A heterojunction photocatalyst composed of zinc rhodium oxide, single crystal-derived bismuth vanadium oxide, and silver for overall pure-water splitting under visible light up to 740 nm.
Hiroshi Irie et al.
A heterojunction photocatalyst composed of zinc rhodium oxide, single crystal-derived bismuth vanadium oxide, and silver for overall pure-water splitting under visible light up to 740 nm
A heterojunction photocatalyst composed of zinc rhodium oxide, single crystal-derived bismuth vanadium oxide, and silver for overall pure-water splitting under visible light up to 740 nm†

Ryoya Kobayashi, a‡ Toshihiro Takashima, b Satoshi Tanigawa, a Shugo Takeuchi, c Bunsho Ohtani d and Hiroshi Irie* a

We recently reported the synthesis of a solid-state heterojunction photocatalyst consisting of zinc rhodium oxide (ZnRh2O4) and bismuth vanadium oxide (Bi4V2O11), which functioned as hydrogen (H2) and oxygen (O2) evolution photocatalysts, respectively, connected with silver (Ag). Polycrystalline Bi4V2O11 (p-Bi4V2O11) powders were utilized to form ZnRh2O4/Ag/p-Bi4V2O11, which was able to photocatalyze overall pure-water splitting under red-light irradiation with a wavelength of 700 nm (R. Kobayashi et al., J. Mater. Chem. A, 2016, 4, 3061). In the present study, we replaced p-Bi4V2O11 with a powder obtained by pulverizing single crystals of Bi4V2O11 (s-Bi4V2O11) to form ZnRh2O4/Ag/s-Bi4V2O11, and demonstrated that this heterojunction photocatalyst had enhanced water-splitting activity. In addition, ZnRh2O4/Ag/s-Bi4V2O11 was able to utilize nearly the entire range of visible light up to a wavelength of 740 nm. These properties were attributable to the higher O2 evolution activity of s-Bi4V2O11.

Introduction

Since the first report of photo-induced water splitting by titanium dioxide (TiO2) and platinum (Pt) electrodes, the potential to convert photon energy into hydrogen (H2) energy by photocatalytic water-splitting using photoelectrodes and powdered photocatalysts has been extensively investigated due to the simplicity of the process and the possibility for large-scale H2 production. Numerous studies have attempted to identify powdered photocatalysts that are able to split water into H2 and oxygen (O2) at a molar ratio of ~2:1 (overall water splitting), particularly under visible-light irradiation for the efficient utilization of sunlight energy. One of the major approaches for overall water splitting is the construction of “Z-scheme” systems, which are composed of two visible-light sensitive photocatalysts. These systems were first reported by Sayama and coworkers, who used Pt-deposited strontium titanate co-doped with chromium and tantalum (Pt/SrTiO3:Cr,Ta) as an H2 evolution photocatalyst (H2 photocatalyst) and Pt-deposited tungsten trioxide (Pt/WO3) as an O2 evolution photocatalyst (O2 photocatalyst). To date, numerous Z-scheme systems consisting of various H2 and O2 photocatalysts have been reported.

Despite the potential of Z-scheme systems for photocatalytic water splitting, most systems reported to date are only able to utilize visible light up to a wavelength of 520 nm. In addition, because conventional Z-scheme systems require a suitable redox mediator, such as iodate (IO3−) or iodide (I−) or ferric (Fe3+) or ferrous (Fe2+) ions, these systems are not capable of splitting “pure” water (i.e., distilled water without chemicals). Recently, solid-state Z-scheme systems that function in the absence of a redox mediator have been reported. However, because the pH of the system required adjustment to 3.5 using sulfuric acid (H2SO4), pure-water splitting was not accomplished.

