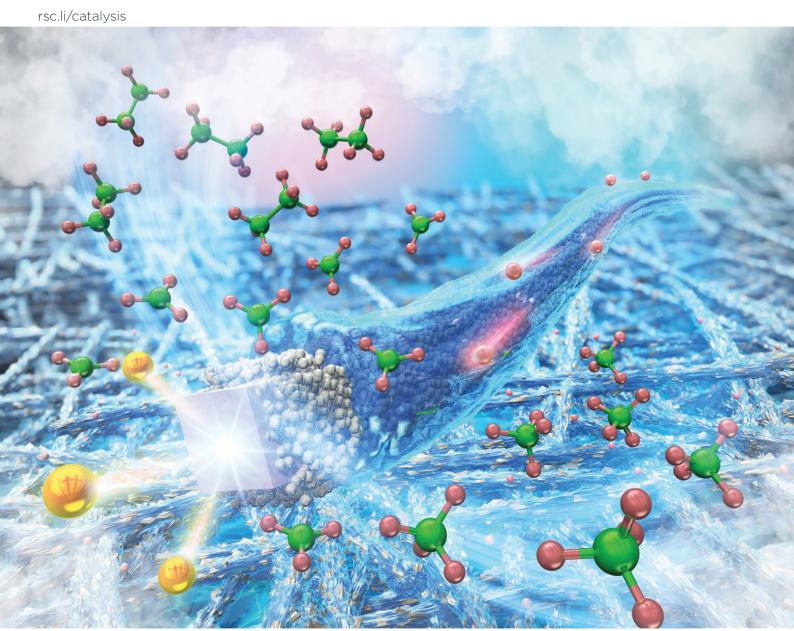
Catalysis Science & Technology

Volume 13 Number 16 21 August 2023 Pages 4571-4884



ISSN 2044-4761



PAPER

Catalysis Science & **Technology**



View Article Online PAPER



Cite this: Catal. Sci. Technol., 2023, **13**, 4640

Photoelectrochemical C-H activation of methane to methyl radical at room temperature†

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Herein, we report a continuous gas-fed photoelectrochemical (PEC) system with a proton exchange membrane for CH₄ activation at ambient temperature and pressure. We found that both water splitting and steam reforming of CH_4 were induced over oxide photoanodes. When the CH_4 concentration was low, O_2 and CO₂ were formed on titanium oxide (TiO₂) and tungsten trioxide (WO₃) photoanodes under ultraviolet light irradiation. We also found that visible light enhanced CH₄ activation and ethane (C₂H₆) formation over the WO₃ photoanode. When the CH₄ concentration increased, O₂ formation was suppressed, with increasing production rates of CO_2 , C_2H_6 , and CO. Under optimised conditions, the selectivity of C_2H_6 reached 57% on a carbon basis over the WO_3 photoanode under visible-light irradiation. The production of C_2H_6 implies the formation of methyl radicals during the CH₄ gas-fed PEC process. We also demonstrated the PEC coupling of ethane to n-butane and the visible-light-induced oxidation of CH₄ without external bias.

Received 7th May 2023, Accepted 7th June 2023

DOI: 10.1039/d3cy00632h

rsc.li/catalysis

Introduction

The catalytic conversion of CH₄ into value-added products is challenging because of its high stability and a large energy gap between its highest occupied and lowest unoccupied molecular orbitals.1,2 Moreover, its electron affinity is low (-1.9 eV),³ the ionization potential (12.6 eV) and the C-H bond dissociation energy (439 kJ mol⁻¹) are high, 4 and the acidity is very weak (p K_{α} = 56).⁵ The dipole moment of CH₄ is zero because of its symmetric structure. Therefore, hightemperature processes are typically used for catalytic CH₄ conversion. However, a low-temperature catalytic process may achieving he promising for high selectivity. Photoelectrochemical (PEC) reactions at room temperature differ from conventional catalytic processes.^{6–10}

There are three pathways that convert CH₄ into methyl radicals ('CH₃), as shown in Fig. 1: electron transfer (ET), proton transfer (PT), and proton-coupled electron transfer (PCET). Among these reactions, ET (CH₄ = 'CH₄⁺ + e⁻, $\Delta_r G$ = 1163 kJ mol⁻¹) and PT (CH₄ = CH₃⁻ + H⁺, $\Delta_r G = 270$ kJ mol⁻¹) are extremely difficult to achieve. In contrast, PCET is more advantageous than stepwise transfer because the transfer of

