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Showcasing research from the collaborative team of Lianzhou Wang from the University of Queensland, Australia, and Can Li from Chinese Academy of Sciences.

Title: Selective production of hydrogen peroxide and oxidation of hydrogen sulfide in an unbiased solar photoelectrochemical cell

Identifying processes capable of producing valuable chemicals by using waste products is significant. This work introduces a dual-functional solar-to-chemical approach which can convert toxic hydrogen sulfide (H$_2$S) to simultaneously produce valuable hydrogen peroxide (H$_2$O$_2$) and elemental sulfur.

As featured in:
Selective production of hydrogen peroxide and oxidation of hydrogen sulfide in an unbiased solar photoelectrochemical cell†

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A solar-to-chemical conversion process is demonstrated using a photoelectrochemical cell without external bias for selective oxidation of hydrogen sulfide (H2S) to produce hydrogen peroxide (H2O2) and sulfur (S). The process integrates two redox couples anthraquinone/anthrahydroquinone and I−/I3−, and conceptually illustrates the remediation of a waste product for producing valuable chemicals.

Broader context

Identifying cost-effective processes for use of solar energy is challenging. Production solely of low-value fuels such as hydrogen necessitates extremely low capital cost systems that have been yet to be identified. Demonstrating a dual-function solar-to-chemical process making higher value chemicals from photogenerated electrons and consuming negative value waste products with the holes can significantly improve the economic sustainability of the process. In this work, we demonstrate a combined photoelectrochemical cell for the remediation of toxic hydrogen sulfide (H2S) and the production of valuable hydrogen peroxide (H2O2). Moreover, we highlight the importance of fine-tuning the selectivity of photochemical reactions by using well-designed transformation processes.

The efficient transformation of solar energy into important products and fuels is essential for the realization of a solar energy economy.1–4 Photochemical processes with dual-functions are attractive due to their potential for activating two or more reaction partners in a single photocatalytic catalytic cycle without the necessity of quenching or sacrificial reagents.5–7 This means that both the photogenerated electron and hole can drive useful redox reactions, therefore making use of the potential energy stored in both carriers.

To utilize a dual-function approach, different strategies can be used to drive useful reactions with the electrons and the holes. In photoelectrochemical–photocatalytic water splitting reactions, H2 and O2 are directly produced simultaneously.8–11 An indirect strategy is to store solar energy in intermediate species and then use the intermediate species to drive the subsequent reactions.7 In many cases, this indirect pathway is kinetically more favourable and therefore more easily implemented. Moreover, an indirect pathway may make the reaction choice more flexible and potentially produce commercially valuable products with high selectivity. We have investigated the dual-function approach to achieve efficient solar energy transformation for target reactions with potentially useful and valuable products.

As is well-known, hydrogen peroxide (H2O2) is an important commodity oxidant.12,13 It is currently produced by an anthraquinone (AQ) process, in which hydrogenation of AQ with H2 produces anthrahydroquinone (H2AQ) and subsequent oxidation of H2AQ by O2 produces H2O2 (Scheme S1†). As an alternative to this process, photochemical reduction of O2 to produce H2O2 is attractive for production of H2O2 as a chemical product or fuel.15–17 Moreover, the production of valuable and easily-storable hydrogen peroxide using a photochemical reaction may avoid the costs and safety concerns of processes using H2.

Enormous quantities of H2S are byproduct of oil and gas production. It is toxic and expensive to manage. At present, H2S is primarily treated using the Claus process wherein it is partially oxidized by O2 to yield S and H2O.18 A solar-to-chemical process to selectively convert H2S and O2 into S and H2O2 (instead of H2O), may have both economic and environmental benefits.
In this study, we coupled two separate photoelectrochemical–
chemical reaction systems: reduction of O₂ with anthrahydro-
droquinone (H₂AQ) to produce hydrogen peroxide (H₂O₂) and
anthraquinone (AQ) which is electro-reduced to H₂AQ, and
oxidation of hydrogen sulfide (H₂S) to elemental sulfur (S) with
I₃⁻ produced by photooxidation of I⁻. To the best of our
knowledge, this is the first reported photochemical approach
that integrates selective H₂S oxidation and O₂ reduction reac-
tions to produce hydrogen peroxide.

