Plasmon-induced electron injection into the large negative potential conduction band of Ga$_2$O$_3$ for coupling with water oxidation†

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In this study, an interfacial modification layer was applied to improve the plasmon-induced light energy conversion of a gallium(III) oxide (Ga$_2$O$_3$) photoelectrode, which possesses a much more negative conduction band potential compared with the reduction potential of photons to hydrogen. The plasmon-induced photocurrent generation under visible light irradiation was observed with Au nanoparticle-loaded Ga$_2$O$_3$ (Au-NPs/Ga$_2$O$_3$). An interfacial modification was carried out by depositing a titanium dioxide (TiO$_2$) thin-film layer on Au-NPs/Ga$_2$O$_3$ via atomic layer deposition. Since the surface states of TiO$_2$ possess excellent hole-trapping ability, this interfacial modification remarkably improved the generation of plasmon-induced photocurrent in the visible region. The photoelectric conversion efficiency of interfacially modified Au-NPs/Ga$_2$O$_3$ showed a TiO$_2$ thin-film thickness dependence because the migration of hot carriers was suppressed with increasing TiO$_2$ thickness. The Au-NPs/Ga$_2$O$_3$ photoelectrode modified with 2 nm-thick TiO$_2$ showed the best photoelectric conversion performance, and the thermodynamic efficiency under irradiation with 600 nm light was approximately two times larger than that of the Au-NPs/TiO$_2$-thin film due to the extremely negative onset potential of Au-NPs/Ga$_2$O$_3$ with TiO$_2$. Therefore, the plasmonic Ga$_2$O$_3$ photoanode with the interfacial TiO$_2$ modification could provide both a high reduction ability for H$_2$ evolution and an oxidation ability for water oxidation, because of the negative conduction band of Ga$_2$O$_3$ and the hole-trapping property from TiO$_2$, respectively.

Introduction

Solar water splitting to produce H$_2$ is a main topic in artificial photosynthesis. To achieve efficient overall water splitting, one indispensable condition is that the bottom of the conduction band (CB) of the semiconductor should be more negative than the reduction potential of H$^+$/H$_2$ (0 V vs. RHE). Therefore, gallium(III) oxide (Ga$_2$O$_3$), which possesses a negative CB (~1.0 to ~1.5 V vs. RHE), is a promising photocatalyst for overall water splitting. The large CB potential of Ga$_2$O$_3$ can also be applied to the reduction of carbon dioxide to CO or HCOOH. However, it is only able to utilize the ultraviolet light of solar radiation due to its wide band gap (~4.9 eV). Band engineering is a standard method for extending the absorption edge of a material. Kudo et al. reported that doping In$_2$O$_3$ into β-Ga$_2$O$_3$ to form a solid solution could efficiently shift the absorption edge towards longer wavelengths, thus maintaining H$_2$ and O$_2$ evolution. Although the absorption edge can be shifted to longer wavelengths by the doping method, the visible light energy is still insufficiently utilized. Moreover, doping causes a positive shift in the CB, thereby decreasing the reduction potential of Ga$_2$O$_3$. Although other methods, such as the addition of cocatalysts and promotors, have also been applied to increase the catalytic performance of Ga$_2$O$_3$, the results are not ideal for the use of visible light.

Recently, localized surface plasmon resonance (LSPR) of noble metal nanoparticles (Au, Ag) has been increasingly studied because it can efficiently increase visible-light absorption and significantly enhance the electromagnetic near-field. Under LSPR excitation, hot carriers are generated in the metal nanoparticles. When settling metal nanoparticles on a semiconductor, a Schottky barrier forms at the interface, and hot carriers with energy higher than the Schottky barrier can transfer to the CB of the semiconductor, thus achieving...
charge separation at the interface.\textsuperscript{17,18} The electrons transferred to the CB of the semiconductor take part in the reduction reactions, such as H\textsubscript{2} evolution, while the holes will be captured at the surface states of the semiconductor and participate in the oxidation reactions.\textsuperscript{19} Importantly, it is expected that this plasmon-induced electron transfer mechanism will not cause a positive shift in the CB of gallium oxide and that visible light will be used effectively while maintaining a high reduction ability.

