



Z-scheme photocatalyst systems employing Rh- and Ir-doped metal oxide materials for water splitting under visible light irradiation†

Akihiko Kudo,^a ^{*ab} Shunya Yoshino,^a Taichi Tsuchiya,^a Yuhei Udagawa,^a Yukihiko Takahashi,^a Masaharu Yamaguchi,^a Ikue Ogasawara,^a Hiroe Matsumoto^a and Akihide Iwase ^{ab}

Received 27th November 2018, Accepted 24th January 2019

DOI: 10.1039/c8fd00209f

Various types of Z-scheme systems for water splitting under visible light irradiation were successfully developed by employing Rh- and Ir-doped metal oxide powdered materials with relatively narrow energy gaps (EG): BaTa₂O₆:Ir,La (EG: 1.9–2.0 eV), NaTaO₃:Ir,La (EG: 2.1–2.3 eV), SrTiO₃:Ir (EG: 1.6–1.8 eV), NaNbO₃:Rh,Ba (EG: 2.5 eV) and TiO₂:Rh,Sb (EG: 2.1 eV), with conventional SrTiO₃:Rh (an H₂-evolving photocatalyst) or BiVO₄ (an O₂-evolving photocatalyst), and suitable electron mediators. The Z-scheme systems were classified into three groups depending on the combination of H₂- and O₂-evolving photocatalysts and electron mediator. The Z-scheme systems combining BaTa₂O₆:Ir,La with BiVO₄, and NaTaO₃:Ir,La with BiVO₄ were active when a [Co(bpy)₃]^{3+/2+} redox couple was used rather than an Fe^{3+/2+} one. The combination of SrTiO₃:Ir with SrTiO₃:Rh gave an activity when the [Co(bpy)₃]^{3+/2+} and Fe^{3+/2+} redox couple ionic mediators were used. The Z-scheme systems combining NaNbO₃:Rh,Ba and TiO₂:Rh,Sb with SrTiO₃:Rh showed activities by using the [Co(bpy)₃]^{3+/2+} and Fe^{3+/2+} redox couples and also *via* interparticle electron transfer by just contact with/without reduced graphene oxide (RGO). These suitable combinations can be explained based on the impurity levels of doped Rh³⁺ and Ir³⁺ toward the redox potentials of the ionic mediators for the Z-scheme systems employing ionic mediators, and *p*-/*n*-type and onset potentials of the photocurrent in the photoelectrochemical properties of those photocatalyst materials for the Z-scheme systems working *via* interparticle electron transfer.

^aDepartment of Applied Chemistry, Faculty of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan. E-mail: a-kudo@rs.kagu.tus.ac.jp

^bPhotocatalysis International Research Center, Research Institute for Science and Technology, Tokyo University of Science, 2641, Yamazaki, Noda-shi, Chiba-ken 278-8510, Japan

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c8fd00209f



Introduction

Artificial photosynthesis has attracted attention from the view point of solar energy conversion to storable chemical energy. Because solar water splitting is one of the representative reactions, photocatalytic water splitting has extensively been studied.^{1–7} Powder-based metal oxide materials are attractive for photocatalytic water splitting because the cost will be low^{8–10} and stability will be high compared with other materials such as chalcogenides. Although the efficiency of powder-based photocatalyst systems is behind that of systems of photovoltaic + electrolysis at the present stage, there are some advantages to powder-based photocatalyst systems.

It is crucial to demonstrate a solar water splitting system employing powder-based oxide photocatalysts. The present stage of research of artificial synthesis is along this topic. A reactor system including a gas separation system of evolved hydrogen from oxygen has been studied in addition to the development of photocatalyst materials aimed towards the practical use of solar water splitting.¹⁰ The separation system can be achieved by the use of a suitable separation membrane. Moreover, the safety issue of the co-evolved H₂ and O₂ has also been examined *via* the use of a suitable gas transportation tube. However, even if an excellent reactor system with a gas separation membrane system is established, which photocatalyst is employed for it is still a key issue as high efficient photocatalysts for real solar water splitting into H₂ and O₂ without any sacrificial electron donors and acceptors have not yet been developed. It is essential to develop an efficient photocatalyst for demonstrating a solar water splitting system taking gas separation and safety issues into account.

High efficiency of a photocatalyst can be brought about by a high quantum yield and a response to light with a long wavelength. From this viewpoint, it is vital to develop photocatalysts that can utilize up to 600–700 nm of the solar spectrum. Although the use of noble metals might prevent the photocatalyst materials from practical use, the usage would be allowed if the amount is small and the materials can be recycled.

There are single particulate and Z-scheme systems in powder-based photocatalysts.^{2,11} Z-scheme photocatalyst systems have the advantage that photocatalysts active for either H₂ or O₂ evolution can be employed. This means that a Z-scheme system can be constructed with various combinations of H₂- and O₂-evolving photocatalysts.^{12–15} SrTiO₃:Rh (an H₂-evolving photocatalyst) and BiVO₄ (an O₂-evolving photocatalyst) are representative metal oxide materials for the Z-scheme system.^{1,2,16} It should be stressed that photocatalyst sheets prepared by a particle transfer method using SrTiO₃:Rh,La and BiVO₄:Mo powders demonstrate a quantum efficiency of 30% at 420 nm and a solar to hydrogen energy conversion efficiency of 1%.^{17–19} This result suggests that the Z-scheme system is a promising photocatalyst system for practical solar water splitting. H₂ evolution separated from O₂ evolution is possible in the Z-scheme system if a suitable reactor is designed.⁸ However, this photocatalyst sheet consisting of the SrTiO₃:Rh,La and BiVO₄:Mo powders responds up to 520 nm because the energy gap (EG) of SrTiO₃:Rh,La and the band gap (BG) of BiVO₄:Mo are 2.3 eV and 2.4 eV, respectively. So, it is a key issue to develop Z-scheme photocatalyst systems consisting of metal oxide photocatalysts with a response at longer wavelengths than 520 nm.



Transition metal doping is one strategy to make wide band gap photocatalysts responsive to visible light.^{1,2} Rh and Ir are effective dopants in this strategy. We have reported that SrTiO₃:Rh (EG: 2.3 eV),²⁰ SrTiO₃:Rh,Sb (EG: 2.2–2.4 eV),²¹ SrTiO₃:Ir (EG: 1.6–1.8 eV),^{20,22} BaTa₂O₆:Ir,La (EG: 1.9–2.0 eV)²³ and NaTaO₃:Ir,La (EG: 2.1–2.3 eV)²⁴ are active for sacrificial H₂ evolution in the presence of electron donors such as methanol, while SrTiO₃:Rh,Sb,²¹ SrTiO₃:Ir²⁰ and TiO₂:Rh,Sb (EG: 2.1 eV)²⁵ are active for sacrificial O₂ evolution in the presence of electron acceptors such as Ag⁺. In these photocatalyst materials, the visible light responses are due to electronic transition from the impurity levels formed by the dopants to the conduction bands of the host materials. These energy and band gaps are close to, or narrower than, those of SrTiO₃:Rh (EG: 2.3 eV)²⁰ and BiVO₄ (BG: 2.4 eV).^{26,27} So, it is attractive to utilize these Rh- and Ir-doped metal oxide photocatalysts for the construction of Z-scheme systems.

There are several types of Z-scheme system employing different electron mediators such as Fe^{3+/2+} and [Co(bpy)₃]^{3+/2+} redox couples,^{16,28,29} and reduced graphene oxide (RGO)^{30–32} as shown in Fig. 1(a) and (b). Moreover, some Z-scheme systems work even without electron mediators, as shown in Fig. 1(c).^{33,34} In this case, electron transfer proceeds through an interface contacted between the particles of the H₂- and O₂-evolving photocatalysts. So, it is important to examine the electron mediator in the Z-scheme system.