The approach of selectively converting H₂S and O₂ to S and
H₂O₂ is shown in Scheme 1 and Scheme S2. The overall reac-
tion consists of two integrated photoelectrochemical–chemical
cycles occurring in the anodic and cathodic compartments
separated by a Nafion membrane. Every cycle comprises one
chemical and one photoelectrochemical reaction.

In the cycle occurring in the anodic compartment, H₂S is
trapped and selectively oxidized to elemental sulfur and protons
through a simple redox reaction (1.1 in Scheme 1) where the
conversion of I₃⁻ to I⁻ is the corresponding reduction reaction.

Subsequently, the resulting I⁻ is restored to I₃⁻ by the pho-
togenerated holes during the photoelectrochemical reaction
(1.2). The use of I⁻/I₃⁻ redox couples will ensure the efficient
oxidation of H₂S, which is superior to the direct oxidation of
H₂S on the electrode surface due to the mass transfer issue.

In the cycle occurring in the cathodic compartment, H₂O₂ is
produced through a simple chemical reaction with H₂AQ
H₂O₂ is shown in Scheme 1 and Scheme S2.

By integrating the two cycles linked by I⁻/I₃⁻ and AQ/H₂AQ
redox couples, the net reaction is the production of S and H₂O₂
from H₂S and O₂ using solar energy. It is worth noting that
I⁻/I₃⁻ and AQ/H₂AQ redox species are negatively charged and
won’t diffuse through the Nafion membrane. Therefore, the
individual redox couples are confined within the anodic and
cathodic compartments, respectively, which will prohibit the
backward reaction and allow for the separation of the final
products. To further clarify the engineering challenges for
potentially implementing the concept in a real practice, a more
detailed flow-stream design (Scheme S4†) of the reaction
processes is presented in Scheme S4†. In this regard, Scheme 1
can be considered as a simplified format of Scheme S4†.

As a proof of concept, we investigated the cathodic and
anodic sides of the reactions on p-type Si (p-Si) or n-type Si (n-Si)
in a three electrode system, respectively (Fig. S1, experimental
details in the ESI†). As shown in Fig. 1a, an onset potential of
-0.1 V vs. reversible hydrogen electrode (RHE) was obtained in
an acidic AQ electrolyte on p-Si, which is approximately 0.25 V
more positive than the value obtained in H₂SO₄. This indicates
the AQ reduction to H₂AQ is more favorable relative to proton
reduction to H₂. At an applied potential of -0.3 V vs. NHE, most
of the photocurrent obtained can be ascribed to the reduction of
AQ to H₂AQ instead of proton reduction (Fig. S2†). This ensures
the high selectivity toward H₂O₂ production instead of H₂
production. Moreover, the onset potential for AQ reduction was
further notably shifted to ca. 0.2 V vs. NHE on the TiO₂/Ti/n+p-Si
electrode due to the extra potential afforded by the surface n-
doping and the possible beneficial effect of Ti/TiO₂ coating for
photoelectrochemical reactions.

The results of the chronocoulometry showed that the TiO₂/
Ti/n+p-Si electrode’s performance decreased quickly initially,
but remained comparatively stable after prolonged testing
(Fig. 1b). During chronocoulometry, the AQ solution in the
cathodic compartment gradually changed from light yellow to
dark green, indicating the generation of H₂AQ (Fig. S3†). This
partially led to the decreased activity observed on TiO₂/Ti/n+p-Si
due to the blocking of light by H₂AQ. The solution can be
restored to the original yellow colour rapidly when sparged with
air, due to the rapid auto-oxidation of H₂AQ to H₂O₂ and AQ
generating H₂O₂ (Scheme S3†). Therefore, the energy from pho-
togenerated electrons can be stored as chemical potential energy
in the form of H₂O₂ and then liberated to reduce O₂ to produce

[a](a) Current–potential curves of (i) p-Si in 0.5 M H₂SO₄ solution,
(ii) p-Si in saturated AQ acidic solution, and (iii) TiO₂/Ti/n+p-Si in
saturated AQ acidic solution. (b) Chronocoulometry on TiO₂/Ti/n+p-
Si in AQ acidic solution. (c) Picture showing the generation of H₂O₂
after bubbling air into aqueous solution containing H₂AQ in the middle
cuvette. (d) Time course of H₂O₂ evolution. Solid squares resemble the
calculated amount based upon the charges and the open squares
represent the amount measured. Light source: AM1.5G, 100 mW cm⁻².
A three electrode system was used during the measurement and 0.5 M
H₂SO₄ was used in the anodic compartment. The surface area of p-Si
is ca. 1.2 cm² and that of TiO₂/Ti/n+p-Si is ca. 0.5 cm².