In plasmon-induced artificial photosynthesis systems using n-type semiconductors, the reducing ability can be improved by changing the type of semiconductor; however, the important point is that it is necessary to efficiently induce water oxidation as the rate-determining step. First, to stably oxidize water for a long time, it is necessary to use an oxide semiconductor in which the photoanode itself is not further oxidized. Second, the surface condition of the photoanode that can efficiently capture holes is required. Recently, we successfully demonstrated that plasmon-induced water oxidation is highly sensitive to the surface states of the crystal facets of SrTiO\textsubscript{3}, and Au nanoparticle-loaded SrTiO\textsubscript{3} that is terminated with a TiO\textsubscript{2} layer shows a high oxidation ability.\textsuperscript{20} In addition, Murakoshi et al. also reported that TiO\textsubscript{2} was beneficial for water oxidation by studying the intermediate species during plasmon-induced oxygen evolution.\textsuperscript{21} Therefore, improving the hole-trapping ability at the interface by the surface states of TiO\textsubscript{2} is an efficient way to enhance the water oxidation efficiency.

In this study, plasmonic Au-NPs were decorated on the surface of single-crystal Ga\textsubscript{2}O\textsubscript{3} (Au-NPs/Ga\textsubscript{2}O\textsubscript{3}) to utilize visible light without shifting its negative CB energy level, which is beneficial for reduction reactions, such as H\textsubscript{2} evolution. To improve the water oxidation reaction of the Au-NPs/Ga\textsubscript{2}O\textsubscript{3} photoelectrode, we also proposed an interfacial modification using a thin TiO\textsubscript{2} layer with a nanometre-scale thickness that was deposited on Au-NPs/Ga\textsubscript{2}O\textsubscript{3} by the atomic layer deposition (ALD) technique. Photocatalytic reactivities were evaluated by monitoring the photocurrent of the photoelectrochemical (PEC) reaction. Based on the excellent hole-trapping ability of the as-prepared material, the plasmon-induced holes are efficiently trapped in the surface states at the interfacial boundary between the Au-NPs and TiO\textsubscript{2} layer, which improves the water oxidation reactivity of the Au-NPs/Ga\textsubscript{2}O\textsubscript{3} photocathode.

### Results and discussion

To optimize the conditions for the plasmonic PEC reaction enhancement of Au-NP-loaded Ga\textsubscript{2}O\textsubscript{3}, we first investigated the particle size effect of Au-NPs loaded on Ga\textsubscript{2}O\textsubscript{3} because the LSPR properties of Au-NPs were very sensitive to their size.\textsuperscript{22,23} Au-NPs with mean sizes ranging from 10 to 50 nm were fabricated on Ga\textsubscript{2}O\textsubscript{3} by annealing Au films with various thicknesses, as depicted in Fig. S1†. Fig. 1a shows the extinction spectra of Au-NPs with different sizes loaded on Ga\textsubscript{2}O\textsubscript{3}. The LSPR peaks showed an obvious red-shift and a broadening of the full width at half maximum (FWHM) as the particle size increased. To evaluate the photocurrent conversion efficiency, we carried out incident photon-to-current efficiency (IPCE) measurements on all Au-NP/Ga\textsubscript{2}O\textsubscript{3} photoelectrodes, as shown in Fig. 1b. Clear peaks were observed at approximately 580 nm in the IPCE action spectra of all Au-NPs/Ga\textsubscript{2}O\textsubscript{3} photoelectrodes, and no detectable photo-response was obtained on the Ga\textsubscript{2}O\textsubscript{3} photoelectrode without Au-NPs (see purple plot in Fig. 1b) in the visible wavelength region. In the case of Au-NP/Ga\textsubscript{2}O\textsubscript{3} photoelectrodes loaded with small particles (≤15 nm), the IPCE band closely corresponded with the extinction spectrum of Au-NPs, indicating that the photocurrent was generated by the LSPR of Au-NPs.\textsuperscript{13} The 15 nm Au-NP-loaded Ga\textsubscript{2}O\textsubscript{3} sample showed the best PEC performance with a peak IPCE value of 0.11% at 580 nm, as shown by the red curve in Fig. 1b. For the 10 nm Au-NP-loaded Ga\textsubscript{2}O\textsubscript{3} sample, its low extinction value caused a lower IPCE than the 15 nm Au-NPs. In contrast, when the particle size became larger than 15 nm, the IPCEs decreased. A possible explanation for the observed decrease in IPCE was the LSPR decay mechanism. For large particles, instead of nonradiative decay, radiative decay becomes the main pathway for LSPR decay, which is unfavourable for electron–hole generation.\textsuperscript{24,25} The near-field enhancement spectra obtained by FDTD calculations (Fig. S2†) show a clear tendency that the large Au-NPs loaded on the Ga\textsubscript{2}O\textsubscript{3} sample exhibited broadening of the LSPR peak, which was consistent with the extinction spectra. This broadening indicated a short dephasing time of LSPR due to significant radiation damping. Consequently, Au-NPs/Ga\textsubscript{2}O\textsubscript{3} with a particle size of 15 nm was the optimized photoelectrode for PEC photocurrent generation at visible wavelengths, and it was used in the following investigation.