In the present paper, sacrificial H₂ and O₂ evolutions over Rh- and Ir-doped metal oxide photocatalysts under visible light irradiation were examined first to see the relationship between the photocatalytic properties and their band structures. Then, these H₂- and O₂-evolving photocatalysts were employed for various types of Z-scheme system for water splitting into H₂ and O₂ in stoichiometric amounts under visible light irradiation, without any sacrificial reagents. The photocatalytic performances for the sacrificial H₂ and O₂ evolutions and the Z-schematic water splitting were discussed based on the band structures and

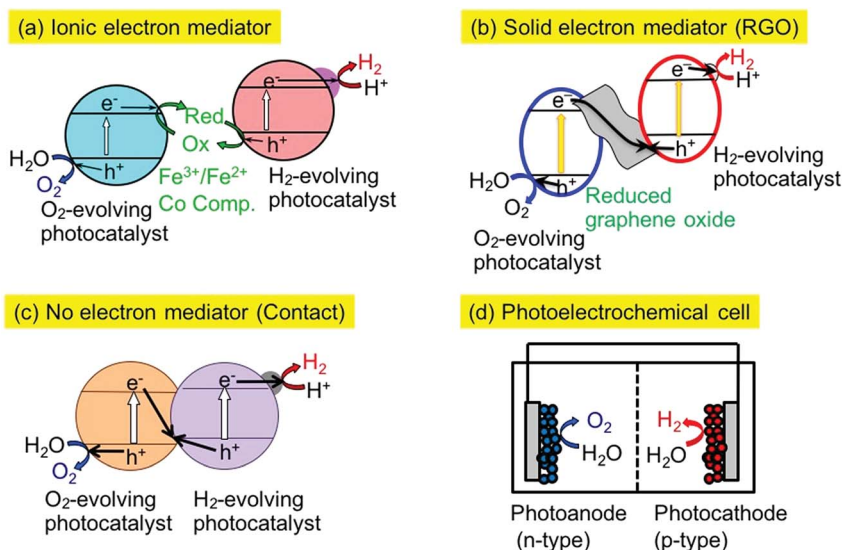


Fig. 1 Various types of powder material-based Z-scheme systems for water splitting.



photoelectrochemical properties of the photocatalyst materials such as p/n-types and the onset potentials of photocurrents.

Experimental

Preparation of Rh- or Ir-doped metal oxide photocatalysts

SrTiO₃:Rh(1%),²⁹ SrTiO₃:Ir(0.2%),²² TiO₂:Rh(x%),Sb(2x%) ($x = 0.5$ or 1.3),²⁵ NaTaO₃:Ir(1%),La(2%),²⁴ BaTa₂O₆:Ir(1%),La(2%)²³ and BiVO₄^{26,27} were prepared by a solid-state reaction, a borate-flux method, and a liquid–solid reaction according to previous reports. In addition to them, NaNbO₃:Rh(x%),Ba(y%) ($x, y = (1.2, 1.44)$ or $(1.0, 2.0)$) was newly prepared by a solid-state reaction. The starting materials, Na₂CO₃ (Kanto Chemical; 99.5 or 99.8%), Nb₂O₅ (Kanto Chemical; 99.99% or Kojundo Chemical; 99.99%), Rh₂O₃ (Wako Chemical; 98%), and BaCO₃ (Kanto Chemical; 99%), were mixed at a molar ratio of Na/Nb/Rh/Ba = 1.05–1.05y : 1 – x : x : y. An excess of sodium was added in the starting materials to compensate for volatilization. The starting materials mixture was calcined at 1173 K for 1 h, and then 1423–1473 K for 10 h once or twice. The excess sodium was washed out with water after the calcination. The obtained powders had nonspecific shapes with aggregations, judging from the SEM images (Jeol; JSM-6700F) (Fig. S1†). The obtained samples were identified using X-ray diffraction (Rigaku; MiniFlex, Cu K α). Diffuse reflectance spectra were obtained by a UV-vis-NIR spectrometer (JASCO, V-570) equipped with an integrator sphere and were converted to absorbance measurements *via* the Kubelka–Munk method.

Preparation of an RGO–metal oxide composite

An RGO-incorporated O₂-evolving photocatalyst was prepared by photocatalytic reduction of graphene oxide (GO) on the photocatalyst according to previous reports.^{30–32} GO prepared by the Hummers' method³⁵ and the O₂-evolving photocatalyst were dispersed in an aqueous methanol (Kanto Chemical; 99.8%) solution (50 vol%). The suspension was irradiated with visible light from a 300 W Xe lamp (PerkinElmer; CERMAX PE300BF) with a long pass filter (HOYA; L42) under a N₂ atmosphere with a pressure of 1 atm to obtain the RGO–photocatalyst composite. The methanol was carefully removed by washing with water. The RGO–photocatalyst composite was collected by filtration and was dried at room temperature in air.

Sacrificial H₂ and O₂ evolutions (half reactions of water splitting)

H₂ and O₂ evolutions from aqueous solutions containing the sacrificial reagents CH₃OH (Kanto Chemical; 99.8%) and AgNO₃ (Kojima Chemical; 99.9% or Toyo Chemical; 99.9%) that were half reactions of water splitting were examined using a top-irradiation reaction cell with a Pyrex window and a 300 W Xe lamp (PerkinElmer; CERMAX PE300BF). NaTaO₃:Ir,La, BaTa₂O₆:Ir,La, NaNbO₃:Rh,Ba, and TiO₂:Rh,Sb were used as prepared, whereas SrTiO₃:Ir without a cocatalyst was reduced under 1 atm of H₂ at 473 K for 2 h as a pretreatment for sacrificial O₂ evolution. The photocatalyst powders (0.1–0.3 g) were suspended in aqueous solutions (120–150 mL) and irradiated with visible light. For the H₂ evolution, Pt (0.3 wt%) cocatalyst, working as an H₂ evolution site, was loaded on photocatalysts by photodeposition from an aqueous methanol solution containing



H₂PtCl₆ (Tanaka Kikinzoku; 37.55% as Pt). The wavelength of the irradiation light was controlled to visible light using long-pass filters (HOYA; L42 and Y44). The amounts of evolved H₂ and O₂ were determined using an online gas chromatograph (Shimadzu; GC-8A, MS-5A column, TCD, Ar carrier).

Z-schematic water splitting

Z-schematic water splitting was conducted using a gas-closed system with a top-irradiation cell with a Pyrex window. H₂-evolving photocatalyst and O₂-evolving photocatalyst powders (0.05 or 0.1 g, respectively) were suspended in 120 mL of water. For the interparticle Z-scheme systems without an electron mediator and with an RGO solid-state electron mediator, water not containing any ionic mediators was used. For the Z-scheme system with ionic mediator, an aqueous solution containing [Co(bpy)₃]SO₄ or FeCl₃ as a mediator was used. The pH was adjusted with H₂SO₄ in each of the Z-scheme systems with and without electron mediator, if necessary. Ru (0.7 wt%) cocatalyst, functioning as an H₂ evolution site, was loaded on SrTiO₃:Rh (an H₂-evolving photocatalyst) by photodeposition from an aqueous methanol solution containing RuCl₃·*n*H₂O (Tanaka Kikinzoku; 36% as Ru in RuCl₃·*n*H₂O). Pt (0.3–1 wt%) was loaded on the NaTaO₃:Ir,La and BaTa₂O₆:Ir,La (H₂-evolving photocatalysts), and SrTiO₃:Ir (an O₂-evolving photocatalyst) by an impregnation method. The photocatalyst powders and an aqueous H₂PtCl₆ solution were placed in a porcelain crucible and dried on a hot plate. The H₂PtCl₆-impregnated NaTaO₃:Ir,La and BaTa₂O₆:Ir,La powders were calcined at 673 K for 2 h in air, whereas the SrTiO₃:Ir was not. The Pt-loaded NaTaO₃:Ir,La and Pt-loaded BaTa₂O₆:Ir,La were subsequently reduced at 673 K for 1 h under 1 atm of H₂ as a pretreatment, while Pt-loaded SrTiO₃:Ir was reduced at 573 K for 1 h. The light source and GC setup were the same as those for the sacrificial H₂ and O₂ evolutions.

