting systems, *i.e.*, a system free from any chemicals except the photocatalyst and water, should be developed.

Nanoparticles of metals, such as copper (Cu), silver (Ag), and gold (Au), show strong photoabsorption (+light scattering) of visible light due to surface plasmon resonance (SPR). The resonance frequency of SPR is strongly dependent on the size, shape, interparticle interactions, dielectric properties, and local environment of the nanoparticles. Recently, plasmonic metal nanoparticles have been applied not only to stained glass but also to chemical sensors and biosensors,<sup>5</sup> surface-enhanced Raman scattering (SERS),<sup>6</sup> fluorescence enhancement,<sup>7</sup> and photocurrent enhancement in photovoltaic cells.<sup>8</sup> It has been reported that electron transfer from Au nanoparticles to a semiconductor occurred under irradiation of visible light ( $\lambda = ca.$  550 nm) due to SPR.<sup>9</sup> Supported Au materials have been used as visible-light-responding photocatalysts for various chemical reactions,<sup>10</sup> including decomposition of organic substrates,<sup>11</sup> selective oxidation of an aromatic alcohol to a carbonyl compound,<sup>12</sup> H<sub>2</sub> formation from alcohols,<sup>13</sup> and reduction of organic compounds.<sup>14</sup> The research groups that reported these photocatalytic reactions concluded that the reactions are induced by SPR of the Au nanoparticles. In our previous study, we found that TiO<sub>2</sub> with both small metal nanoparticles and large Au particles shows activity for H<sub>2</sub> formation<sup>15</sup> and O<sub>2</sub> formation<sup>16</sup> with a sacrificial reagent such as 2-propanol and hexavalent chromium under irradiation of visible light.

<sup>a</sup>Department of Molecular Engineering, Graduate School of Engineering, Kyoto University, Kyotodaigaku Katsura, Nishikyo-ku, Kyoto 615-8510, Japan. E-mail: atsutana@apch.kindai.ac.jp

<sup>b</sup>Elements Strategy Initiative for Catalysts & Batteries (ESICB), Kyoto University, 1-30 Goryo-Ohara, Nishikyo-ku, Kyoto 615-8245, Japan

<sup>c</sup>Department of Applied Chemistry, Faculty of Science and Engineering, Kindai University, Kowakae, Higashiosaka, Osaka 577-8502, Japan

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c6sc05135a



We have focused on an SPR-based photocatalyst powder for overall water splitting to  $\text{H}_2$  and  $\text{O}_2$  in an aqueous suspension without any sacrificial reagents or pH adjustment under irradiation of visible light. Recently, Zhong *et al.* developed photoelectric conversion and photoelectrochemical water splitting systems that use Au nanoparticles loaded onto a  $\text{SrTiO}_3$  single-crystal photoelectrode irradiated by visible light.<sup>17</sup> In their study, the stoichiometric evolution of  $\text{H}_2$  and  $\text{O}_2$  was simultaneously obtained from two separate solution chambers with a chemical bias by regulating the pH values of the chambers. In the present study, we used an  $\text{Au}/\text{TiO}_2$  sample for overall water splitting without using any reagents under irradiation of visible light. Here, we report that samples of  $\text{Au}/\text{TiO}_2$  with co-catalysts were successfully prepared by a combination of photodeposition (PD) or impregnation (IM) and colloid photodeposition in the presence of hole scavenger (CPH) methods, and the samples exhibited larger  $\text{H}_2$  and  $\text{O}_2$  evolution rates than those of a co-catalyst-free  $\text{Au}/\text{TiO}_2$  sample under the irradiation of visible light. Water splitting occurred in an aqueous suspension of  $\text{Au}/\text{TiO}_2$  with  $\text{NiO}_x$  even under irradiation of light through an R-62 filter.

Fig. 1 shows the time courses of evolution of  $\text{H}_2$  and  $\text{O}_2$  from water over  $\text{Au}(1.0)/\text{TiO}_2$  under a dark condition (0–3 h) or irradiation of visible light (3–24 h) in the absence of any additives. No gas evolved in the dark between 0 and 3 h, indicating that no thermocatalytic  $\text{H}_2$  and  $\text{O}_2$  formation occurred in the case of  $\text{Au}(1.0)/\text{TiO}_2$ . Just after irradiation with visible light,  $\text{H}_2$  and  $\text{O}_2$  evolved from the suspension of  $\text{Au}(1.0)/\text{TiO}_2$ . Since  $\text{H}_2$  and  $\text{O}_2$  increased linearly with the photoradiation time, the rates of  $\text{H}_2$  and  $\text{O}_2$  evolution were determined to be 0.94 and 0.46  $\mu\text{mol h}^{-1}$ , respectively. The overall photocatalytic reaction is expressed as eqn (1).



The ratio of moles of  $\text{H}_2$  and  $\text{O}_2$  ( $\text{H}_2/\text{O}_2$  ratio) was calculated from eqn (2):

$$\text{H}_2/\text{O}_2 \text{ ratio} = n(\text{H}_2)/n(\text{O}_2), \quad (2)$$



Fig. 1 Time courses of evolution of  $\text{H}_2$  and  $\text{O}_2$  from water over  $\text{Au}(1.0)/\text{TiO}_2$  under irradiation with visible light from a Xe lamp with an L-42 filter. After 10 h and 17 h of irradiation and evacuation, the suspension was irradiated again.

where  $n(\text{H}_2)$  and  $n(\text{O}_2)$  are the amounts of  $\text{H}_2$  and  $\text{O}_2$  during the photocatalytic reaction, respectively.