To further improve the water oxidation ability of Au-NPs/Ga\textsubscript{2}O\textsubscript{3}, an interfacial modification was conducted by the introduction of a thin TiO\textsubscript{2} layer, which has a high hole-trapping ability. Because the CB alignment of TiO\textsubscript{2} is much more positive than that of Ga\textsubscript{2}O\textsubscript{3}, electrons cannot efficiently transfer from the CB of TiO\textsubscript{2} to that of Ga\textsubscript{2}O\textsubscript{3}.\textsuperscript{3} Therefore, a thin TiO\textsubscript{2} layer was deposited on Au-NPs/Ga\textsubscript{2}O\textsubscript{3} as the final layer, as shown in Fig. S3† to maintain direct contact between the Au-NPs and Ga\textsubscript{2}O\textsubscript{3} and to provide effective charge separation. Moreover, Au-NPs were partially inlaid in the TiO\textsubscript{2} layer (inset in Fig. 2b) without destroying the direct contact between the Au-NPs and Ga\textsubscript{2}O\textsubscript{3} by the reported ALD procedure of TiO\textsubscript{2}.\textsuperscript{19}

![Fig. 1](image-url)
Light absorption and carrier separation are two main factors contributing to photocurrent generation. To directly study the relationship between light absorption and PEC properties, the absorption spectrum of Au-NPs was calculated as the difference between the \((1 - T - R)\) spectrum of substrate with Au-NPs and without Au-NPs in Fig. 2a, where \(T\) and \(R\) are the transmission and reflection, respectively. Since the particle size and distribution of Au-NPs were similar, the red-shift of the peak position of the LSPR band from 585 to 645 nm was mainly caused by the refractive index increase in the surrounding media after TiO\(_2\) deposition.\(^{25}\) In addition, the absorption value at the LSPR peak also increased as the thickness of the TiO\(_2\) layer increased. In contrast, the absorption at wavelengths shorter than 550 nm maintained almost the same value, which was only determined by the interband transition of Au.\(^{19}\) The PEC performance of these modified samples is presented in Fig. 2b, and all the TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) photoelectrodes show an IPCE increase in the visible region compared with that of the Au-NPs/Ga\(_2\)O\(_3\) photoelectrode. Notably, 2-nm-TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) showed the maximum IPCE value, which reached 0.17% at approximately 600 nm. Moreover, the stable photocurrent under 600 nm irradiation was approximately 1.5 times larger than that of Au-NPs/Ga\(_2\)O\(_3\), as shown in Fig. S8.\(^{†}\) The photocurrent of 2-nm-TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) also showed a good stability because the photocurrent after 7.5 hours irradiation maintained 90% of the initial value of quasi-steady photocurrent, as shown in Fig. S9.