Photoelectrochemical measurements

A squeegee method was used to prepare the SrTiO₃:Rh(1%) photoelectrode and a drop-casting method was used for the NaTaO₃:Ir(1%),La(2%) and BaTa₂O₆:Ir(1%),La(2%) with and without H₂-reduction; SrTiO₃:Ir(0.2%) with H₂-reduction; NaNbO₃:Rh(1%),Ba(2%) and TiO₂:Rh(0.5%),Sb(1%) without H₂-reduction, and BiVO₄ photoelectrodes using powdered photocatalyst materials. For the SrTiO₃:Rh(1%) photoelectrode, a paste consisting of 20 mg of SrTiO₃:Rh(1%) photocatalyst powder, 20 μL of acetylacetone (Kanto Chemical; 99.5%) and 40 μL of distilled water was coated on an indium tin oxide transparent electrode (ITO).³⁶ For the other photoelectrodes, the photocatalyst powders were dispersed in ethanol (1–2 mg mL⁻¹) by sonication. The suspensions were drop-cast onto a fluorine-doped tin oxide transparent electrode (FTO) to obtain 1–2 mg cm⁻² of photocatalyst on the FTO. The H₂-reduced SrTiO₃:Ir-loaded FTO substrate was not calcined, whereas the other photocatalyst-loaded ITO and FTO substrates were calcined at 573–673 K for 2 h in air. The photoelectrochemical properties were evaluated with a three-electrode system consisting of working, Ag/AgCl reference, and Pt counter electrodes with a potentiostat (Hokuto Denko; HZ-series or HSV-110) using a conventional H-type cell with a Nafion membrane. The electrolyte was 0.1 mol L⁻¹ K₂SO₄, 0.025 mol L⁻¹ KH₂PO₄ + 0.025 mol L⁻¹ Na₂HPO₄ pH buffer



was added, if necessary. A 300 W Xe lamp (PerkinElmer; CERMAX PE300BF) with a long-pass filter (HOYA; L42) was employed as a light source.

Results

Photocatalytic activities for sacrificial H₂ and O₂ evolutions over Rh- and Ir-doped metal oxide materials and their band structures

Sacrificial H₂ and O₂ evolutions of half reactions were carried out as test reactions of water splitting over Rh- and Ir-doped metal oxide photocatalysts using a sacrificial electron donor and acceptor to see the ability for photocatalytic H₂ or O₂ evolution, as shown in Table 1, prior to conducting water splitting.

The energy gaps were determined from the diffuse reflectance spectra and wavelength dependence of the photocatalytic activities as shown in Fig. 2 and 3. In general, trivalent and tetravalent Rh and Ir species are doped at the Ti⁴⁺, Nb⁵⁺ and Ta⁵⁺ sites in metal oxide materials.^{20–25,37,38} Among the species, Rh³⁺ and Ir³⁺ contribute to the visible light response for metal oxide photocatalysts.^{20,24,37,38} Sb⁵⁺ was codoped with Rh³⁺ at the Ti⁴⁺ and Nb⁵⁺ sites for charge compensation to enhance the formation of Rh³⁺ and Ir³⁺ and suppress the formation of Rh⁴⁺ and Ir⁴⁺ as efficient recombination centers between photogenerated electrons and holes, while Ba²⁺ and La³⁺ were replaced at the alkali and alkaline earth metal sites for the same purpose. SrTiO₃:Ir was reduced with H₂ at 473 K to form the dopant Ir³⁺.

In the case of the Ir-doped photocatalysts, SrTiO₃:Ir was active for both the sacrificial H₂ and O₂ evolutions,^{20,22} whereas BaTa₂O₆:Ir,La and NaTaO₃:Ir,La were active only for the sacrificial H₂ evolution.^{23,24} BaTa₂O₆:Ir,La and NaTaO₃:Ir,La were not active for sacrificial O₂ evolution even if they were reduced with H₂ at 673 K, as SrTiO₃:Ir was, to reduce the Ir⁴⁺ species. The Rh-doped photocatalysts

Table 1 Sacrificial H₂ and O₂ evolutions under visible light irradiation over Rh- or Ir-doped metal oxide photocatalysts^a

| Photocatalyst | Energy gap/eV | Incident light/nm | Activity/ μmol h ⁻¹ | | Ref. |
|--|---------------|-------------------|-----------------------------------|-----------------------------|-----------|
| | | | H ₂ ^b | O ₂ ^c | |
| Pt/NaTaO ₃ :Ir(1%),La(2%) | 2.1–2.3 | λ > 420 | 3.2 | — | 24 |
| NaTaO ₃ :Ir(1%),La(2%) | 2.1–2.3 | λ > 420 | — | 0 | 24 |
| Pt/BaTa ₂ O ₆ :Ir(1%),La(2%) | 1.9–2.0 | λ > 420 | 4.6 | — | 23 |
| BaTa ₂ O ₆ :Ir(1%),La(2%) | 1.9–2.0 | λ > 420 | — | 0 | 23 |
| Pt/SrTiO ₃ :Ir(0.2%) | 1.6–1.8 | λ > 440 | 8.6 | — | 20 |
| SrTiO ₃ :Ir(0.2%) ^d | 1.6–1.8 | λ > 420 | — | 4.3 | 20 |
| Pt/NaNbO ₃ :Rh(1%),Ba(2%) | 2.5 | λ > 420 | 0.2 | — | This work |
| NaNbO ₃ :Rh(1%),Ba(2%) | 2.5 | λ > 420 | — | 5.3 | This work |
| Pt/TiO ₂ :Rh(0.5%),Sb(1%) | 2.1 | λ > 440 | 0 | — | This work |
| TiO ₂ :Rh(0.5%),Sb(1%) | 2.1 | λ > 440 | — | 7.5 | 25 |

^a Photocatalyst: 0.1–0.3 g; light source: 300 W Xe lamp with long-pass filters (λ > 420 nm or λ > 440 nm); reaction cell: top-irradiation cell with a Pyrex window. ^b Cocatalyst: Pt (0.3 wt%, photodeposition); reactant solution: 10 vol% aqueous methanol solution. ^c Cocatalyst: none; reactant solution: 0.02–0.05 mol L⁻¹ aqueous AgNO₃ solution (120–150 mL).

^d Treatment: H₂-reduction at 473 K for 2 h.



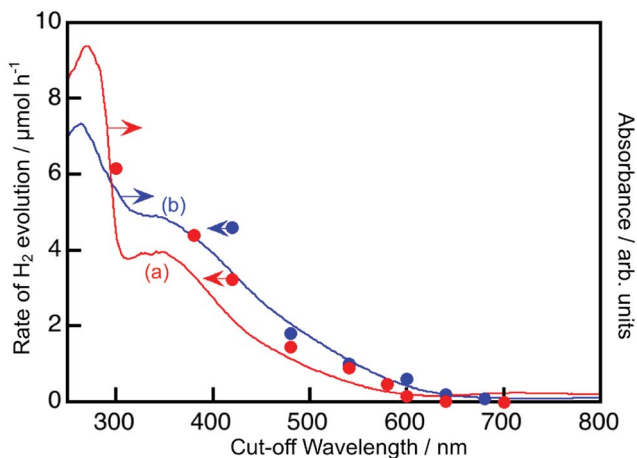


Fig. 2 The wavelength dependence of H₂ evolution from a 10 vol% aqueous methanol solution (closed circles) and diffuse reflectance spectra (solid line) of (a) NaTaO₃:Ir(1%),La(2%) and (b) BaTa₂O₆:Ir(1%),La(2%). Photocatalyst: 0.1 g, cocatalyst: Pt (photo-deposition) for H₂ evolution, reactant solution: 120 mL, light source: 300 W Xe lamp with long-pass filters, and reaction cell: top-irradiation cell with a Pyrex window. Samples of diffuse reflectance spectra were reduced at 473 K.