As shown in Fig. 1, the  $\text{H}_2/\text{O}_2$  ratio was almost 2.0 regardless of the irradiation time, indicating that  $\text{H}_2$  and  $\text{O}_2$  evolution from water occurred with a high stoichiometry, as shown in eqn (1). To evaluate the stability of  $\text{Au}/\text{TiO}_2$  in  $\text{H}_2$  and  $\text{O}_2$  production from water,  $\text{Au}/\text{TiO}_2$  was used again. Irradiation with visible light of the reaction mixture again induced evolution of  $\text{H}_2$  and  $\text{O}_2$ , and the formation continued from 10 to 17 h and from 17 to 24 h without deactivation.

It is known that the photocatalytic activity for overall water splitting over metal oxides is dependent on the presence of a co-catalyst.<sup>18</sup> Various co-catalysts were loaded onto  $\text{TiO}_2$  using the PD method (Pt, Au, Pd, Rh, Ag) and IM method (Ni, Ru), and then, the Au particles were fixed on  $\text{TiO}_2\text{-M}$  using the CPH method.  $\text{Au}(1.0)/\text{TiO}_2\text{-M}(0.5)$  samples were used for evolution of  $\text{H}_2$  and  $\text{O}_2$  from water over various photocatalysts under visible light irradiation, and the effects of M on the reaction rates were compared. The amounts of  $\text{H}_2$  and  $\text{O}_2$  evolution for 4 h are shown in Table 1. The amounts of  $\text{H}_2$  and  $\text{O}_2$  evolution of all samples with co-catalysts, except for Pt, prepared in this study were larger than that of the M-free  $\text{Au}(1.0)/\text{TiO}_2$  sample. Among the co-catalysts used in this study, Ni had the greatest effect on  $\text{H}_2$  and  $\text{O}_2$  evolution.

Fig. 2 shows the absorption spectra of  $\text{TiO}_2$ ,  $\text{TiO}_2\text{-NiO}_x(0.5)$ ,  $\text{Au}(1.0)/\text{TiO}_2$ , and  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  samples. The bare  $\text{TiO}_2$  sample exhibited absorption only at  $\lambda < 400$  nm because of the band gap excitation. Loading Ni species onto  $\text{TiO}_2$  resulted in an increase in the baseline of the photoabsorption, which has generally been observed. In the spectra of the  $\text{Au}(1.0)/\text{TiO}_2$  and  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  samples, a strong photoabsorption was observed at around 550 nm, and it was attributed to SPR of the supported Au nanoparticles.<sup>9–17</sup> Since photoabsorption due to Ni species was also included, the  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  sample exhibited stronger photoabsorptions at 700–800 nm.

Fig. 3(a) shows a TEM photograph of the  $\text{TiO}_2\text{-NiO}_x(0.5)$  sample simply prepared by the traditional IM method.  $\text{NiO}_x$  particles were observed, and the average diameter was determined to be 9.3 nm (Fig. S1(a)†), indicating that the  $\text{NiO}_x$

Table 1 Effect of modification of  $\text{Au}(1.0 \text{ wt}\%)/\text{TiO}_2$  with various metal co-catalysts (0.5 wt%) on water splitting<sup>a</sup>

Cocat.	Modification method	Amount of products (4 h)/ $\mu\text{mol}$	
		$\text{H}_2$	$\text{O}_2$
None	—	3.9	1.9
Pt	PD	2.7	1.1
Au		10	5.2
Pd		10	4.9
Rh		9.3	4.7
Ag		8.0	3.9
$\text{NiO}_x$	IM	22	11
$\text{RuO}_x$		6.1	3.0

<sup>a</sup> Reaction conditions: catalyst, 300 mg (co-catalyst-loaded); pure water, 300  $\text{cm}^3$ , Xe lamp (300 W) with an L-42 filter; reaction vessel, Pyrex side-irradiation type.





Fig. 2 Absorption spectra of  $\text{TiO}_2$ ,  $\text{TiO}_2\text{-NiO}_x(0.5)$ ,  $\text{Au}(1.0)/\text{TiO}_2$ , and  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$ .

particles were successfully deposited on the surface of  $\text{TiO}_2$  using the IM method. Fig. 3(b) shows a TEM image of  $\text{Au}(1.0)/\text{TiO}_2$  prepared by the CPH method using an Au colloidal solution. Gold particles were observed in the image, indicating that Au nanoparticles were deposited on the  $\text{TiO}_2$  surface by the CPH method.

The average diameter of the Au particles in the sample was determined to be 13 nm (Fig. S1(b)<sup>†</sup>), which is in good agreement with the average diameter of the original colloidal Au nanoparticles before Au loading (Fig. S2<sup>†</sup>). In the TEM photograph of the  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  sample (Fig. 3(c)), both smaller and larger particles were observed, and the average diameters were determined to be 9.1 and 13 nm (Fig. S1(c and d)<sup>†</sup>), respectively. These results indicate that the CPH method induced no change in the  $\text{NiO}_x$  particles during the loading of the Au particles and that the Au particles were successfully loaded onto the  $\text{TiO}_2\text{-NiO}_x$  without a change in the original particle size, as in the case of loading Au onto bare  $\text{TiO}_2$ .<sup>15</sup>

Ni K-edge XANES spectra of  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  and  $\text{TiO}_2\text{-NiO}_x(0.5)$  are shown in Fig. 4(a), for which Ni foil and NiO were used as references. The similar XANES spectra of  $\text{Au}/\text{TiO}_2\text{-NiO}_x$ ,  $\text{TiO}_2\text{-NiO}_x$  and NiO clearly proves that the Ni species is



Fig. 4 (a) Ni K-edge XANES spectra of Ni foil, NiO,  $\text{TiO}_2\text{-NiO}_x(0.5)$  and  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$ ; (b) XPS spectra of  $\text{Au}(1.0)/\text{TiO}_2$ ,  $\text{TiO}_2\text{-NiO}_x(0.5)$  and  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  around Ni 2p components.