\(^{†}\) This result indicated that the interfacial modification by TiO\(_2\) was beneficial for improving the PEC performance of Au-NPs/Ga\(_2\)O\(_3\). Notably, after comparing the 2-nm-TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) and pristine Au-NPs/Ga\(_2\)O\(_3\), the IPCE peak of 2-nm-TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) increased by 1.5 times, while the absorption increased by only 1.1 times at the peak LSPR wavelength. We suspect that much better charge separation occurred at the interface, resulting from the good hole-capturing ability of TiO\(_2\), which was an important factor for IPCE enhancement, as depicted in Fig. 2c. After the deposition of TiO\(_2\), the surface states of TiO\(_2\) efficiently capture the plasmon-induced holes for efficient water oxidation. Moreover, the hot electrons generated at the Au-NPs/Ga\(_2\)O\(_3\) interface could be smoothly transferred to the CB of Ga\(_2\)O\(_3\) due to the direct contact between Au and Ga\(_2\)O\(_3\). Based on this mechanism, hot carriers should have enough energy to achieve the hot-electron injection and water oxidation. The flat-band potential of 2-nm-TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) was estimated to be \(-0.80\) V vs. RHE after the deposition of 2 nm TiO\(_2\) as shown in Fig. S10a.\(^{†}\) The energy barrier between the flat-band potential of Ga\(_2\)O\(_3\) for hot-electron injection and the oxidation potential of water (+1.23 V vs. RHE) is estimated as 2.03 eV (610 nm). Therefore, under the irradiation of light with the wavelength of 600 nm which is the peak wavelength of the IPCE action spectrum in Fig. 2b, both hot-electron injection and water oxidation can be achieved simultaneously.

As shown in Fig. 2a and b, the redshift of the TiO\(_2\)/Au-NPs/Ga\(_2\)O\(_3\) IPCE peaks is not as obvious as their redshift in the absorption spectra. This observation could be explained by the threshold of photon energy needed for exciting electron/hole...
separation at the Au-NPs/Ga2O3 interface, as discussed in Fig. S10.† This result suggested another insight, in that the electron injected into the CB of Ga2O3 had a high negative potential energy. The energy generated under light irradiation at 600 nm on the Ga2O3 photoanode, \( \eta_{\text{photo}} \) was evaluated by being compared to an ideally nonpolarizable dark electrode as expressed in formula (1)

\[
\eta_{\text{photo}} = \frac{I_{\text{max}}(1.23 \text{ V vs. RHE} - V_{\text{max}})}{P_{\text{in}}} \times 100(\%)
\]

where \( I_{\text{max}} \) and \( V_{\text{max}} \) are the maximum output current and voltage, which generate the maximum electric power, respectively. \( P_{\text{in}} \) is the incident light intensity.28

The value of \( \eta_{\text{photo}} \) is the thermodynamic energy-conversion efficiency of the photoelectrode, and the \( \eta_{\text{photo}} \) value for 2-nm-TiO2/Au-NPs/Ga2O3 under light irradiation at 600 nm was calculated as 0.06% from the \( I-V \) characteristics shown in Fig. S11.† This value was approximately twice as large as that of the Au-NPs/TiO2-thin film (0.03%) due to the extremely negative onset potential. Therefore, the plasmonic Ga2O3 photoanode modified with the thin TiO2 layer could simultaneously achieve water oxidation and hot-electron injection with a negative reduction potential under visible light irradiation.