The potential to form 'CH₃ is more negative than that for 'OH/H₂O (+2.38 V vs. SHE). These potentials are suitable for titanium oxide (TiO2) photocatalysts. Fig. 2a shows the band diagram of anatase TiO2, in which the valence band maximum (VBM) is located at approximately 3.0 V vs. SHE. Oxide semiconductors without partially filled d levels also exhibit a similar VBM.14 Therefore, many semiconductor photocatalysts can activate CH4 via the PCET mechanism. The nonoxidative coupling of methane (NOCM) is a wellknown photocatalytic reaction (2CH₄ \rightarrow C₂H₆ + H₂, ΔG_{298K} = 68.6 kJ mol⁻¹).^{15,16}

However, the reported photocatalytic activities for NOCM are quite low. 17-24 In addition, TiO2 can only use UV light as the band gap (E_{φ}) of anatase TiO₂ is 3.2 eV.²⁵

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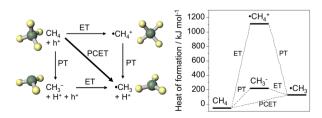


Fig. 1 Activation of CH₄ to methyl radical through electron transfer (ET), proton transfer (PT), and proton-coupled electron transfer (PCET). The heat of formation was calculated by MOPAC PM3.

H⁺ and e⁻ together can avoid the formation of high-energy chemical intermediates. ^{11–13} The $\Delta_r G$ of PCET (CH₄ = *CH₃ + $H^+ + e^-$) is 198.7 kJ mol⁻¹. Thus, the potential of the 'CH₃/ CH₄ couple is +2.06 V versus the standard hydrogen electrode $(SHE).^7$

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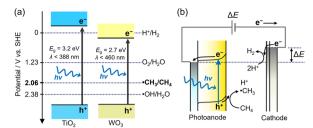


Fig. 2 (a) Energy band diagram of TiO₂ and WO₃. (b) PEC process using photoanode and cathode under applied bias (ΔE).

The PEC process can overcome the following limitations of TiO2 photocatalysis: low activity and lack of visible-light sensitivity (Fig. 2b). The external potential applied to the semiconductor electrodes improves the charge separation of the photoexcited carriers. Moreover, the applied voltage the use of visible light-responsive semiconductors with a narrow E_g even though the conduction band minimum is too positive to induce the hydrogen reaction (HER). Tungsten oxide evolution photocatalysts theoretically inactive for are NOCM accompanied by HER, but the PEC process enables the HER on the cathode by applying voltages between the two electrodes.

Herein, we investigate the PEC process for CH4 activation using TiO2 and WO3 photoanodes. 7-10,26,27 We developed a continuous gas-flow PEC reactor using a proton exchange membrane (PEM) as a solid electrolyte. 7,28-30 The all-solidstate PEM-PEC cell is suitable for hydrophobic CH₄, which is insoluble in water. The maximum concentration of CH4 is only 0.0016 M in water while that of water is 55.5 M in liquid (Fig. 3).4 However, in the case of humidified CH₄ gas, the saturated concentration of H₂O(g) is 0.0013 M (3.16 kPa) at 25 °C, but the concentration of CH₄ is 0.041 M (101 kPa). We studied the probability of a gas-fed PEC process for CH₄ activation under both UV and visible-light irradiation.

Results and discussion

Photoanode materials and light wavelengths

CH₄ activation through PEC was tested using the PEM-PEC cell (Fig. S1 in ESI†) in a two-electrode system at 25 °C under

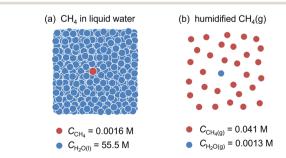


Fig. 3 (a) Molar concentrations of (a) dissolved CH₄ and H₂O in liquid water, and (b) gaseous CH₄ and water vapor in humidified condition at 25 °C.