NiO. X-ray photoelectron spectroscopy (XPS) was used to obtain information on the surfaces of the  $\text{NiO}_x$  co-catalysts in the  $\text{Au}/\text{TiO}_2\text{-NiO}_x$  samples. Normalized Ni 2p XPS spectra of  $\text{Au}/\text{TiO}_2\text{-NiO}_x(0.5)$ ,  $\text{TiO}_2\text{-NiO}_x(0.5)$ ,  $\text{Au}(1.0)/\text{TiO}_2$  and  $\text{TiO}_2$  are shown in Fig. S3,<sup>†</sup> of which the Ni 2p spectra have an overlap with the Auger parameters of Ti.<sup>19</sup> The subtracted XPS spectra obtained from the spectra of various samples ( $\text{Au}/\text{TiO}_2\text{-NiO}_x$ ,  $\text{TiO}_2\text{-NiO}_x$ ,  $\text{Au}/\text{TiO}_2$ ) and  $\text{TiO}_2$  are shown in Fig. 4(b). No peak is observed in the spectrum of  $\text{Au}/\text{TiO}_2$ . In the spectra of  $\text{TiO}_2\text{-NiO}_x$  and  $\text{Au}/\text{TiO}_2\text{-NiO}_x$ , peaks due to Ni ( $2p_{3/2}$ ) that are assignable to  $\text{Ni}^{2+}$ , such as NiO, are observed at 856.3 eV.<sup>20</sup> On the other hand, peaks due to Ni ( $2p_{3/2}$ ) that are assignable to  $\text{Ni}^0$ , such as Ni metal, are also observed at 852.7 eV (ref. 21) in the spectrum of  $\text{Au}/\text{TiO}_2\text{-NiO}_x$ . Although the corresponding change was not observed by XAFS measurement, partial formation of Ni metal is confirmed by the XPS spectrum, in which both signals assigned to  $\text{Ni}^{2+}$  and  $\text{Ni}^0$  are observed. It is expected that the surface of NiO in the  $\text{TiO}_2\text{-NiO}_x$  is reduced to Ni metal during the deposition of the Au particles by the CPH method under irradiation with UV light. Fig. S4<sup>†</sup> shows the time courses of evolution of  $\text{H}_2$  in methanol suspensions of  $\text{TiO}_2\text{-NiO}_x(0.5)$  and  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$  samples under irradiation with UV light. For the first hour,  $\text{TiO}_2\text{-NiO}_x$  showed a very low activity for  $\text{H}_2$  evolution, and the continuous formation of  $\text{H}_2$  at a constant rate was observed after the induction period. These results indicate that the state of the Ni species in  $\text{TiO}_2\text{-NiO}_x$  changes in the early stage of the photocatalytic reaction, *i.e.*, the surface of NiO in  $\text{TiO}_2\text{-NiO}_x$  was reduced to the  $\text{Ni}^0$  species during the induction period. In contrast, there was no induction period for photocatalytic  $\text{H}_2$  production over  $\text{Au}/\text{TiO}_2\text{-NiO}_x$ , indicating that some of the  $\text{NiO}_x$  particles had been reduced to metallic Ni.

In our previous study on the photocatalytic activity for  $\text{H}_2$  formation from 2-propanol over  $\text{Au}/\text{TiO}_2\text{-Pt}$  samples, Pt exhibited the greatest effect on  $\text{H}_2$  evolution.<sup>15</sup> The two types of metal particles had different functionalities, *i.e.*, the large Au particles contributed to the strong light absorption, and the small Pt particles acted as reduction sites for the  $\text{H}_2$  evolution. However, the activity of the  $\text{Au}/\text{TiO}_2\text{-Pt}$  samples was much smaller than that of the other samples in this study, and the reaction rate gradually decreased (Fig. S5<sup>†</sup>), suggesting that the  $\text{H}_2\text{-O}_2$  consumption reaction occurred on the Pt nanoparticles.

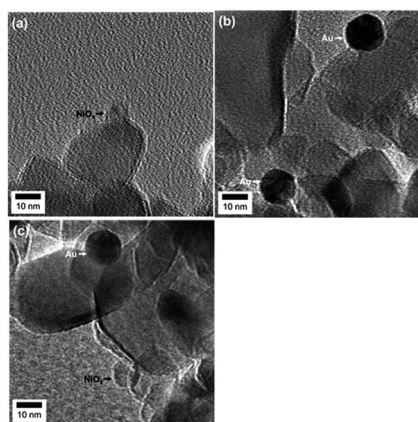


Fig. 3 TEM images of (a)  $\text{TiO}_2\text{-NiO}_x(0.5)$ , (b)  $\text{Au}(1.0)/\text{TiO}_2$ , and (c)  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$ .