To further verify the hole-trapping ability of the TiO2 layer, the IPCE values of 2-nm-TiO2/Au-NPs/Ga2O3 and Au-NPs/Ga2O3 were measured in an electrolyte with triethanolamine (TEOA), as shown in Fig. 3. TEOA is a sacrificial hole scavenger due to its fast reaction kinetics based on one-electron oxidation.29 For Au-NPs/Ga2O3 without TiO2 modification, the oxidation reaction with water by holes was difficult, as discussed above. The addition of TEOA dramatically increased the oxidation reactivity even though the hole-trapping ability of the Ga2O3 surface was poor, as illustrated in Fig. S12a.† The high IPCE of 2-nm-TiO2/Au-NPs/Ga2O3 without TEOA in Fig. 3b indicated that the hot holes trapped at the surface states of 2-nm-TiO2/Au-NPs/Ga2O3 oxidized water efficiently even without the addition of TEOA, as shown in Fig. S12b.† Although the hole-trapping ability of TiO2 could improve the oxidation reactivity and charge separation, the positive effect of interfacial modification on the IPCE showed a dependence on the thickness of TiO2. When the TiO2 thickness was larger than 2 nm, the IPCE improvement decreased even though the absorption increased. To understand the PEC performance difference of TiO2/Au-NPs/Ga2O3 with different thicknesses of the TiO2 layer, the near-field distribution at the interface of TiO2/Au-NPs/Ga2O3 that determined the plasmon-induced carrier generation was calculated by a finite-difference time-domain (FDTD) simulation (Fig. 4). For Au-NPs/Ga2O3, the hot spot of the near-field was located at the interface between Au-NPs and Ga2O3, which are represented as the two bright spots in Fig. 4a. Regarding 2-nm-TiO2/Au-NPs/Ga2O3, the near-field intensity was enhanced at the three-phase boundary of TiO2/Au-NPs/Ga2O3 (Fig. 4b). However, the near-field intensity at the three-phase boundary decreased as the TiO2 thickness increased (Fig. 4c and d). Though the near-field became stronger at the interface of TiO2/Au-NPs with increasing distance from the Ga2O3 surface in Fig. 4c and d, the carriers generated at the Au-NPs/TiO2 interface and then injected into the CB of TiO2 contributed less to the IPCE, as discussed in Fig. S6.† Moreover, trapped holes at the three-phase boundary should migrate to the surface to participate in the water oxidation reaction. The thick TiO2 modification layer would also suppress hole migration to the surface because of the extended path. Consequently, 2-nm TiO2 interfacial-modified Au-NPs/Ga2O3 showed the best PEC improvement.

**Fig. 3** IPCE action spectra of (a) Au-NPs/Ga2O3 and (b) 2-nm-TiO2/Au-NPs/Ga2O3 measured in a KClO4 aqueous solution with and without TEOA.

**Fig. 4** Near-field distributions of Au-NPs/Ga2O3 modified with (a) 0, (b) 2, (c) 3, and (d) 4 nm TiO2 layers, which was calculated by an FDTD simulation.

**Conclusions**

We demonstrated plasmon-induced photocurrent generation on wide bandgap Ga2O3 under visible light irradiation. The IPCE of Au-NPs/Ga2O3 was improved by an interfacial modification consisting of the deposition of a TiO2 layer, which exhibits a high hole-trapping ability. The partial inlaying of Au-NPs with the TiO2 layer could be beneficial for trapping plasmon-induced holes at the interfacial boundary between Au-NPs and Ga2O3.
TiO₂ and improving the oxidation reactivity while maintaining efficient electron transfer. The 2-nm-thick TiO₂ interfacial modification shows up to a 1.5-times higher IPCE in the visible region than that without TiO₂. The thermodynamic energy-conversion efficiency for the 2-nm-TiO₂/Au-NPs/Ga₂O₃ photoelectrode under light irradiation at 600 nm was approximately twice as large as that of the Au-NPs/TiO₂-thin film due to the extremely negative onset potential.

Based on the above observations, the plasmonic Ga₂O₃ photoanode with the interfacial modification of a thin TiO₂ layer could demonstrate both a high ability for reduction, such as H₂ evolution, and oxidation ability for water oxidation because of the negative CB of Ga₂O₃ and the hole-trapping property of TiO₂, respectively. We believe this interfacial modification has enormous potential for use in artificial photosynthesis and could be applied in various fields and devices for photon energy conversion through structural optimization.