TiO₂:Rh,Sb²⁵ and NaNbO₃:Rh,Ba were active for sacrificial O₂ evolution using Ag⁺ as an electron acceptor. NaNbO₃:Rh,Ba showed very low activity for the sacrificial H₂ evolution. These properties will be discussed based on the band structure in the Discussion section. These results of the sacrificial H₂ and O₂ evolutions suggest that NaTaO₃:Ir,La and BaTa₂O₆:Ir,La can be used as H₂-evolving

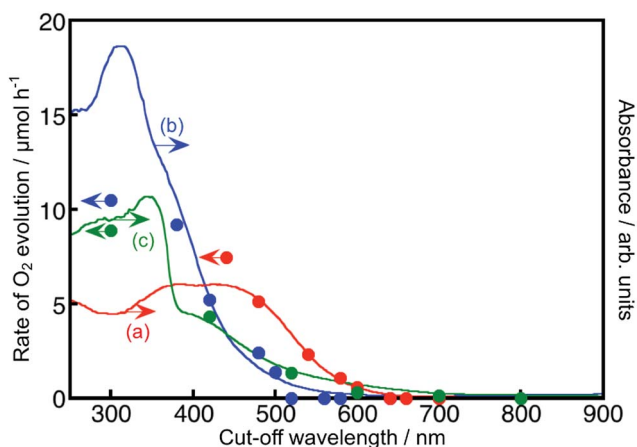


Fig. 3 The wavelength dependence of O₂ evolution from a 0.05 mol L⁻¹ aqueous silver nitrate solution (closed circles) and diffuse reflectance spectra (solid line) of (a) TiO₂:Rh(1.3%),Sb(2.6%), (b) NaNbO₃:Rh(1.2%),Ba(1.44%) and (c) SrTiO₃:Ir(0.2%) with H₂ reduction at 473 K. Photocatalyst: 0.1–0.3 g, reactant solution: 150 mL, light source: 300 W Xe lamp with long-pass filters, and reaction cell: top-irradiation cell with a Pyrex window.



photocatalysts for the construction of Z-scheme systems, while SrTiO₃:Ir, NaNbO₃:Rh,Ba and TiO₂:Rh,Sb are expected to be employed as O₂-evolving photocatalysts.

Fig. 2 and 3 show the diffuse reflectance spectra and wavelength dependence of the photocatalytic H₂ and O₂ evolutions of the Rh- and Ir-doped metal oxide photocatalysts in the presence of sacrificial reagents. The wavelengths were controlled with long-pass filters. It is vital to see the wavelength dependency of the photocatalytic activity because it is not guaranteed that photocatalysts with visible light absorption bands always give activities under visible light irradiation. The onsets of the wavelength dependence agreed with those of the diffuse reflection spectra. The onset wavelengths for the H₂ evolutions were 640 and 600 nm for BaTa₂O₆:Ir,La and NaTaO₃:Ir,La, respectively. These onset wavelengths were longer than the 540 nm of SrTiO₃:Rh (a conventional H₂-evolving photocatalyst). The onset wavelengths for O₂ evolution were 600, 500 and 700 nm for TiO₂:Rh,Sb, NaNbO₃:Rh,Ba and SrTiO₃:Ir, respectively. It is noteworthy that TiO₂:Rh,Sb and SrTiO₃:Ir responded at longer wavelengths than the BiVO₄ (BG: 2.4 eV) (a conventional O₂-evolving photocatalyst).

Fig. 4 shows the band structures of the Rh- and Ir-doped metal oxide photocatalysts. The impurity levels of Rh³⁺ and Ir³⁺ were estimated from the energy gaps determined by diffuse reflection spectra supposing that the valence band consisting of O 2p located at +3 V vs. NHE at a pH of 0.³⁹ The absorption bands in the visible light region shown in Fig. 2 and 3 are due to electronic transition from the impurity levels consisting of Rh³⁺ and Ir³⁺ to the conduction bands of the host materials. The impurity levels formed with electron-filled orbitals of Ir³⁺ were around 1.0–1.2 V for NaTaO₃ and BaTa₂O₆, while Ir³⁺ in SrTiO₃ formed an impurity level around 1.4–1.6 V that was deeper than those in the cases of the tantalates. The energy levels formed with electron-filled orbitals of Rh³⁺ located around 2.0–2.1 V that were similar to those of SrTiO₃:Rh and SrTiO₃:Rh,Sb.^{20,21} The reason Rh³⁺ forms a deeper impurity level than Ir³⁺ is due to Ir⁴⁺ being more stable than Rh⁴⁺ in metal oxides. Therefore, electronic transition from the Ir³⁺ impurity level to a conduction band is easier than that from Rh³⁺, resulting in the formation of the shallow impurity level by Ir³⁺.

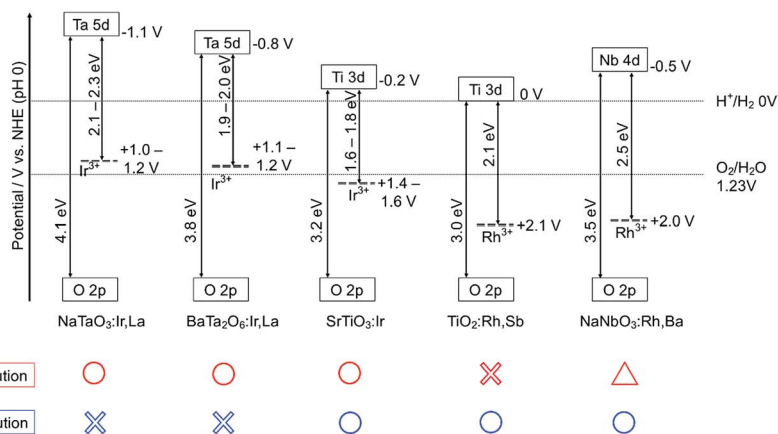


Fig. 4 The band structures of Rh- or Ir-doped metal oxide photocatalysts at pH 0.



Z-schematic systems for photocatalytic water splitting employing Rh- and Ir-doped metal oxide materials

The combination of SrTiO₃:Rh and BiVO₄ photocatalysts can be a benchmark of a Z-scheme photocatalyst system. The Z-schematic water splitting proceeds using Fe^{3+/2+} and [Co(bpy)₃]^{3+/2+} redox couples as ionic mediators (Fig. 1(a))^{16,28,29} and also *via* interparticle electron transfer between SrTiO₃:Rh and BiVO₄ particles with and without RGO (Fig. 1(b) and (c)).^{30,33,34} In general, water splitting *via* Z-schematic interparticle electron transfer by contact between the particles of the H₂- and O₂-evolving photocatalysts with and without RGO can be achieved (Fig. 1(b) and (c)) when the H₂- and O₂-evolving photocatalysts satisfy the following two requirements; (i) H₂- and O₂-evolving photocatalysts possess p- and n-type semiconductor properties, respectively, (ii) there is a certain electrode potential at which the cathodic photocurrent of the p-type semiconductor overlaps with the anodic photocurrent of the n-type semiconductor, being similar to water splitting using a photoelectrochemical cell working with no applied external bias as shown in Fig. 1(d).^{31,32} Moreover, H₂- and O₂-evolving photocatalysts must have contact with each other for interparticle electron transfer. In contrast to this, a Z-scheme system employing an ionic electron mediator could work regardless of the p- or n-type properties of the H₂- or O₂-evolving photocatalysts, if the photocatalysts have potentials for the reduction or oxidation of redox couple ionic mediators and the adsorption abilities for the redox couples. The SrTiO₃:Rh and BiVO₄ photocatalysts satisfy these factors resulting in all of the Z-scheme systems showing activities for water splitting into H₂ and O₂ in stoichiometric amounts without any sacrificial reagents (Fig. 1(a)–(d)).