This was confirmed by testing the water formation reaction from a mixture of  $H_2$  and  $O_2$  in the dark using  $Au/TiO_2$ -Pt, as shown in Fig. 5(a). The amounts of  $H_2$  and  $O_2$  in a closed-gas circulation system decreased with time, indicating that water formation occurs on  $Au/TiO_2$ -Pt. On the other hand,  $Au/TiO_2$ - $NiO_x$  and  $Au/TiO_2$  samples showed a smaller rate of backward reaction between  $H_2$  and  $O_2$  into  $H_2O$  (consumption rates of  $H_2$  and  $O_2$ ) than that of the  $Au/TiO_2$ -Pt samples, as shown in Fig. 5(b and c). The small rate of the reverse reaction over  $Au/TiO_2$  indicates that the formation of  $H_2$  and  $O_2$  was scarcely affected by the reverse reaction. Therefore, the reaction rate of  $H_2$  and  $O_2$  formation reflects the photocatalytic activity of  $Au/TiO_2$  for water splitting. A linear relationship between the yields and time in Fig. 1, *i.e.*, zero-order kinetics, suggests that the reaction rate over  $Au/TiO_2$  was determined by photon flux and photon utilization efficiency because the concentration of water on the  $Au/TiO_2$  surface is constant. These results indicated that the actual rates of  $H_2$  and  $O_2$  evolution on the  $Au/TiO_2$ -Pt sample should be higher than those recorded by monitoring the gas phase of the reaction system.  $TiO_2$ ,  $TiO_2$ -Pt(0.5),  $TiO_2$ - $NiO_x$ (0.5),  $Au(1.0)/TiO_2$ , and  $Au(1.0)/TiO_2$ - $NiO_x$ (0.5) samples were used for the evolution of  $H_2$  and  $O_2$  from water under visible light irradiation from a Xe lamp with an L-42 filter. The rates of  $H_2$  and  $O_2$  evolution are shown in Fig. S6.† No  $H_2$  or  $O_2$  was evolved in the case of  $TiO_2$ ,  $TiO_2$ -Pt or  $TiO_2$ - $NiO_x$ . These results indicate that the visible light coming from a filtered Xe lamp did not cause band gap excitation of  $TiO_2$  and that photocatalysis and/or thermocatalysis of  $TiO_2$ -Pt and  $TiO_2$ - $NiO_x$  were negligible under the present conditions. The  $Au(1.0)/TiO_2$  sample, which was active in the overall water splitting, showed  $H_2$  and  $O_2$  evolution rates of 0.94 and 0.46  $\mu\text{mol h}^{-1}$ , respectively. The  $Au(1.0)/TiO_2$ - $NiO_x$ (0.5) sample exhibited much larger  $H_2$  and  $O_2$  formation rates of 5.5 and 2.7  $\mu\text{mol h}^{-1}$ , respectively, indicating that the  $NiO_x$  co-catalyst loaded onto  $TiO_2$  effectively acted as reduction sites for  $H_2$  evolution. Loading both large Au particles and small co-catalyst particles on the  $TiO_2$  surface without alloying or nanoparticle coagulation has been difficult, as stated above. This requisite was successfully achieved, and a large reaction rate was obtained, as predicted, by the  $Au/TiO_2$ - $NiO_x$  sample prepared

by the combination of the traditional IM method for  $NiO_x$  co-catalyst particles and the CPH method for large Au particles.

To examine the effect of the amount of Au on the rates of  $H_2$  and  $O_2$  formation, various amounts of  $Au(X)$  were loaded onto  $TiO_2$ - $NiO_x$ (0.5) and  $TiO_2$  samples using the CPH method.  $Au(X)/TiO_2$ - $NiO_x$ (0.5) and  $Au(X)/TiO_2$  samples were used for water splitting under irradiation of visible light, and the rates of  $H_2$  and  $O_2$  formation are shown in Fig. 6(a and b), respectively. The amounts of  $H_2$  and  $O_2$  increased linearly with the photo-irradiation time in all  $Au(X)/TiO_2$ - $NiO_x$ (0.5) and  $Au(X)/TiO_2$  samples, and the formation rates of  $H_2$  and  $O_2$  were determined from the slopes of the time- $H_2$  and  $O_2$  evolution plots. The formation rates of  $H_2$  and  $O_2$  increased almost linearly with an increase in  $X$  until  $X = 1.0$  wt% and gradually increased after  $X = 1.0$  wt%. In a previous study,<sup>15</sup> the light absorption due to SPR at 550 nm of a sample prepared by the CPH method increased with an increase in Au loading until 1.0 wt% and gradually increased after  $X = 1.0$  wt%. The Au loading dependency of the light absorption due to SPR was similar to that of the formation rates of  $H_2$  and  $O_2$ , and a linear correlation was observed between the reaction rate and the light absorption due to SPR. We concluded that SPR photoabsorption by the Au particles was one of the important factors determining the photocatalytic activity in this study.

To examine the effect of the amount of the  $NiO_x$  co-catalyst on the rates of  $H_2$  and  $O_2$  formation,  $TiO_2$ - $NiO_x$ ( $Y$ ) samples with various Ni loadings ( $Y$ ) were prepared, and Au particles (1.0 wt%) were introduced to the samples using the CPH method. The  $Au(1.0)/TiO_2$ - $NiO_x$ ( $Y$ ) samples were used for overall water splitting under irradiation of visible light; the rates of  $H_2$  and  $O_2$  formation are shown in Table 2. The Ni-free sample ( $Au(1.0)/TiO_2$ ) exhibited small rates of  $H_2$  and  $O_2$  formation (0.94 and 0.46  $\mu\text{mol h}^{-1}$ , respectively), as shown above. Only a small amount of  $NiO_x$  loading ( $Y = 0.1$  wt%) increased the formation rate, indicating that the  $NiO_x$  co-catalyst effectively acted as the reduction center in the sample. The formation rate increased until  $Y = 0.5$  wt%, and a further increase in  $Y$  decreased the formation rate. The maximum rates of  $H_2$  and  $O_2$  formation (5.5 and 2.7  $\mu\text{mol h}^{-1}$ , respectively) were obtained at



Fig. 5 Water formation from  $H_2$  and  $O_2$  in the dark on (a)  $Au(1.0)/TiO_2$ -Pt(0.5), (b)  $Au(1.0)/TiO_2$ - $NiO_x$ (0.5) and (c)  $Au(1.0)/TiO_2$  samples. This experiment was carried out in pure water (300  $\text{cm}^3$ ) using a closed-gas circulation system containing a stoichiometric mixture of  $H_2$  and  $O_2$  gases.