Recently, we developed novel solid-state photocatalysts by inserting silver (Ag) as an electron mediator between zinc rhodium oxide (ZnRh2O4, Eox of 1.2 eV) as an H2 photocatalyst and defective silver antimonate (Ag1−xSbO1−y, Ey of 2.7 eV) or bismuth vanadium oxide (Bi3V2O11) as an O2 photocatalyst (ZnRh2O4/Ag/Ag1−xSbO1−y or ZnRh2O4/Ag/Bi3V2O11). Using these systems, overall pure-water splitting proceeded via the inserted Ag, which mediated the transfer of photoexcited electrons from the conduction band (CB) of the O2 photocatalyst to the valence band (VB) of the H2 photocatalyst. ZnRh2O4/Ag/Ag1−xSbO1−y and ZnRh2O4/Ag/Bi3V2O11 utilized visible light up to the valence band (VB) of the H2 photocatalyst.
to wavelengths of 545 and 700 nm, respectively, a property that was determined by the photoactivity of Ag$_{1-x}$SbO$_x$ and Bi$_4$V$_2$O$_11$. In the previous study, we utilized polycrystalline Bi$_4$V$_2$O$_11$ (p-Bi$_4$V$_2$O$_11$) powder, which was prepared by a normal solid-state reaction, for the synthesis of ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$.

In the present study, Bi$_4$V$_2$O$_11$ powder was obtained by pulverizing single crystals of Bi$_4$V$_2$O$_11$ (s-Bi$_4$V$_2$O$_11$) to form the powdered photocatalyst ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$, which displayed enhanced water-splitting activity compared to ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$. Notably, ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ was able to utilize visible light up to wavelengths of 740 nm, which represents nearly the entire visible light spectrum and to our knowledge, is the longest wavelength reported to date (ESI 1†).

**Experimental**

**Sample preparation**

A melting–slow cooling method was applied to grow single crystals of Bi$_4$V$_2$O$_11$ (s-Bi$_4$V$_2$O$_11$) by melting (940 °C) and slow cooling (4 °C h$^{-1}$ to 740 °C) of stoichiometric mixtures of commercial bismuth oxide (Bi$_2$O$_3$, purity 99.9%; Kanto Kagaku) and vanadium oxide (V$_2$O$_5$, purity 99.0%; Kanto Kagaku) powders. The obtained single crystals adopted a thin plate-like sheet structure and had a thickness of ~0.2 mm and transverse dimensions of ~1 mm × 2 mm. The thin sheets of Bi$_4$V$_2$O$_11$ were used directly for Laue photography and X-ray diffractometer analyses, and were further pulverized for use in all other experiments.

ZnRh$_2$O$_4$ powders were synthesized using a solid-state reaction method. Briefly, stoichiometric amounts of commercial zinc oxide (ZnO, purity 99.0%; Kanto Kagaku) and rhodium oxide (Rh$_2$O$_3$, purity 99.9%; Kanto Kagaku) powders were mixed and calcined at 1000 °C for 24 h and the obtained powders were thoroughly ground. As a reference, the Bi$_2$O$_3$ and V$_2$O$_5$ powders were mixed and calcined at 850 °C for 8 h to prepare poly-crystal powders of Bi$_4$V$_2$O$_11$ (p-Bi$_4$V$_2$O$_11$), which were thoroughly ground prior to experimental use.

A powdered heterojunction photocatalyst composed of ZnRh$_2$O$_4$, s-Bi$_4$V$_2$O$_11$, and Ag (ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$) was prepared using the following simple method. ZnRh$_2$O$_4$, Ag$_2$O, and s-Bi$_4$V$_2$O$_11$ powders were mixed at a molar ratio of 1 : 1 : 1.2 in an identical manner to that described above. The mixed powders were pressed into pellets by applying a force of 60 kN, and the pellets were then heated at 750 °C for 2 h. The pellets were ground into a fine powder, which was soaked in an aqueous solution (50 mL) of 3 M nitric acid (HNO$_3$, Kanto Kagaku) for 15 min. The powder was filtered and thoroughly washed with distilled water, and was then dried at 65 °C for 12 h. As a reference, ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$ was also prepared using the same procedure.