Various types of Z-scheme photocatalyst systems employing Ir- and Rh-doped photocatalysts for water splitting into H₂ and O₂ under visible light irradiation are shown in Table 2. Here, the absolute evaluation of the performance of photocatalyst systems for water splitting is how much H₂ and O₂ is obtained under certain experimental conditions. In this sense, the activities of the different Z-scheme systems in Table 2 are comparable with each other, but not with those of Table 1, because of the almost identical experimental conditions for the water splitting, even if the kinetics would be different among the systems.

For the construction of Z-scheme systems, BiVO₄ (an O₂-evolving photocatalyst) was combined with BaTa₂O₆:Ir,La and NaTaO₃:Ir,La (H₂-evolving photocatalysts), while SrTiO₃:Rh (an H₂-evolving photocatalyst) was combined with TiO₂:Rh,Sb, NaNbO₃:Rh,Ba and SrTiO₃:Ir (O₂-evolving photocatalysts) as suggested by their H₂ and O₂ evolution abilities. In addition to the suspension system, the photoelectrochemical properties of photocatalyst powders immobilized on a conducting substrate as shown in Fig. 1(d) were examined using a Pt counter electrode without any sacrificial reagents to see the cathodic or anodic photocurrent and the onset potentials of semiconductor properties, not as a water splitting device, as shown in Fig. 5, in order to consider the potential overlap for Z-schematic water splitting *via* interparticle electron transfer with and without RGO. It has been reported that SrTiO₃:Rh^{36,40} and BiVO₄^{32,41–44} function as a photocathode and photoanode, respectively. NaTaO₃:Ir,La showed only an anodic photocurrent. Although BaTa₂O₆:Ir,La and SrTiO₃:Ir showed cathodic and anodic photocurrents, the photocurrents were poor and the onset potentials shifted with the sweeping direction of the CV curves. This result implies that



Table 2 Z-schematic water splitting under visible light irradiation using Rh- or Ir-doped metal oxide photocatalysts^a

| H ₂ photocat. | O ₂ photocat. | Mediator | Initial pH | Activity/ $\mu\text{mol h}^{-1}$ | | Ref. |
|---|--|---|------------|----------------------------------|----------------|-----------|
| | | | | H ₂ | O ₂ | |
| Pt/NaNbO ₃ :Ir(1%),La(2%) ^b | BiVO ₄ | None ^e | 4.2 | Trace | Trace | This work |
| Pt/NbTaO ₃ :Ir(1%),La(2%) ^b | BiVO ₄ | RGO ^e | 4.2 | Trace | Trace | This work |
| Pt/NbTaO ₃ :Ir(1%),La(2%) ^b | BiVO ₄ | Fe ^{3+/2+} ^f | 2.4 | Trace | Trace | This work |
| Pt/NbTaO ₃ :Ir(1%),La(2%) ^b | BiVO ₄ | [Co(bpy) ₃] ^{3+/2+} ^g | 4.2 | 0.8 | 0.3 | This work |
| Pt/BaTa ₂ O ₆ :Ir(1%),La(2%) ^b | BiVO ₄ | None ^e | 4.2 | 0.9 | 0.4 | This work |
| Pt/BaTa ₂ O ₆ :Ir(1%),La(2%) ^b | BiVO ₄ | RGO ^e | 4.2 | 0.9 | 0.4 | This work |
| Pt/BaTa ₂ O ₆ :Ir(1%),La(2%) ^b | BiVO ₄ | Fe ^{3+/2+} ^f | 2.4 | 0.1 | 0.4 | This work |
| Pt/BaTa ₂ O ₆ :Ir(1%),La(2%) ^b | BiVO ₄ | [Co(bpy) ₃] ^{3+/2+} ^g | 4.2 | 5.9 | 2.1 | 22 |
| Ru/SrTiO ₃ :Rh(1%) ^c | Pt/SrTiO ₃ :Ir(0.2%) ^d | None ^e | 3.5 | 0.4 | Trace | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | Pt/SrTiO ₃ :Ir(0.2%) ^d | RGO ^e | 3.5 | 0.8 | Trace | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | Pt/SrTiO ₃ :Ir(0.2%) ^d | Fe ^{3+/2+} ^f | 2.4 | 2.5 | 1.0 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | Pt/SrTiO ₃ :Ir(0.2%) ^d | [Co(bpy) ₃] ^{3+/2+} ^g | 7.8 | 5.1 | 2.4 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | NbNbO ₃ :Rh(1%),Ba(2%) | None ^e | 2.4 | 2.1 | 1.1 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | NbNbO ₃ :Rh(1%),Ba(2%) | Fe ^{3+/2+} ^f | 2.4 | 5.7 | 2.3 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | NbNbO ₃ :Rh(1%),Ba(2%) | [Co(bpy) ₃] ^{3+/2+} ^g | 3.8 | 4.1 | 1.7 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | TiO ₂ :Rh(0.5%),Sb(1%) | None ^e | 3.5 | 5.4 | 2.4 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | TiO ₂ :Rh(0.5%),Sb(1%) | Fe ^{3+/2+} ^f | 2.4 | 12 | 5.3 | This work |
| Ru/SrTiO ₃ :Rh(1%) ^c | TiO ₂ :Rh(0.5%),Sb(1%) | [Co(bpy) ₃] ^{3+/2+} ^g | 3.5 | 28 | 13 | This work |

^a Photocatalyst: 0.05 or 0.1 g each; light source: 300 W Xe lamp with a long-pass filter ($\lambda > 420$ nm); reaction cell: top-irradiation cell with a Pyrex window. ^b Cocatalyst: Pt (0.3 wt%), impregnation at 673 K for 2 h and subsequent H₂-reduction at 673 K for 1 h). ^c Cocatalyst: Ru (0.7 wt%, photodeposition). ^d Cocatalyst: Pt (1 wt%), impregnation without calcination and subsequent H₂-reduction at 573 K for 1 h). ^e Reactant solution: H₂SO₄ solution. ^f Reactant solution: 2 mmol L⁻¹ FeCl₃ solution. ^g Reactant solution: 0.02 mmol L⁻¹. ^h Reactant solution: 0.5 mmol L⁻¹ [Co(bpy)₃]SO₄ solution (120 mL).