Fig. 6 Effect of Au loading amounts ( $X$ ) on the rate of evolution of  $H_2$  and  $O_2$  from water over (a)  $Au(X)/TiO_2$  and (b)  $Au(X)/TiO_2$ - $NiO_x$ (0.5) samples under irradiation of visible light.





**Table 2** Effect of NiO<sub>x</sub>(Y) loading amounts on the rate of evolution of H<sub>2</sub> and O<sub>2</sub> from water over Au/TiO<sub>2</sub>-NiO<sub>x</sub>(Y) samples under irradiation of visible light

Entry	NiO <sub>x</sub> loading (Y)/wt%	Size of NiO <sub>x</sub> /nm	Formation rate/ $\mu\text{mol h}^{-1}$	
			H <sub>2</sub>	O <sub>2</sub>
1	—	—	0.99	0.49
2	0.1	6.6	2.7	1.3
3	0.5	9.1	5.5	2.7
4	1.0	15	3.8	1.9
5	2.0	18	1.8	0.95

Y = 0.5 wt%. The average size of the NiO<sub>x</sub> nanoparticles in Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>(Y) was determined by TEM (Fig. S7†). NiO<sub>x</sub> particles were loaded onto TiO<sub>2</sub> when the amount of NiO<sub>x</sub> was small (<10 nm, Y = 0.1 and 0.5 wt%); however, the size of the NiO<sub>x</sub> particles drastically increased to 15 nm at Y = 1.0 wt%, indicating that the IM method was suitable for loading a small amount of small particles on TiO<sub>2</sub>. Since the particle size of NiO<sub>x</sub> with Y = 0.5 was smaller (<10 nm) than that with Y > 1.0 and the concentration of the Ni species with Y = 0.5 was higher than that with Y = 0.1, the photocatalytic activity of the Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>(0.5) samples was higher than those of the other samples. These results suggested that the NiO<sub>x</sub> particles acted as reduction sites in the Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>(Y) samples and that the reaction is sensitive to the structure of the NiO<sub>x</sub> particles.

Fig. 7 shows time courses of the evolution of H<sub>2</sub> and O<sub>2</sub> from water over Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>(0.5) under a dark condition (0–5 h) or irradiation with visible light from a Xe lamp with L-42 (5–13 h, 29–37 h) or O-54 (13–21 h) or R-62 (21–29 h). Fig. 7 is different from an ordinary action spectrum, and the results indicate the effects of both the wavelength of light and amount of photons. No gas was evolved in the dark between 0 and 5 h, indicating that no thermocatalytic H<sub>2</sub> and O<sub>2</sub> formation occurred in the case of Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>(0.5). The value of H<sub>2</sub>/O<sub>2</sub> was almost 2.0 regardless of the irradiation time and the cut-off filter used. The formation rates of H<sub>2</sub> and O<sub>2</sub> decreased with an increase in the filter number (L-42 > O-54 > R-62), corresponding to the decrease in photoabsorption (Fig. S8(a)†). It should be noted that water

splitting continuously occurred, even under irradiation of light through an R-62 filter. To the best of our knowledge, this is the first report showing H<sub>2</sub> and O<sub>2</sub> formation from water splitting free from any additives over an Au plasmonic photocatalyst under irradiation of red light (>600 nm). Irradiation of visible light from a Xe lamp with L-42 to the reaction mixture again induced evolution of H<sub>2</sub> and O<sub>2</sub> from water, and the formation continued from 29 to 37 h without deactivation after irradiation of visible light from different cut-off filters.

Other research groups also reported H<sub>2</sub> formation<sup>13a,22a</sup> and O<sub>2</sub> formation<sup>22</sup> over Au/TiO<sub>2</sub> in the presence of a sacrificial reagent under irradiation of visible light, indicating that Au/TiO<sub>2</sub>-related materials have a sufficient potential for H<sub>2</sub> formation (H<sup>+</sup>/H<sub>2</sub>: 0 V NHE pH 0) and oxidization of H<sub>2</sub>O (H<sub>2</sub>O/O<sub>2</sub>: 1.23 V NHE pH 0). Therefore, the simultaneous evolution of H<sub>2</sub> and O<sub>2</sub> by water splitting in this study is reasonable and is attributed to the acceleration of the positive reaction and suppression of the reverse reaction by co-catalysts introduced to Au/TiO<sub>2</sub>. Energy (ca. 2.5 or 2.1 eV) corresponding to light ( $\lambda$  = ca. 500 nm or 600 nm) that the Au/TiO<sub>2</sub> materials absorb is reasonably large for both H<sub>2</sub> and O<sub>2</sub> formations even though some over-potentials are required for these formations. In our previous study, we examined the action spectra in H<sub>2</sub> formation<sup>15</sup> and O<sub>2</sub> formation<sup>16</sup> over Au/TiO<sub>2</sub>-Pt in the presence of sacrificial reagents under irradiation with visible light and reported that both spectra showed a similar tendency of absorption spectra. Since rates of water splitting were very small under the irradiation of weak monochromated light, we analyzed the results shown in Fig. 7, and the intensity of the light coming through the cut-off filters is shown in Fig. S8(a)†. From the results, the difference in the intensity of light irradiated to Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub> was calculated in three ranges (Fig. S8(b)†). Based on the incident photons from 520 to 650 nm and the difference in the formation rates in the case of O54 and R62, the value of the apparent quantum efficiency (AQE) was calculated to be 0.013%. In the same way, the values of AQE were calculated based on the incident photons in other ranges and plotted against the wavelength of light irradiated to Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub> as well as that of AQE from 520 to 650 nm. As shown in Fig. S9,† the wavelength-dependency of AQE was roughly consistent with the spectrum of Au(1.0)/TiO<sub>2</sub>. We think that this action spectrum is direct evidence that the plasmon-induced water splitting is really induced over Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>. As shown in the action spectrum (Fig. S9†), the upper limit of light wavelength available for water splitting over Au/TiO<sub>2</sub>-NiO<sub>x</sub> seems to be ca. 700 nm (corresponding to ca. 1.8 eV).