**Characterization**

A Laue camera (SA-HFM3, Rigaku) was used for the characterization of Bi$_4$V$_2$O$_11$ single crystals. The crystal structures of the single crystals and powder obtained by pulverizing single crystals were determined by X-ray diffraction (XRD) using a PW-1700 X-ray diffractometer (PANalytical). The structure of the ZnRh$_2$O$_4$/Ag/Bi$_4$V$_2$O$_11$ powder was also determined by XRD. The Brunauer–Emmett–Teller (BET) surface area was determined using a nitrogen adsorption apparatus (Micromeritics, TriStar 3000, Shimadzu). UV-visible absorption (UV-vis) spectra were obtained by the diffuse reflection method using a V-650 spectrometer (Jasco) with barium sulfate (BaSO$_4$) as the reflectance standard. Photoacoustic (PA) spectroscopy measurements were conducted in a nitrogen atmosphere under monochromic light generated from a 300 W xenon (Xe) lamp (LX300, Eagle) equipped with a monochromator (CT-101T, Jasco) and modulated by a light chopper at 80 Hz. The PA signal was amplified and monitored using a digital lock-in amplifier (LI5640, NF).

A scanning electron microscope (SEM, JSM-6500F, JEOL Ltd) was also utilized with element maps obtained by energy-dispersive X-ray spectrometry (EDS).

**O$_2$ evolution activity by the half reaction of water**

Action spectra for O$_2$ evolution were measured in 3 mL water containing either s-Bi$_4$V$_2$O$_11$ or p-Bi$_4$V$_2$O$_11$ powder (30 mg) and Ce$^{4+}$ (cerium sulfate (Ce(SO$_4$)$_2$), 0.1 mol L$^{-1}$; Kanto Kagaku) as a sacrificial agent. The pH of the solution was not adjusted prior to the spectral measurements, which were performed with constant stirring using a magnetic stirrer and under illumination with monochromatic light (570 ± 5 to 750 ± 5 nm) generated from a diffraction grating-type illuminator (CRM-FD, Jasco) equipped with a 300 W Xe lamp (C2578-02, Hamamatsu Photonics). Higher-order diffracted light was cut off using an appropriate glass filter. The amount of evolved O$_2$ was monitored using a gas chromatograph (GC-8A, Shimadzu). The wavelength dependence of the AQE was then evaluated. AQE values for O$_2$ evolution were calculated using the equation: AQE (%) = 100 × 4 × O$_2$ evolution rate/incident photon rate, because O$_2$ evolution is represented by the formula: 2H$_2$O + 4 h$^+$ → O$_2$ + 4H$^+$. 

**Water-splitting reactions**

To evaluate the photocatalytic activity, ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$, or ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$ composite powder (60 mg) was suspended in 12 mL pure water (pH unadjusted) under an argon atmosphere (50 kPa) and constant stirring using a magnetic stirrer. A Xe lamp (LA-251Xe, Hayashi Tokei) equipped with an optical filter (irradiated wavelength > 420 nm; Y-44, Hoya) and light-emitting diode (LED) lamps with wavelengths of 545 (LEDH60-545, Hamamatsu Photonics), 610 (LEDH60-600, Hamamatsu Photonics), 700 (LEDH60-700, Hamamatsu Photonics), and 740 nm (LEDH60-740, Hamamatsu Photonics) were used for light irradiation. The amount of evolved H$_2$ and O$_2$ was monitored using an online GC-8A gas chromatograph. AQE values were calculated using the amount of evolved O$_2$ in the same way as described above.

Photocatalytic overall water-splitting by ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ was also evaluated using pure water containing 33% isotopic water (H$_2$O, purity 97 atm% $^{18}$O; Sigma-Aldrich) under light irradiation emitted from the 740 nm LED. The evolved gas was detected using...
a gas chromatograph/mass spectrometer (GC/MS; GCMS-QP 2010 Ultra, Shimadzu), which was operated in the selective-ion mode and monitored ions with masses of 28 ($^{14}$N$^{14}$N), 32 ($^{16}$O$^{16}$O), 34 ($^{18}$O$^{16}$O), and 36 ($^{18}$O$^{18}$O). The measurement conditions, other than those used for pure water containing isotropic water, were the same as those used in the photocatalytic overall pure-water splitting tests.