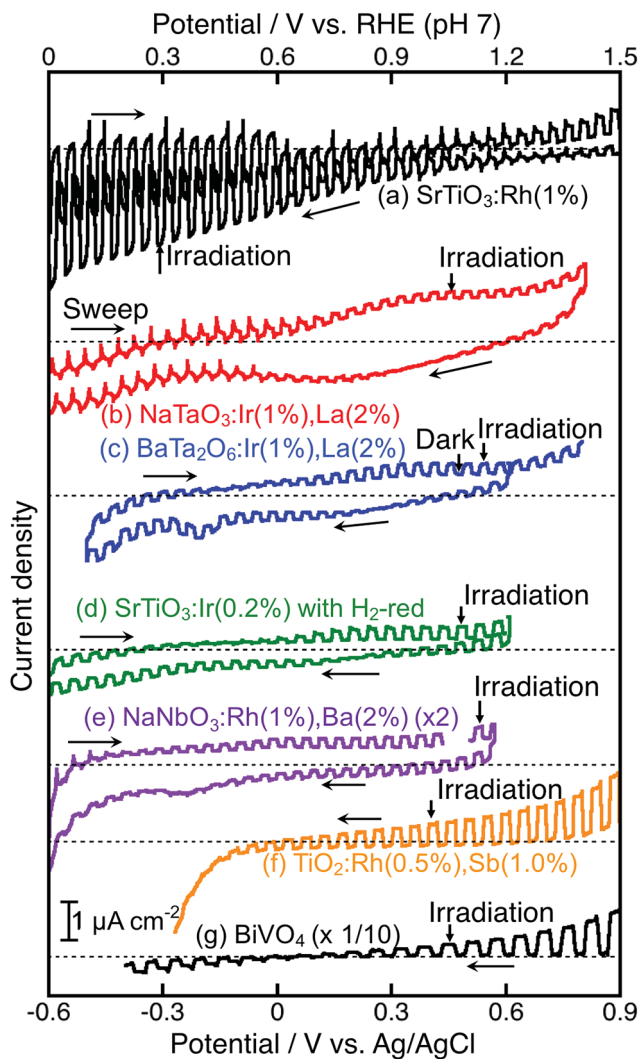


Fig. 5 Current vs. potential curves of (a) $\text{SrTiO}_3\text{:Rh}(1\%)$, (b) $\text{NaTaO}_3\text{:Ir}(1\%),\text{La}(2\%)$, (c) $\text{BaTa}_2\text{O}_6\text{:Ir}(1\%),\text{La}(2\%)$, (d) $\text{SrTiO}_3\text{:Ir}(0.2\%)$ with H_2 reduction, (e) $\text{NaNbO}_3\text{:Rh}(1\%),\text{Ba}(2\%)$ (x2), (f) $\text{TiO}_2\text{:Rh}(0.5\%),\text{Sb}(1.0\%)$, and (g) BiVO_4 (x 1/10). Electrolyte: $0.1 \text{ mol L}^{-1} \text{ K}_2\text{SO}_4$ aqueous solution (pH 7, phosphate buffer was added if necessary), light source: 300 W Xe lamp ($\lambda > 420 \text{ nm}$).

those photocurrents might not be due to H_2 and O_2 evolutions, but possibly due to redox reactions of the doped Ir species. In contrast, $\text{TiO}_2\text{:Rh,Sb}$,⁴⁵ and $\text{NaNbO}_3\text{:Rh,Ba}$ gave clear anodic photocurrents indicating an n-type semiconductor character. The onset potential of $\text{NaNbO}_3\text{:Rh,Ba}$ was more negative than that of $\text{TiO}_2\text{:Rh,Sb}$, whereas the anodic photocurrent of $\text{NaNbO}_3\text{:Rh,Ba}$ was much smaller than that of $\text{TiO}_2\text{:Rh,Sb}$. These anodic photocurrents overlapped with the cathodic photocurrent of $\text{SrTiO}_3\text{:Rh}$ at a certain electrode potential.

The Z-scheme systems were classified into three groups depending on the combination of H_2 - and O_2 -evolving photocatalysts and an electron mediator;



being active for only a $[\text{Co}(\text{bpy})_3]^{3+/2+}$ redox couple, active for $[\text{Co}(\text{bpy})_3]^{3+/2+}$ and $\text{Fe}^{3+/2+}$ redox couple ionic mediators, active not only for $[\text{Co}(\text{bpy})_3]^{3+/2+}$ and $\text{Fe}^{3+/2+}$ redox couples but also *via* interparticle electron transfer with and without RGO. $\text{NaTaO}_3:\text{Ir},\text{La} + \text{BiVO}_4$ and $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La} + \text{BiVO}_4$ were active when not $\text{Fe}^{3+/2+}$ but a $[\text{Co}(\text{bpy})_3]^{3+/2+}$ redox couple was used. Although the $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La} + \text{BiVO}_4$ showed activities *via* interparticle electron transfer at a pH of 4.2 with and without RGO, the activities were smaller than that with the ionic electron mediator $[\text{Co}(\text{bpy})_3]^{3+/2+}$. $\text{SrTiO}_3:\text{Rh} + \text{SrTiO}_3:\text{Ir}$ was active when the $[\text{Co}(\text{bpy})_3]^{3+/2+}$ and $\text{Fe}^{3+/2+}$ redox couple ionic mediators were used, whereas it was not active *via* interparticle electron transfer with and without RGO at pH 3.5. $\text{SrTiO}_3:\text{Rh} + \text{NaNbO}_3:\text{Rh},\text{Ba}$ and $\text{SrTiO}_3:\text{Rh} + \text{TiO}_2:\text{Rh},\text{Sb}$ were active for the $[\text{Co}(\text{bpy})_3]^{3+/2+}$ and $\text{Fe}^{3+/2+}$ redox couples and *via* interparticle electron transfer without RGO. These Z-scheme systems with RGO using $\text{NaNbO}_3:\text{Rh},\text{Ba}$ and $\text{TiO}_2:\text{Rh},\text{Sb}$ were not examined in detail, because the GOs were not suitably photoreduced on the $\text{NaNbO}_3:\text{Rh},\text{Ba}$ and $\text{TiO}_2:\text{Rh},\text{Sb}$ due to their poor reducing activities, as expected from their poor H_2 evolution activities as shown in Table 1. $\text{SrTiO}_3:\text{Rh} + \text{TiO}_2:\text{Rh},\text{Sb}$ showed the best performances among the Z-scheme systems in Table 2.

Discussion

H_2 and O_2 evolution abilities (shown in Table 1) can be considered based on the band structure, as shown in Fig. 4. Photogenerated holes in the Ir^{3+} levels in $\text{NaTaO}_3:\text{Ir},\text{La}$ and $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La}$ have no potentials for water oxidation. In contrast, the Ir^{3+} level of $\text{SrTiO}_3:\text{Ir}$ possesses the water oxidation potential, though the driving force is not so large. Conduction bands consisting of Ta 5d orbitals in $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La}$ and $\text{NaTaO}_3:\text{Ir},\text{La}$ possess thermodynamically enough potentials for water reduction to form H_2 . On the other hand, the photogenerated holes in the Rh^{3+} levels in $\text{NaNbO}_3:\text{Rh},\text{Ba}$ and $\text{TiO}_2:\text{Rh},\text{Sb}$ have enough potential for water oxidation to form O_2 . These energy levels were consistent with the H_2 and O_2 evolution abilities, as shown in Table 1. Of course, other kinetic factors of the active sites would exist for the H_2 and O_2 evolution abilities in addition to the energy levels of the thermodynamic factor.

Let us consider the reason why the Z-scheme systems shown in Table 2 are classified into three groups, based on the band structure and photoelectrochemical properties. Fig. 6 shows energy diagrams for the Z-schemes employing $\text{Fe}^{3+/2+}$ and $[\text{Co}(\text{bpy})_3]^{3+/2+}$ redox couples at pH 2.4 and 4.0, respectively. It is assumed that the band levels shift with -0.059 V pH^{-1} because those materials are metal oxides.