Based on the proposed working mechanism for H<sub>2</sub> and O<sub>2</sub> formation in the presence of a sacrificial reagent, the expected energy diagram and working mechanism for H<sub>2</sub> and O<sub>2</sub> formation from water over Au/TiO<sub>2</sub>-NiO<sub>x</sub> under irradiation with visible light are shown in Scheme 1. Four processes would occur: (1) the incident photons are absorbed by Au particles through their SPR excitation,<sup>10</sup> (2) electrons are injected from the Au particles into the conduction band of TiO<sub>2</sub>, (3) the resultant electron-deficient Au particles oxidize H<sub>2</sub>O to O<sub>2</sub> and return to their original metallic state, and (4) electrons in the conduction band of TiO<sub>2</sub> transfer to the NiO<sub>x</sub> nanoparticles



**Fig. 7** Time courses of evolution of H<sub>2</sub> and O<sub>2</sub> from water over Au(1.0)/TiO<sub>2</sub>-NiO<sub>x</sub>(0.5) under irradiation of visible light from a Xe lamp with various filters. After 13, 21 and 29 h of irradiation and evacuation, the suspension was irradiated again.





**Scheme 1** Expected reaction mechanism for the production of  $\text{H}_2$  and  $\text{O}_2$  from water over a  $\text{Au}/\text{TiO}_2\text{-NiO}_x$  sample.

as a co-catalyst at which reduction of  $\text{H}^+$  to  $\text{H}_2$  occurs. Rapid electron transfer from Au to the  $\text{TiO}_2$  film under visible light irradiation was observed using femtosecond transient absorption spectroscopy.<sup>9b</sup> In addition to  $\text{O}_2$  evolution in the presence of a sacrificial reagent,<sup>22</sup> Shi *et al.* demonstrated enhancement in the photocurrent generation and photocatalytic water oxidation sensitized by Au showing SPR under irradiation with visible light.<sup>23</sup> Process (3) is supported by these results. Reduction of  $\text{H}^+$  by electrons in the conduction band of  $\text{TiO}_2$  is difficult because the level is very close to the reduction potential. Therefore, continuous evolution of  $\text{H}_2$  is generally achieved by introducing a co-catalyst on  $\text{TiO}_2$ . The co-catalyst effect observed in this study supports process (4). As shown in Fig. 1 and Table 1,  $\text{Au}(1.0)/\text{TiO}_2$  evolved  $\text{H}_2$  and  $\text{O}_2$ , indicating that Au particles loaded by the CPH method also work as a co-catalyst. We also prepared Au-loaded tin(IV) oxide ( $\text{SnO}_2$ ) and  $\text{Au}/\text{SnO}_2\text{-NiO}_x$  using the CPH method, and used it for water splitting under the same conditions. Evolution of  $\text{H}_2$  and  $\text{O}_2$  over these samples was negligible because the level of the conduction band of  $\text{SnO}_2$  is positive to the potential for  $\text{H}^+$  reduction, *i.e.*, insufficient for  $\text{H}^+$  reduction. The difference in the results between  $\text{TiO}_2$  and  $\text{SnO}_2$  indirectly supports process (4).

## Conclusions

The  $\text{Au}/\text{TiO}_2$  sample continuously yielded  $\text{H}_2$  and  $\text{O}_2$  from water in the absence of additives under visible light irradiation.  $\text{Au}/\text{TiO}_2$  with  $\text{NiO}_x$  particles was successfully prepared by the combination of photodeposition and impregnation methods. We observed that modification of the  $\text{Au}/\text{TiO}_2$  sample with Ni drastically improved the performance of the photocatalyst, and the samples continuously split water even under irradiation with red light. The backward reaction between the evolved  $\text{H}_2$  and  $\text{O}_2$  into  $\text{H}_2\text{O}$  could be suppressed using  $\text{NiO}_x$ , although the Pt co-catalyst enhanced the consumption rates and  $\text{H}_2$  and  $\text{O}_2$ . These results suggest that separate loading of the  $\text{NiO}_x$  co-catalyst without alloying with Au particles is effective for enhancing the activity of an Au plasmonic photocatalyst for overall water splitting.

## Experimental section

Commercial  $\text{TiO}_2$  powder (P25,  $50 \text{ m}^2 \text{ g}^{-1}$ ) with an anatase/rutile phase was supplied by Degussa.

Loading of the co-catalysts (M: Pt, Au, Pd, Rh, Ag) on  $\text{TiO}_2$  (preparation of  $\text{TiO}_2\text{-M}$ ) was performed by the PD method.  $\text{TiO}_2$  powder was suspended in  $10 \text{ cm}^3$  of an aqueous solution of methanol (50 vol%) in a test tube, and the test tube was sealed with a rubber septum under argon (Ar). An aqueous solution of the co-catalyst source was injected into the sealed test tube and then photoirradiated for 2 h at  $\lambda > 300 \text{ nm}$  by a 400 W high-pressure mercury arc (Eiko-sha, Osaka) with magnetic stirring in a water bath continuously kept at 298 K. The co-catalyst source was reduced by photogenerated electrons, and metal was deposited on the surface of the  $\text{TiO}_2$  particles. Analysis of the liquid phase after photodeposition revealed that the co-catalyst source had been almost completely (>99.9%) deposited on the  $\text{TiO}_2$  particles. The resultant powder was washed repeatedly with distilled water and then dried at 310 K overnight under air.