**Results and discussion**

**Characterization**

A back-reflection Laue pattern taken from normal to the plate surface of a Bi$_4$V$_2$O$_{11}$ single crystal is shown in Fig. S1 (ESI 2†). The distribution of diffraction spots revealed that Bi$_4$V$_2$O$_{11}$ was a single crystal. XRD patterns for a single crystal of Bi$_4$V$_2$O$_{11}$ and the powders obtained by pulverizing the single crystals of Bi$_4$V$_2$O$_{11}$ were also determined (Fig. 1). For the single Bi$_4$V$_2$O$_{11}$ crystal in the direction normal to the plate surface, only (00l) peaks were detected, indicating that the plate face of the single crystal corresponded to the (001) plane. This assumption is reasonable because Bi$_4$V$_2$O$_{11}$ is an Aurivillius-type bismuth layer-structured oxide (BLSO) and consists of alternating (Bi$_2$O$_2$)$^{2+}$ layers and oxygen-deficient pseudo-perovskite blocks of (VO$_{3.5+0.5}$)$_2^+/C_0$ along the c-axis. Thus, because the growth rate of BLSO crystals in the c-axis direction is much lower than that along the a(b)-axis, single crystals of Bi$_4$V$_2$O$_{11}$ in the form of thin plate-like sheets with plate faces in the (001) plane were obtained. For the pulverized powder, all of the observed XRD peaks could be assigned to those for Bi$_4$V$_2$O$_{11}$. The BET surface areas of pulverized s-Bi$_4$V$_2$O$_{11}$ and as-prepared ZnRh$_2$O$_4$ powders were 0.179 and 3.60 m$^2$/g, respectively.

UV-vis absorption and PA spectra of s-Bi$_4$V$_2$O$_{11}$ are shown in Fig. 2. Although the UV-vis absorption intensity decreased with increasing wavelength, relatively strong intensity was observed in longer wavelength regions. In contrast, the PA absorption of s-Bi$_4$V$_2$O$_{11}$ decreased with increasing wavelength, a property that reflects true photoabsorption, which will be discussed later.

The XRD pattern of ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_{11}$ following HNO$_3$ treatment is shown in Fig. 3. The XRD peaks mainly correspond to two phases originating from ZnRh$_2$O$_4$ and Bi$_4$V$_2$O$_{11}$, although trace peaks attributable to a type of Ag oxide, such as AgVO$_3$, were also detected. However, Ag peaks were not observed. This result is plausible because most of the Ag was likely removed by the HNO$_3$ treatment and the amount of Ag remaining in the composite was below the limit of detection.

UV-vis absorption spectra of s-Bi$_4$V$_2$O$_{11}$, ZnRh$_2$O$_4$, and ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_{11}$ with and without HNO$_3$ treatment are shown in Fig. 4. As can be seen in the spectra, untreated ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_{11}$ showed greater absorption at wavelengths...
longer than ~600 nm compared to HNO₃-treated ZnRh₂O₄/Ag/ s-Bi₄V₂O₁₁. After the HNO₃ treatment, the absorption by ZnRh₂O₄/ Ag/s-Bi₄V₂O₁₁, at wavelengths longer than ~600 nm decreased and the spectral profile was in between those of ZnRh₂O₄ and s-Bi₄V₂O₁₁. Photos of pulverized s-Bi₄V₂O₁₁, as-prepared ZnRh₂O₄, and ZnRh₂O₄/Ag/p-Bi₄V₂O₁₁ after HNO₃ treatment are shown in Fig. S2 (ESI 4†).