Scheme 1 Schematic illustration on the selective production of H₂O₂
and S from O₂ and H₂S on n-type electrode.

Fig. 1 (a) Current–potential curves of (i) p-Si in 0.5 M H₂SO₄ solution,
(ii) p-Si in saturated AQ acidic solution, and (iii) TiO₂/Ti/n+p-Si in
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H₂O₂. The amount of H₂O₂ produced gradually increased with the reaction time. The Faradaic efficiency was calculated to be ca. 90% (Fig. 1d).

We investigated the anodic reactions on functionalized Pt/p+n-Si electrode. The p⁺ doping of the n-Si electrode allows for increased photocurrent for the oxidation reaction. Deposition of a Pt catalyst film can protect the Si underneath as well as catalyze Ι⁻ oxidation to I₃⁻. As shown in Fig. 2a, Pt/p+n-Si electrode showed an onset potential of ca. 0.2 V vs. RHE and delivered a photocurrent of ca. 12 mA cm⁻² at an applied potential of as low as 0 V vs. RHE in an acidic KI electrolyte. These values are outstanding compared with our previous functionalized n-Si electrode which showed a more cathodic onset potential of 0.1 V vs. RHE. Moreover, the Pt/p+n-Si electrode showed greater stability during chronoamperometry (Fig. 2b).

During chronoamperometry, the KI solution in the anodic compartment gradually changed to red, indicating the generation of I₃⁻ (middle cuvette of Fig. 2c). This corresponds well with the UV-Vis analysis of the reaction solution (Fig. S4†). The enhanced absorption with accumulative I₃⁻ could also lead to reduced activity on Pt/p+n-Si as observed on TiO₂/Ti/n+p-Si. H₂S was bubbled into the solution containing I₃⁻ and the solution rapidly changed to a turbid yellow. The yellow precipitate was identified to be ζ-S using X-ray diffraction (XRD) analysis (Fig. S5†). The energy from photogenerated holes can thus be stored as chemical potential energy in the form of I₃⁻ and then discharged by chemically oxidizing H₂S to S and protons. The amount of I₃⁻ produced increased with the reaction time and the Faradaic efficiency was calculated to be greater than 90% (Fig. 2d).

After separately verifying the anodic and cathodic reactions in three electrode systems, we investigated the integration of the two photoelectrochemical–chemical reaction pairs in a single two electrode system. Single photoelectrodes in the anodic (for n-Si) or cathodic (for p-Si) compartments were used as the light absorber. As shown in Fig. S6a, p-Si showed a negligible photocurrent at negative applied bias when using AQ and H₂SO₄ in the cathodic and anodic compartments, respectively. However, the photocurrent increased significantly when KI was added to the H₂SO₄ in the anodic compartment. The photocurrent and onset potential for AQ reduction was further improved on the TiO₂/Ti/n+p-Si electrode (Fig. 3b). As Ι⁻ oxidation is thermodynamically more favorable than water oxidation, the use of KI can relieve the stringent requirement on the anodic side. However, TiO₂/Ti/n+p-Si only delivered a negligible photocurrent at zero applied bias. As the conduction band level of p-Si is higher than what is required for AQ and protons reductions, this low photocurrent at zero bias should be ascribed to the inefficient oxidation power of the photo-generated holes.