Materials and methods

Sample fabrication and structure characterization

The Sn-doped single-crystal β-Ga₂O₃ wafer (Novel Crystal Technology, Inc.) with an orientation of (−201) was cut to a size of 9.0 × 9.0 × 0.7 mm³. These Ga₂O₃ substrates were successively rinsed with acetone and methanol in an ultrasonic bath for 5 min each. To fabricate Au-NPs on the surface of Ga₂O₃, a thin gold layer was deposited onto the substrates by electron-beam evaporation at room temperature. The deposition pressure was approximately 2.0 × 10⁻⁶ Pa, and the evaporation rate was set to approximately 0.16 Å s⁻¹. Subsequently, the samples were annealed in air at 800 °C for 1 h. The fabrication processes are shown in Fig. S3 in the ESI.† The particle size of Au-NPs was controlled by changing the thickness of the Au film.

The TiO₂ layer was deposited by a commercial hot-wall flow-type ALD reactor (SUNALETM R series, Picosun, Finland) at 300 °C with a deposition rate of 0.05 nm per cycle. TiCl₄ and deionized water vapor were used as the Ti and O sources, and N₂ was used as the carrier gas and purge gas. The pulse time and purge time were set as 0.1 and 4.0 s, respectively. X-Ray diffraction chart was applied to check the phase structure of Ga₂O₃ by RIGAKU RINT-2000/PC using Cu Kα radiation. The valence of Ga, Ti and O was measured by an X-ray photoelectron spectrometer (XPS, JPS-9200, JEOL).

Optical properties and morphology characterization

A photonic multichannel analyser (PMA C7473, Hamamatsu Photonics) system was applied to measure the optical reflectance and transmittance spectra. Bandgap of Ga₂O₃ was estimated by the Tauc plots obtained from the transmittance spectra measured by a UV-Vis spectrophotometer (UV-3100PC, SHIMADZU). The surface morphology was identified by field-emission scanning electron microscopy (FE-SEM, JSM-6700FT, JEOL) with a maximum resolution of 1 nm. Additionally, ImageJ software was used to analyse the mean particle size.

Photoelectrochemical measurement

To obtain the ohmic contact, an In–Ga alloy with a weight ratio of 4:1 was coated on the backside and sidewall of the Au-NPs/Ga₂O₃ substrates. Then, the samples were connected to a copper plate in a Teflon reaction cell, which was connected to an electrochemical analyser (ALS/CH Instruments 852C, ALS) with a copper lead wire. The irradiation window consisted of a pinhole with a diameter of 2.0 mm on the lid of the cell. A three-electrode system consisting of a platinum wire and a saturated calomel electrode (SCE) as the counter electrode and reference electrode, respectively, was applied to measure the PEC properties. In addition, a 0.1 M KClO₄ aqueous solution without an electron donor was used as the electrolyte. During the photocurrent measurement, a potential of +0.3 V vs. SCE was applied to the working photoelectrode. The IPCE was calculated by formula (2):

\[
\text{IPCE}(\lambda) = \frac{1240 \times I(A \text{cm}^{-2})}{\lambda(nm) \times P_in(W \text{cm}^{-2})}
\]

where \(I\) is the photocurrent density, \(\lambda\) is the wavelength of incident light and \(P_in\) is the incident light intensity. In addition, Mott–Schottky experiments were carried out at a constant frequency of 5000 Hz in a scan window of −1.5 to 1.0 V vs. SCE in the three-electrode system described above.

Numerical simulations

Full-field electromagnetic wave simulations were performed using the FDTD method (FDTD Solutions, Lumerical). The investigated structure was simulated using perfectly matched layers along the z-direction and periodic boundary conditions along the x- and y-directions with a period of 20 nm. An ellipsoid sphere with a diameter of 15 nm in the x and y directions and 10 nm in the z direction was used to model the Au-NPs. In the simulation, the refractive index of Au was taken from the optical constants of Johnson and Christy. Ga₂O₃ and TiO₂ were treated as dielectric materials with refractive indices of 1.8 and 2.4, respectively.

Conflicts of interest

There are no conflicts to declare.

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