Loading of co-catalysts (M: Ni, Ru) on  $\text{TiO}_2$  (preparation of  $\text{TiO}_2\text{-M}$ ) was performed by the IM method.  $\text{TiO}_2$  powder was suspended in  $10 \text{ cm}^3$  of an aqueous solution of a co-catalyst source in a glass dish and was evaporated to dryness at 333 K. The product was dried overnight at room temperature and then calcined at 573 K for 1 h in air.

Colloidal Au nanoparticles were prepared using the method reported by Frens.<sup>24</sup> To  $750 \text{ cm}^3$  of an aqueous tetrachloroauric acid ( $\text{HAuCl}_4$ ) solution ( $0.49 \text{ mmol dm}^{-3}$ ),  $100 \text{ cm}^3$  of an aqueous solution containing sodium citrate ( $39 \text{ mmol dm}^{-3}$ ) was added. The solution was heated and boiled for 1 h. After the color of the solution changed from deep blue to deep red, the solution was boiled for an additional 30 min. After the solution was cooled to room temperature, Amberlite MB-1 (ORGANO,  $60 \text{ cm}^3$ ) was added to remove excess sodium citrate. After 1 h of treatment, MB-1 was removed from the solution using a glass filter. Loading of Au particles on the  $\text{TiO}_2\text{-M}$  samples was performed by the CPH method.<sup>25</sup> Preparation of  $\text{TiO}_2\text{-M}$  having 1.0 wt% Au as a typical sample is described. A  $\text{TiO}_2\text{-M}$  sample (168 mg) was suspended in  $20 \text{ cm}^3$  of an aqueous solution of colloidal Au nanoparticles ( $0.085 \text{ mg cm}^{-3}$ ) in a test tube, and the test tube was sealed with a rubber septum under Ar. An aqueous solution of oxalic acid ( $50 \mu\text{mol}$ ) was injected into the sealed test tube. The mixture was photoirradiated at  $\lambda > 300 \text{ nm}$  by a 400 W high-pressure mercury arc under Ar with magnetic stirring in a water bath continuously kept at 298 K. The resultant powder was washed repeatedly with distilled water and then dried at 310 K overnight under air. Co-catalyst-free samples ( $\text{Au}/\text{TiO}_2$ ) were also prepared by the same method using bare  $\text{TiO}_2$  samples. When samples with different Au contents were prepared, the amount of  $\text{TiO}_2\text{-M}$  (or  $\text{TiO}_2$ ) was changed (volume and concentration of the Au colloidal solution being fixed). Hereafter, an Au-loaded  $\text{TiO}_2\text{-M}$  sample having Y wt% of M and X wt% of Au is designated as  $\text{Au}(X)/\text{TiO}_2\text{-M}(Y)$ ; for example, a sample having 0.5 wt% Ni and 1.0 wt% Au is shown as  $\text{Au}(1.0)/\text{TiO}_2\text{-NiO}_x(0.5)$ . Oxalic acid is necessary for complete Au loading on  $\text{TiO}_2$  (ref. 25) and may protect citrate from covering Au particles. Since the numbers of co-catalyst particles was much larger than that of Au particles,<sup>15</sup> the co-catalysts will act effectively.

Diffuse reflectance spectra of the samples were obtained with a JASCO Corporation V-670 spectrometer equipped with an



integrating sphere. Spectralon, which was supplied by Labsphere Inc., was used as a standard reflection sample such as BaSO<sub>4</sub>. The morphology of the samples was observed under a JEOL JEM-2100F transmission electron microscope (TEM) operated at 200 kV at the Joint Research Center of Kindai University. X-ray photoelectron spectroscopy (XPS) measurements were conducted on an ESCA-3400 spectrometer (Shimadzu, Japan). A sample was mounted on a silver sample holder using conductive carbon tape and was analyzed using Mg K $\alpha$  radiation in a vacuum chamber in 0.1 eV steps. The position of the carbon peak (284.6 eV) for C 1s was used to calibrate the binding energy for all the samples. Ni K-edge (8.3 keV) X-ray absorption fine structure (XAFS) measurements were made in the fluorescence mode at the BL01B1 beamline of the SPring-8 synchrotron radiation facility (Hyogo, Japan). A typical data reduction procedure (e.g., background removal or normalization) was carried out with Athena (version 0.9.20).

Reactions were conducted in a Pyrex side-irradiation vessel connected to a glass closed gas circulation system. A 300 mg sample of Au/TiO<sub>2</sub>-M powder was dispersed in pure water (300 cm<sup>3</sup>) using a magnetic stirrer, and this reactant solution was evacuated under vacuum several times to completely remove any residual air. Following this, a small amount of Ar gas was introduced into the reaction system prior to irradiation under a 300 W xenon lamp (Cermex, PE300BF) filtered with various filters with a 15 A output current. The amounts of H<sub>2</sub> and O<sub>2</sub> in the gas phase were measured using a Shimadzu GC-8A gas chromatograph equipped with an MS-5A column.

## Acknowledgements

This study was partially supported by the Program for Element Strategy Initiative for Catalysts & Batteries (ESICB), commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan; the Precursory Research for Embryonic Science and Technology (PRESTO), supported by the Japan Science and Technology Agency (JST); Grant-in-Aid for Scientific Research (No. 26289307, 15K18269) from the Japan Society for the Promotion of Science (JSPS); Program for the Strategic Research Foundation at Private Universities 2014–2018 from MEXT and Kindai University. The XAFS experiments were performed with the approval of SPring-8 (Proposal no. 2014B1439 and 2015A1487). Atsuhiko Tanaka is grateful to the JSPS for a Research Fellowship for young scientists.