In an SEM image of HNO₃-treated ZnRh₂O₄/Ag/s-Bi₄V₂O₁₁ powder, small ZnRh₂O₄ (~50–100 nm) and large Bi₄V₂O₁₁ particles (~10 μm) were clearly visible (Fig. 5a). Notably, the particle size of each photocatalytic material was identical to that before preparation of the heterojunction photocatalyst (Fig. 5b and c). STEM imaging and EDS-based elemental mapping of HNO₃-treated ZnRh₂O₄/Ag/Bi₄V₂O₁₁ were also performed (Fig. 6a–e). As was observed in the SEM image, the s-Bi₄V₂O₁₁ and ZnRh₂O₄ particles were clearly distinguishable (Fig. 6a and b) based on size differences. In addition, Ag was distributed (Fig. 6e) between the areas of Bi (Fig. 6c) and Rh (Fig. 6d), indicating that the Ag was inserted between the particles of ZnRh₂O₄ and Bi₄V₂O₁₁.

**Action spectra for O₂ evolution of Bi₄V₂O₁₁**

To examine and compare the activity of s-Bi₄V₂O₁₁ with that of p-Bi₄V₂O₁₁ as an O₂ evolution photocatalyst, the half reaction of water over s-Bi₄V₂O₁₁ and p-Bi₄V₂O₁₁ was evaluated using an aqueous Ce(SO₄)₂ solution containing Ce⁴⁺ as the sacrificial agent (Fig. 7). Aqueous Ce(SO₄)₂ is yellowish and transparent, and absorbs visible light up to a wavelength of ~550 nm. Thus, we irradiated s-Bi₄V₂O₁₁ and p-Bi₄V₂O₁₁ with light at wavelengths longer than 570 nm and found that both materials were able to produce O₂ under visible light up to 750 nm. This property indicates that the maximum Eg value of Bi₄V₂O₁₁ was 1.65 eV. The AQE values for s-Bi₄V₂O₁₁ were ~2–3-fold larger than those of p-Bi₄V₂O₁₁. As s-Bi₄V₂O₁₁ is considered to have higher crystallinity and anisotropy than p-Bi₄V₂O₁₁, photogenerated electrons and holes would therefore have enhanced mobility and separation (Fig. S3 in the ESI 4†).

It should be noted that the AQE values for O₂ evolution by s-Bi₄V₂O₁₁ were not consistent with the corresponding UV-vis absorption spectrum. A discrepancy between AQE values and absorption is frequently encountered, particularly for absorption in longer wavelength regions.32,33 In contrast, the AQE values for O₂ evolution coincided well with the PA absorption spectrum, which is generally accepted as corresponding to true absorption.30 Thus, it can be concluded that the O₂ evolution reaction proceeded via photoinduced band excitation (Fig. S3 in the ESI 4†). This excitation can be assigned to that originating from the VB, which contains O 2p and Bi 6s orbitals from the (Bi₂O₂)²⁺ layers, to the CB, which is composed of a mixture of Bi 6p orbitals and antibonding O 2p and V 3d orbitals of (VO₃.₅)²⁻ blocks.34 The obtained Eg value (1.65 eV) is smaller than the previously reported values of ~1.96–2.2 eV.34–37 Although the reason for this difference is unclear, it may be attributable to the greater amount of oxygen defects in our samples (larger than 0.5 in VO₃.₅/₂O₃). The oxygen defect states form an isolated band below the CB bottom, whose width increases with the concentration of the defects, reaches the CB bottom, and finally starts to overlap with the CB, similar to the case of TiO₂.38 In addition, it was reported that the band-gap of Bi₄V₂O₁₁ changes depending on the morphologies and preparation procedures.37

We previously reported that ZnRh₂O₄ can utilize visible light at wavelengths up to 770 nm and is also likely capable of utilizing infrared light for H₂ evolution.32 Thus, ZnRh₂O₄/Ag/ s-Bi₄V₂O₁₁ is expected to be sensitive to visible light up to at least 750 nm.

---

**Fig. 5** SEM images of ZnRh₂O₄/Ag/s-Bi₄V₂O₁₁ powder after HNO₃ treatment (a), as-prepared ZnRh₂O₄ (b) and pulverized s-Bi₄V₂O₁₁ (c) powders.