$\text{NaTaO}_3:\text{Ir},\text{La} + \text{BiVO}_4$ and $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La} + \text{BiVO}_4$ were active with a $[\text{Co}(\text{bpy})_3]^{3+/2+}$ redox couple at pH 4.2, but not with $\text{Fe}^{3+/2+}$ at pH 2.4. Photogenerated holes in the Ir^{3+} levels in $\text{NaTaO}_3:\text{Ir},\text{La}$ and $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La}$ (an H_2 -evolving photocatalyst) possess small driving forces for oxidation of Fe^{2+} (an electron mediator) at pH 2.4 as shown in Fig. 6(a), whereas they possess enough potential for oxidation of $[\text{Co}(\text{bpy})_3]^{2+}$ at pH 4.2 as shown in Fig. 6(b). The activities from the interparticle electron transfer were very small or negligible because of poor photoresponse and poor overlaps of the potentials giving cathodic photocurrents of $\text{NaTaO}_3:\text{Ir},\text{La}$ and $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La}$ and an anodic photocurrent of BiVO_4 as shown in Fig. 5, and also may be due to poor contact between $\text{NaTaO}_3:\text{Ir},\text{La}$ or $\text{BaTa}_2\text{O}_6:\text{Ir},\text{La}$ (an H_2 -evolving photocatalyst) and BiVO_4 (an O_2 -



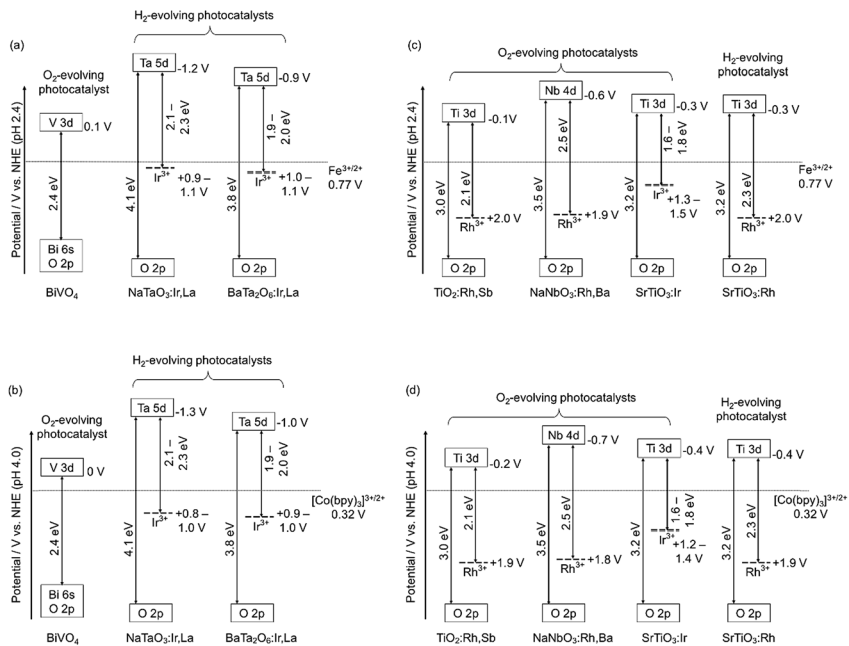


Fig. 6 The band structures of Rh- or Ir-doped metal oxide photocatalysts, and redox potentials of Fe and Co-complex ionic electron mediators at pH 2.4 and 4.0. (a) and (b) represent Z-scheme systems of Ir-doped metal oxides as H₂-evolving photocatalysts combined with BiVO₄. (c) and (d) represent Z-scheme systems of Rh-doped metal oxides and SrTiO₃:Ir as O₂-evolving photocatalysts combined with SrTiO₃:Rh.

evolving photocatalyst) in the suspension at pH 4.2. In contrast to them, SrTiO₃:Rh + SrTiO₃:Ir was active when the [Co(bpy)₃]^{3+/2+} and Fe^{3+/2+} redox couple ionic mediators were used, because the conduction band of SrTiO₃:Ir (an O₂-evolving photocatalyst) has enough potential for the reduction of Fe³⁺ and [Co(bpy)₃]³⁺ (Fig. 6(c) and (d)). However, because the anodic photocurrent of SrTiO₃:Ir hardly overlapped with the cathodic photocurrent of SrTiO₃:Rh, the activities by interparticle electron transfer with and without RGO were negligible. The conduction bands of TiO₂:Rh,Sb and NaNbO₃:Rh,Ba (O₂-evolving photocatalysts) also possessed enough potential for the reduction of Fe³⁺ and [Co(bpy)₃]³⁺ as well as SrTiO₃:Ir (Fig. 6(c) and (d)). Moreover, in these cases, the anodic photocurrents of the TiO₂:Rh,Sb and NaNbO₃:Rh,Ba photoelectrodes overlapped enough with the cathodic photocurrent of SrTiO₃:Rh. So, it is reasonable that SrTiO₃:Rh + NaNbO₃:Rh,Ba and SrTiO₃:Rh + TiO₂:Rh,Sb were active not only for the [Co(bpy)₃]^{3+/2+} and Fe^{3+/2+} redox couples but also *via* interparticle electron transfer with and without RGO. The activity of SrTiO₃:Rh + TiO₂:Rh,Sb was higher than that of SrTiO₃:Rh + NaNbO₃:Rh,Ba for all of the types of Z-scheme system. In the cases with the use of ionic electron mediators, it is probably due to the higher activity for O₂ evolution and the narrower energy gaps of TiO₂:Rh,Sb than those of NaNbO₃:Rh,Ba, as shown in Table 1. The reason why SrTiO₃:Rh + TiO₂:Rh,Sb showed a higher activity than SrTiO₃:Rh + NaNbO₃:Rh,Ba *via* interparticle electron transfer is that TiO₂:Rh,Sb gave much larger anodic photocurrents than NaNbO₃:Rh,Ba, as shown in Fig. 5.



Conclusions

We have successfully developed Z-scheme photocatalyst systems for water splitting under visible light irradiation employing Rh- and Ir-doped metal oxide photocatalysts with longer wavelength responses than conventional SrTiO₃:Rh and BiVO₄. The impurity levels of doped Ir³⁺ and Rh³⁺ that contributed to the visible light responses for the photocatalytic reactions were determined from diffuse reflectance spectra and supposing +3.0 V vs. NHE of a valence band of the oxide photocatalyst materials. The impurity levels of Ir³⁺ in NaTaO₃:Ir,La and BaTa₂O₆:Ir,La have sufficient potentials for the oxidation of the electron mediator [Co(bpy)₃]²⁺, but insufficient potentials for water oxidation to form O₂ and oxidation of the electron mediator Fe²⁺. The conduction bands of the NaTaO₃:Ir,La and BaTa₂O₆:Ir,La have enough potential for water reduction to form H₂. Therefore, the NaTaO₃:Ir,La and BaTa₂O₆:Ir,La could be used as H₂-evolving photocatalysts only when a [Co(bpy)₃]^{3+/2+} redox couple was used. The impurity levels of Ir³⁺ in SrTiO₃:Ir and Rh³⁺ in TiO₂:Rh,Sb and NaNbO₃:Rh,Ba have potentials for water oxidation and their conduction bands possess the potentials for reduction of the electron mediators Fe³⁺ and [Co(bpy)₃]³⁺. This property means that SrTiO₃:Ir, TiO₂:Rh,Sb and NaNbO₃:Rh,Ba could be employed as O₂-evolving photocatalysts for the construction of Z-scheme systems employing ionic electron mediators. Moreover, photoelectrochemical measurements using photocatalyst powders immobilized on conducting substrate revealed that the n-type characters and relatively negative onset potentials of the TiO₂:Rh,Sb and NaNbO₃:Rh,Ba photoanodes enabled the Z-scheme systems to work by interparticle electron transfer. Although the efficiencies of the present Z-scheme systems are low at the present stage, these will be improved by interfacial controls from a kinetic point of view in basic research. These results and discussion will contribute to the design of a highly active photocatalyst system for water splitting into H₂ and O₂, aiming for the demonstration of actual solar water splitting using a suitable reactor.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers 17H06440 and 17H06433 in Scientific Research on Innovative Areas "Innovations for Light-Energy Conversion (I⁴LEC)".