## References

- (a) A. Kudo and Y. Miseki, *Chem. Soc. Rev.*, 2009, **38**, 253; (b) R. Abe, *J. Photochem. Photobiol., C*, 2010, **11**, 179; (c) X. Chen, S. Shen, L. Guo and S. S. Mao, *Chem. Rev.*, 2010, **110**, 6503.
- (a) K. Maeda, K. Teramura, D. Lu, T. Takata, N. Saito, Y. Inoue and K. Domen, *Nature*, 2006, **440**, 295; (b) K. Maeda, K. Teramura, D. Lu, N. Saito, Y. Inoue and K. Domen, *Angew. Chem., Int. Ed.*, 2006, **45**, 7806.
- K. Maeda, M. Higashi, D. Lu, R. Abe and K. Domen, *J. Am. Chem. Soc.*, 2010, **132**, 5858.
- (a) Y. Sasaki, H. Nemoto, K. Saito and A. Kudo, *J. Phys. Chem. C*, 2009, **113**, 17536; (b) Y. Sasaki, H. Kato and A. Kudo, *J. Am. Chem. Soc.*, 2013, **135**, 5441.
- M. E. Stewart, C. R. Anderton, L. B. Thompson, J. Maria, S. K. Gray, J. A. Rogers and R. G. Nuzzo, *Chem. Rev.*, 2008, **108**, 494.
- P. L. Stiles, J. A. Dieringer, N. C. Shah and R. P. Van Duyne, *Annu. Rev. Anal. Chem.*, 2008, **1**, 601.
- J. R. Lakowicz, K. Ray, M. Chowdhury, H. Szmazinski, Y. Fu, J. Zhang and K. Nowaczyk, *Analyst*, 2008, **133**, 1308.
- H. A. Atwater and A. Polman, *Nat. Mater.*, 2010, **9**, 205.
- (a) Y. Tian and T. Tatsuma, *J. Am. Chem. Soc.*, 2005, **127**, 7632; (b) A. Furube, L. Du, K. Hara, R. Katoh and M. Tachiya, *J. Am. Chem. Soc.*, 2007, **129**, 14852.
- (a) M. Xiao, R. Jiang, F. Wang, C. Fang, J. Wang and J. C. Yu, *J. Mater. Chem. A*, 2013, **1**, 5790; (b) S. C. Warren and E. Thimsen, *Energy Environ. Sci.*, 2012, **5**, 5133; (c) X. Zhou, G. Liu, J. Yu and W. Fan, *J. Mater. Chem.*, 2012, **22**, 21337; (d) S. Linic, P. Christopher and D. B. Ingram, *Nat. Mater.*, 2011, **10**, 911; (e) T. Tatsuma, *Bull. Chem. Soc. Jpn.*, 2013, **86**, 1.
- E. Kowalska, R. Abe and B. Ohtani, *Chem. Commun.*, 2009, 241.
- (a) S. Naya, M. Teranishi, T. Isobe and H. Tada, *Chem. Commun.*, 2010, **46**, 815; (b) A. Tanaka, K. Hashimoto and H. Kominami, *J. Am. Chem. Soc.*, 2012, **134**, 14526–14533.
- (a) H. Yuzawa, T. Yoshida and H. Yoshida, *Appl. Catal., B*, 2012, **115**, 294; (b) A. Tanaka, S. Sakaguchi, K. Hashimoto and H. Kominami, *Catal. Sci. Technol.*, 2012, **2**, 907.
- (a) X. Ke, S. Sarina, J. Zhao, X. Zhang, J. Chang and H. Zhu, *Chem. Commun.*, 2012, **48**, 3509; (b) A. Tanaka, Y. Nishino, S. Sakaguchi, T. Yoshikawa, K. Imamura, K. Hashimoto and H. Kominami, *Chem. Commun.*, 2013, **49**, 2551.
- A. Tanaka, S. Sakaguchi, K. Hashimoto and H. Kominami, *ACS Catal.*, 2013, **3**, 79.
- A. Tanaka, K. Nakanishi, R. Hamada, K. Hashimoto and H. Kominami, *ACS Catal.*, 2013, **3**, 1886.
- Y. Zhong, K. Ueno, Y. Mori, X. Shi, T. Oshikiri, K. Murakoshi, H. Inoue and H. Misawa, *Angew. Chem., Int. Ed.*, 2014, **53**, 10350.
- K. Maeda, *J. Photochem. Photobiol., C*, 2011, **12**, 237.
- G. M. Ingo, S. Dire and F. Babonneau, *Appl. Surf. Sci.*, 1993, **70**, 230.
- A. N. Mansour, *Surf. Sci. Spectra*, 1994, **3**, 231.
- A. N. Mansour, *Surf. Sci. Spectra*, 1994, **3**, 211.
- (a) C. G. Silva, R. Juarez, T. Marino, R. Molinari and H. Garcia, *J. Am. Chem. Soc.*, 2011, **133**, 595; (b) A. Primo, T. Marino, A. Corma, R. Molinari and H. Garcia, *J. Am. Chem. Soc.*, 2011, **133**, 6930.
- X. Shi, K. Ueno, N. Takabayashi and H. Misawa, *J. Phys. Chem. C*, 2013, **117**, 2494.
- G. Frens, *Nature Phys. Sci.*, 1973, **241**, 20.
- A. Tanaka, A. Ogino, M. Iwaki, K. Hashimoto, A. Ohnuma, F. Amano, B. Ohtani and H. Kominami, *Langmuir*, 2012, **28**, 13105.