**Fig. 6** STEM images of ZnRh₂O₄/Ag/s-Bi₄V₂O₁₁ after HNO₃ treatment. STEM image (a), its enlargement (b), and EDS element maps (c–e), in which blue (c), red (d), and yellow (e) colors correspond to Bi, Rh, and Ag, respectively.

**Fig. 7** Action spectra for O₂ evolution by the half reaction of water over s-Bi₄V₂O₁₁ (solid circles) and p-Bi₄V₂O₁₁ (open circles) in the presence of Ce⁴⁺. The UV-visible absorption (red line) and PA (blue line) spectra of s-Bi₄V₂O₁₁ are also shown.
Overall water splitting

The time courses of \( \text{H}_2 \) and \( \text{O}_2 \) evolution from pure water by \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) powder under visible-light irradiation (\( > 420 \text{ nm} \)) are shown in Fig. S4 (ESI 5†). Under these conditions, the linear generation of \( \text{H}_2 \) and \( \text{O}_2 \) at a molar ratio of 2 to 1 was observed. We performed this experiment with newly prepared powders and observed similar \( \text{H}_2 \) and \( \text{O}_2 \) evolution rates, confirming the reproducibility of the data. In addition, we characterized the prepared \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) powder after the water-splitting reaction under the same conditions as used in Fig. S4 (ESI 5†) by XRD and STEM/EDS and found that the sample did not appear to have changed (Fig. S5 and S6 in the ESI 5†). We also confirmed that the water-splitting reaction did not occur in the dark (data not shown).

The time courses of \( \text{H}_2 \) and \( \text{O}_2 \) evolution resulting from water splitting by \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) and \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{p-Bi}_4\text{V}_2\text{O}_{11} \) under irradiation with monochromatic light with wavelengths of 545, 610, 700, and 740 nm were next measured (Fig. 8a–d). Under all conditions, \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) evolved \( \text{H}_2 \) and \( \text{O}_2 \) from water at a molar ratio of 2 to 1. The \( \text{H}_2 \) and \( \text{O}_2 \) evolution rates of \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) irradiated with 610 nm and 700 nm light were \( \sim \) two- and three-fold larger, respectively, than those of \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{p-Bi}_4\text{V}_2\text{O}_{11} \). In addition, the induction period for linear \( \text{H}_2 \) and \( \text{O}_2 \) evolution was shortened. Upon irradiation with 740 nm light, \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) evolved \( \text{H}_2 \) and \( \text{O}_2 \) at a ratio of 2 to 1 after the induction period, whereas \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{p-Bi}_4\text{V}_2\text{O}_{11} \) only produced a trace amount of \( \text{H}_2 \). Thus, overall water splitting induced by 740 nm light was only achieved with \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) and was attributable to the enhanced \( \text{O}_2 \)-evolution activity of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \). Although the reason for the delay in \( \text{H}_2 \) and \( \text{O}_2 \) evolution is unclear, this phenomenon has been observed with other materials.\(^{27}\) The delay might be due to existing defects,\(^{29}\) redox reactions other than water-splitting reactions,\(^{39-42}\) reconstruction of surface states,\(^{43}\) or adsorption of \( \text{H}_2 \) and \( \text{O}_2 \) molecules on the photocatalyst surface.\(^{43,44}\) However, the delay can be shortened by enhancing the activity.

As shown in Fig. 7, the AQE value of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \) for \( \text{O}_2 \) was \( \sim 0.2\% \) even at 750 nm and \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \) was expected to evolve \( \text{O}_2 \) under the entire range of visible light (\( \sim 770 \text{ nm} \)). Thus, further enhancement of \( \text{O}_2 \) evolution activity by \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \) would allow \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) to utilize the entire range of visible light and even near-infrared light, as the \( E_g \) value of \( \text{ZnRh}_2\text{O}_4 \) is 1.2 eV,\(^{33}\) for the overall water-splitting.