References

- 1 A. Kudo, H. Kato and I. Tsuji, *Chem. Lett.*, 2004, **33**, 1534.
- 2 A. Kudo and Y. Miseki, *Chem. Soc. Rev.*, 2009, **38**, 253.
- 3 F. E. Osterloh, *Chem. Mater.*, 2008, **20**, 35.
- 4 Y. Inoue, *Energy Environ. Sci.*, 2009, **2**, 364.
- 5 R. Abe, *J. Photochem. Photobiol., C*, 2010, **11**, 179.
- 6 T. Hisatomi, J. Kubota and K. Domen, *Chem. Soc. Rev.*, 2014, **43**, 7520.



- 7 K. Maeda and K. Domen, *Bull. Chem. Soc. Jpn.*, 2016, **89**, 627.
- 8 B. A. Pinaud, J. D. Benck, L. C. Seitz, A. J. Forman, Z. Chen, T. G. Deutsch, B. D. James, K. N. Baum, G. N. Baum, S. Ardo, H. Wang, E. Miller and T. F. Jaramillo, *Energy Environ. Sci.*, 2013, **6**, 1983.
- 9 D. M. Fabian, S. Hu, N. Singh, F. A. Houle, T. Hisatomi, K. Domen, F. E. Osterloh and S. Ardo, *Energy Environ. Sci.*, 2015, **8**, 2825.
- 10 T. Yamada and K. Domen, *Chem. Eng.*, 2018, **2**, 36.
- 11 A. Kudo, in "Photocatalysis", *Contemporary Catalysis; Science, Technology and Applications*, ed. P. Kamer, D. Vogt and J. Thybaut, Royal Society of Chemistry, Cambridge, 2017, ch. 3.7, pp. 326–343.
- 12 A. J. Bard, *J. Photochem.*, 1979, **10**, 59.
- 13 A. Kudo, *MRS Bull.*, 2011, **36**, 32.
- 14 K. Maeda, *ACS Catal.*, 2013, **3**, 1486.
- 15 Y. Wang, H. Suzuki, J. Xie, O. Tomita, D. J. Martin, M. Higashi, D. Kong, R. Abe and J. Tang, *Chem. Rev.*, 2018, **118**, 5201.
- 16 H. Kato, M. Hori, R. Konta, Y. Shimodaira and A. Kudo, *Chem. Lett.*, 2004, **33**, 1348.
- 17 Q. Wang, T. Hisatomi, Q. Jia, H. Tokudome, M. Zhong, C. Wang, Z. Pan, T. Takata, M. Nakabayashi, N. Shibata, Y. Li, I. D. Sharp, A. Kudo, T. Yamada and K. Domen, *Nat. Mater.*, 2016, **15**, 611.
- 18 Q. Wang, T. Hisatomi, Y. Suzuki, Z. Pan, J. Seo, M. Katayama, T. Minegishi, H. Nishiyama, T. Takata, K. Seki, A. Kudo, T. Yamada and K. Domen, *J. Am. Chem. Soc.*, 2017, **139**, 1675.
- 19 Q. Wang, T. Hisatomi, M. Katayama, T. Takata, T. Minegishi, A. Kudo, T. Yamada and K. Domen, *Faraday Discuss.*, 2017, **197**, 491.
- 20 R. Konta, T. Ishii, H. Kato and A. Kudo, *J. Phys. Chem. B*, 2004, **108**, 8992.
- 21 R. Niishiro, S. Tanaka and A. Kudo, *Appl. Catal., B*, 2014, **150**, 187.
- 22 S. Suzuki, H. Matsumoto, A. Iwase and A. Kudo, *Chem. Commun.*, 2018, **54**, 10606.
- 23 A. Iwase and A. Kudo, *Chem. Commun.*, 2017, **53**, 6156.
- 24 A. Iwase, K. Saito and A. Kudo, *Bull. Chem. Soc. Jpn.*, 2009, **82**, 514.
- 25 R. Niishiro, R. Konta, H. Kato, W. J. Chun, K. Asakura and A. Kudo, *J. Phys. Chem. C*, 2007, **111**, 17420.
- 26 A. Kudo, K. Omori and H. Kato, *J. Am. Chem. Soc.*, 1999, **121**, 11459.
- 27 A. Iwase, H. Kato and A. Kudo, *J. Sol. Energy Eng.*, 2010, **132**, 21106.
- 28 Y. Sasaki, A. Iwase, H. Kato and A. Kudo, *J. Catal.*, 2008, **259**, 133.
- 29 Y. Sasaki, H. Kato and A. Kudo, *J. Am. Chem. Soc.*, 2013, **135**, 5441.
- 30 A. Iwase, Y. H. Ng, Y. Ishiguro, A. Kudo and R. Amal, *J. Am. Chem. Soc.*, 2011, **133**, 11054.
- 31 K. Iwashina, A. Iwase, Y. H. Ng, R. Amal and A. Kudo, *J. Am. Chem. Soc.*, 2015, **137**, 604.
- 32 A. Iwase, S. Yoshino, T. Takayama, Y. H. Ng, R. Amal and A. Kudo, *J. Am. Chem. Soc.*, 2016, **138**, 10260.
- 33 Y. Sasaki, H. Nemoto, K. Saito and A. Kudo, *J. Phys. Chem. C*, 2009, **113**, 17536.
- 34 Q. Jia, A. Iwase and A. Kudo, *Chem. Sci.*, 2014, **5**, 1513.
- 35 W. S. Hummers and R. E. Offeman, *J. Am. Chem. Soc.*, 1958, **80**, 1339.
- 36 K. Iwashina and A. Kudo, *J. Am. Chem. Soc.*, 2011, **133**, 13272.
- 37 S. Kawasaki, K. Akagi, K. Nakatsuji, S. Yamamoto, I. Matsuda, Y. Harada, J. Yoshinobu, F. Komori, R. Takahashi, M. Lippmaa, C. Sakai, H. Niwa, M. Oshima, K. Iwashina and A. Kudo, *J. Phys. Chem. C*, 2012, **116**, 24445.



- 38 S. Kawasaki, R. Takahashi, K. Akagi, J. Yoshinobu, F. Komori, K. Horiba, H. Kumigashira, K. Iwashina, A. Kudo and M. Lippmaa, *J. Phys. Chem. C*, 2014, **118**, 20222.
- 39 D. E. Scaife, *Sol. Energy*, 1980, **25**, 41.
- 40 S. Kawasaki, K. Nakatsuji, J. Yoshinobu, F. Komori, R. Takahashi, M. Lippmaa, K. Mase and A. Kudo, *Appl. Phys. Lett.*, 2012, **101**, 033910.
- 41 K. Sayama, A. Nomura, Z. Zou, R. Abe, Y. Abe and H. Arakawa, *Chem. Commun.*, 2003, 2908.
- 42 K. Sayama, A. Nomura, T. Arai, T. Sugita, R. Abe, M. Yanagida, T. Oi, Y. Iwasaki, Y. Abe and H. Sugihara, *J. Phys. Chem. B*, 2006, **110**, 2908; F. F. Adbi, L. Han, A. H. M. Smets, M. Zeman, B. Dam and R. van de Krol, *Nat. Commun.*, 2013, **4**, 2195.
- 43 Y. Park, K. J. McDonald and K.-S. Choi, *Chem. Soc. Rev.*, 2013, **42**, 2321.
- 44 Q. Jia, K. Iwashina and A. Kudo, *Proc. Natl. Acad. Sci. U. S. A.*, 2012, **109**, 11564.
- 45 M. Yamaguchi, R. Niishiro, Q. Jia, Y. Kuang, K. Kitamura, A. Iwase, T. Minegishi, T. Yamada, K. Domen and A. Kudo, to be submitted.