We then tentatively tried Pt/p+n-Si in a two electrolyte system with the expectation that an unbiased system could be established due to the high oxidation potential afforded by p+n-Si. As shown in Fig. 3a, Pt/p+n-Si showed a negligible photocurrent at zero bias when using KI and H₂SO₄ in the anodic and cathodic compartments, respectively. However, the photocurrent increased notably to 8 mA cm⁻² when adding AQ to H₂SO₄ in the cathodic compartment (Fig. 3c). The increased current is expected because AQ is more favorably reduced than protons (Fig. 1a). The selectivity for the H₂AQ production is calculated to be ca. 98% by comparing the photocurrent shown in Fig. 1a and
Taking the solar energy stored in the form of I$_3^-$ and H$_2$AQ during reactions 1.2 and 2.2 (Scheme 1) into consideration, the solar-to-chemical conversion efficiency was estimated to be ca. 1.1%. Therefore, by using KI and AQ as the electrolyte, Pt/p-n Si can affect the simultaneous oxidation of I$^-$ to I$_3^-$ and the reduction of AQ to H$_2$AQ under zero applied bias (Fig. S7†). This is due to the fact that the combined use of KI and AQ species in the anodic and cathodic compartments can considerably decrease the potential required to run the photoelectrochemical cell.

When a carbon plate was used as the counter electrode instead of Pt, a negative shift in the onset potential and a higher photocurrent was observed at zero bias possibly due to the more efficient reduction of AQ on the carbon. This has been further testified by cyclic voltammetry on carbon and Pt electrodes in the presence of acidic AQ electrolyte (Fig. S8†). Using carbon to replace Pt would significantly reduce the cost of the system and the overpotential for H$_2$ evolution on carbon is quite high (Fig. S8a†), thus the use of carbon will ensure the high selectivity toward AQ reduction. No H$_2$ was observed in the cathodic compartment by gas chromatography, suggesting the high selectivity to H$_2$AQ instead of H$_2$ production. Our results suggest that the energy from the photogenerated electrons and holes can be stored simultaneously in the form of H$_2$AQ and I$_3^-$ redox couples and subsequently released to produce H$_2$O$_2$ and S by reaction with O$_2$ and H$_2$S. Therefore, integrating the photochemical—chemical reaction pairs, solar energy is continuously driving S and H$_2$O$_2$ production while treating H$_2$S with O$_2$.

Recently we reported the direct splitting of H$_2$S to produce H$_2$ and S using solar energy.7 Although the as-produced H$_2$ can be used to produce H$_2$O$_2$ through the traditional AQ process, unbiased production of H$_2$ was not demonstrated. However, using the more thermodynamically favourable reduction of AQ instead of protons, we can generate H$_2$O$_2$ selectively at zero bias without producing H$_2$. The present approach represents a potentially more efficient and safer route for the production of H$_2$O$_2$ and S from O$_2$ and H$_2$S.

We also note that the onset potential for AQ reduction on the p-Si photocathode is much higher than expected. For example, the onset potential for proton reduction on Pt/TiO$_2$/Ti/n-p-Si is 0.5 V vs. RHE, while that for AQ reduction on TiO$_2$/Ti/n-p-Si is only 0.2 V vs. NHE even though AQ is more easily reduced than protons. We ascribed this observation to the lack of a suitable catalyst for TiO$_2$/Ti/n-p-Si. As the loading of a suitable cocatalyst can significantly improve rates, it is anticipated that the AQ reduction reaction could be promoted by employing a suitable catalyst.19–22 Moreover, even deactivation is observed on Pt/p-n’Si during the reactions (Fig. 3d), it is possible to further improve its performance by a structural modification or by optimizing the coating process.23–25 These efforts might enable an efficient system for the unbiased production of H$_2$O$_2$ and S by treating H$_2$S. However, to make this concept commercially viable, we should not underestimate the technological challenges including the long-term stability issue.

Conclusions
A solar-driven process which requires no external bias is demonstrated with the dual-function of selective production of H$_2$O$_2$ and S from O$_2$ and H$_2$S. By combining the AQ/AQH$_2$ and I$^-$/I$_3^-$ redox couples, the indirect photoreduction of O$_2$ to H$_2$O$_2$ and photooxidation of H$_2$S to S were integrated to achieve a photochemical—chemical cycle with an overall efficiency of 1.1%. This work not only demonstrates an innovative route for the environmental remediation of toxic and abundant H$_2$S and the simultaneous generation of a valuable chemical product but also highlights the importance of tuning the selectivity of photochemical reactions by using well-designed transformation processes.

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Notes and references