The mechanisms of \( \text{O}_2 \) evolution on BiVO(010) and (011) facets were previously proposed.\(^{45}\) On both surfaces, water molecules favorably adsorb on Bi sites. On the (010) surface, photogenerated holes induce the removal of two protons from the adsorbed water molecule in a stepwise manner, and the resulting O adatom obtains an electron by bonding with adjacent O anions to form a peroxy intermediate (Bi–O–O–V),\(^{46,47}\) Following the adsorption of a second water molecule at the same Bi site, a second O adatom is formed by the identical process and then obtains an electron from the nearby peroxy group, leading to the formation of a superoxo intermediate. A rapid rearrangement results in the formation of \( \text{O}_2 \), which is then desorbed from the surface. On the (010) surface, the V–O bond does not participate in the reaction, and a hydroperoxo intermediate (Bi–O–O–H) is formed after the adsorption of the second water molecule. Two protons are removed from the adsorbed water molecule in a stepwise manner, and \( \text{O}_2 \) is released from the surface. For both the (010) and (011) surfaces, it is likely that \( \text{O}_2 \) forms via peroxy species on BiVO, similar to the process that occurs on TiO\(_2\).\(^{46,47}\) In the case of \( \text{Bi}_4\text{V}_2\text{O}_{11} \), because the VB is composed of hybrid O 2p and Bi 6s orbitals of the (BiO)\(_2\) layers, the intermediate species would be the hydroperoxo group.

Fig. 9 shows the action spectrum for overall pure-water splitting by \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \). We calculated the total number of incident photons from each LED light source and the \( \text{O}_2 \)-evolution rates from the slopes of the plots in Fig. 8a–d and then estimated the AQE values (Table S1 in the ESI 6†). Because the \( \text{H}_2 \) and \( \text{O}_2 \) evolution rates were 2:1 for all wavelengths, the obtained AQE values for \( \text{O}_2 \) evolution were nearly identical to those for \( \text{H}_2 \) evolution. The shape of the action spectrum for overall water splitting by \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \) was more similar to that of the PA spectrum of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \) than that of the UV-vis absorption spectrum of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \). An identical phenomenon was observed for the action spectrum of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \) for \( \text{O}_2 \) evolution in aqueous Ce\(^{4+}\) solution (Fig. 7), indicating that the overall pure-water splitting reaction proceeded via the band-gap excitation of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \), as well as \( \text{ZnRh}_2\text{O}_4 \), which has an \( E_g \) value of 1.2 eV, and can therefore absorb longer wavelength light than \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \). For this reason, the AQE values reflected the active photoabsorption capacity of \( \text{s-Bi}_4\text{V}_2\text{O}_{11} \).

To confirm the liberation of \( \text{O}_2 \) from water by \( \text{ZnRh}_2\text{O}_4/\text{Ag}/\text{s-Bi}_4\text{V}_2\text{O}_{11} \), water splitting with water containing 33% \( \text{H}_2\text{O} \)
under irradiation with 740 nm light (740 nm LED, the same intensity in Fig. 8d) was next examined (Fig. 10). The amount of $^{16}\text{O}^{16}\text{O}$ (calc. $^{16}\text{O}^{16}\text{O}$) was obtained using the equation calc. $^{16}\text{O}^{16}\text{O} = \text{obs.}^{16}\text{O}^{16}\text{O} - (\text{obs.}^{14}\text{N}^{14}\text{N}/0.78) \times 0.21$, because the detected $^{14}\text{N}^{14}\text{N}$ (N$_2$) originated from external air that entered the GC/MS system rather than from air dissolved in water, as was demonstrated in our previous report. 26, 27 Under irradiation with 740 nm light for 120 h, $^{18}\text{O}^{18}\text{O}$, $^{16}\text{O}^{18}\text{O}$, and $^{18}\text{O}^{18}\text{O}$ were detected at a ratio of 4.00:3.97:1.03, which was close to the theoretical ratio of 4:4:1 for overall water-splitting. In addition, the time course of total $\text{O}_2$ evolution ($^{16}\text{O}^{16}\text{O} + ^{16}\text{O}^{18}\text{O} + ^{18}\text{O}^{18}\text{O}$) using water containing 33% H$_2^{18}\text{O}$ was consistent with that using normal H$_2^{16}\text{O}$ (solid circles with a solid line in Fig. 10, the same data as in Fig. 8d with the same symbol). Therefore, it was confirmed that O$_2$ was evolved from water by ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ under irradiation with 740 nm light. Based on these results, we confidently concluded that ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ was capable of overall pure-water splitting under visible-light irradiation with a wavelength of 740 nm (Scheme S1 in the ESI 7). In a previous study, 27 we attempted to scale up the overall pure-water splitting reaction by increasing the amounts of ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$ and pure water by a factor of 10 (600 mg of photocatalyst was suspended in 120 mL pure water). Using this approach, the amounts of evolved H$_2$ and O$_2$ increased ~40 fold, although the amounts of photocatalyst and water were increased only tenfold. Further improvements in the yields of H$_2$ and O$_2$ evolution may be possible by optimization of the ratio of the photocatalyst and water, modifying the shape and/or volume of the reaction vessel, how the light is irradiated, and other chemical engineering-based modifications.

Conclusions

We prepared the solid-state heterojunction photocatalyst ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ and demonstrated that this material simultaneously evolves H$_2$ and O$_2$ from pure water at a molar ratio of ~2 to 1 under irradiation with nearly the entire range of visible light at wavelengths of up to 740 nm. Through the use of s-Bi$_4$V$_2$O$_11$ in place of p-Bi$_4$V$_2$O$_11$, the AQE for overall water splitting was increased and the sensitivity of the system was increased to wavelengths up to 740 nm. ZnRh$_2$O$_4$ was used as the H$_2$ photocatalyst in the present system because it has an $E_g$ value of 1.2 eV and is therefore capable of effectively utilizing both visible and infrared light. Despite this desirable property, ZnRh$_2$O$_4$ is not suitable for large-scale systems because it contains Rh, which is a rare chemical element. Moreover, in this system, HNO$_3$ treatment is required for removing the excess Ag to achieve overall pure-water splitting, because Ag acts as a sacrificial agent for O$_2$ evolution. Such treatment might damage ZnRh$_2$O$_4$ and Bi$_4$V$_2$O$_11$, leading to decreased photocatalytic activity. To avoid such damage and potentially further improve the activity, we replaced Ag with gold (Au), because Au is stable and does not act as a sacrificial agent, and confirmed that an Au-inserted ZnRh$_2$O$_4$ and Bi$_4$V$_2$O$_11$ system is capable of overall pure-water splitting. Detailed studies of ZnRh$_2$O$_4$/Au/s-Bi$_4$V$_2$O$_11$ are currently underway in our laboratory.

Acknowledgements

This study was partially supported by the Cooperative Research Program of Institute for Catalysis, Hokkaido University (Grant #15A1002). We express gratitude to Prof. Dr Tanaka and Ms Maruyama for their support with the back-reflection Laue pattern measurements. We also thank Mr G. Newton for the careful reading of the manuscript.

Notes and references


Fig. 9 Action spectra for $\text{O}_2$ evolution from pure water by ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ (solid circles) and ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$ (open circles) under irradiation with LED light sources. Note that the AQE values for H$_2$ evolution were almost identical to those for $\text{O}_2$ evolution, as H$_2$ and O$_2$ evolution at a ratio of 2:1 was observed. The UV-visible absorption (red line) and PA (blue line) spectra of s-Bi$_4$V$_2$O$_11$ are also shown. The AQE values of ZnRh$_2$O$_4$/Ag/p-Bi$_4$V$_2$O$_11$ irradiated with 610 nm and 700 nm LED are cited from ref. 27.

Fig. 10 GC/MS spectrometry results for the splitting of water containing 33% H$_2^{18}$O by ZnRh$_2$O$_4$/Ag/s-Bi$_4$V$_2$O$_11$ irradiated with 740 nm LED light.