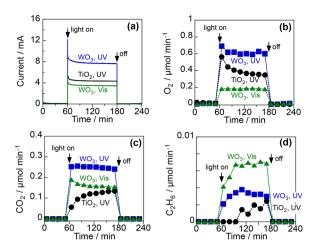


Fig. 4 PEC activation of 10 vol% CH₄ using WO₃ and TiO₂ photoanodes under UV light (6.5 mW cm⁻² at 365 nm) and visible light (6.8 mW cm $^{-2}$ at 453 nm): (a) the overall current at 1.2 V, (b) the rate of O_2 evolution, (c) the rate of CO_2 formation, and (d) the rate of C_2H_6 formation on the photoanode side.

atmospheric pressure. Fig. 4 shows the time course of the PEC process using the TiO₂ and WO₃ photoanodes under a continuous flow of 10 vol% CH4 and 3 vol% H2O(g) balanced with Ar. The cathode, which was separated from the photoanode using PEM, was a Pt/carbon electrocatalyst maintained under a humidified Ar flow. Humidification of the fed gases enhanced the proton conductivity of the PEM. The photoanode was irradiated with UV (365 nm) or blue light (453 nm). Before photoirradiation, the PEC system was kept in the dark to establish an adsorption-desorption equilibrium. Under irradiation, a good photocurrent response was observed for each condition when 1.2 V was applied between the photoanode and cathode catalysts (Fig. 4a). The incident photon-to-current conversion efficiencies (IPCE) at steady state were 19.8% and 11.3% for the WO₃ and the TiO₂ photoanodes, respectively, at 365 nm. The IPCE at 453 nm was 8.4% for the WO₃ photoanode. This high quantum efficiency suggests efficient charge separation in the spacecharge layer formed by the applied potential.

O₂, CO₂, and a small amount of C₂H₆ were obtained as products on the photoanodes (Fig. 4b-d). Carbon monoxide could not be analysed under these conditions because of its interference with the Ar diluent. The production of O2 and CO₂ suggests that both water vapour and CH₄ were oxidised on the photoanodes. The Faraday efficiencies (FE) of O2 and CO2 were approximately 50% and 40%, respectively, under UV irradiation for both photoanodes (Table S1 in ESI†). The FE of O₂ decreased to 34% and that of CO₂ increased to 59% under visible-light irradiation of the WO₃ photoanode. The production rate of C₂H₆ also increased when 453 nm visible light was used instead of 365 nm UV light. These results suggest that CH₄ oxidation to CO₂ and C₂H₆ is more plausible than water oxidation under visible-light irradiation. The production of C₂H₆ implies that 'CH₃ is generated by the PEC process; this is because the homocoupling of 'CH₃ is

involved in the formation mechanism of C₂H₆ in photo-Kolbe electrolysis.31-33

Methane concentration and light intensity

Fig. 5 shows the effect of the concentration of CH₄ fed into the WO₃ photoanode under visible-light irradiation. The O₂ evolution rate decreased significantly when the CH₄ concentration increased to 50 vol%. The IPCE was 10.5%, and the FEs for O2, CO2, and C2H6 were 5.1%, 81.7%, and 4.9%, respectively (Table S2 in the ESI†). For the cathode catalyst, stoichiometric H₂ evolution (FE of ~100%) was observed indicating that the steam reforming of methane $(CH_4 + 2H_2O_{(g)} \rightarrow CO_2 + 4H_2)$ was mainly promoted in this PEM-PEC reactor. To the best of our knowledge, this is the first report of the gas-fed PEC steam reforming of methane, which is an uphill reaction $(\Delta G_{298K} = 114 \text{ kJ mol}^{-1})$. ^{15,16} Notably, the purity of the evolved H2 can be sustained by the membrane separation from CH₄ and the oxidised products. The H₂ production rate, and thus the photocurrent, did not depend on the CH₄ concentration, suggesting that the charge-separation efficiency was determined by the applied potential rather than the surface reactions.

Fig. 6 shows the PEC properties of the WO₃ photoanode under the flow of 97 vol% CH₄ and 3 vol% H₂O vapour.⁷ When the light intensity is 3.6 mW cm⁻², the FEs of O_2 , CO₂, CO, and C₂H₆ were 1.5%, 72.3%, 8.3%, and 14.0%, respectively. The sum of the FE values was 96%, suggesting that unidentified products were limited, and no methanol was formed. The FE of C2H6 was not very high because only two electrons were donated from CH₄ to produce a C₂H₆ molecule and eight electrons produced a CO₂

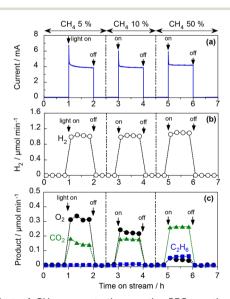


Fig. 5 Effect of CH₄ concentration on the PEC reactions over the WO_3 photoanode: (a) the overall current at 1.2 V, (b) the rate of H_2 evolution on the cathode side, and (c) the rate of products formation on the photoanode side under visible-light irradiation (6.8 mW cm⁻² at 453 nm)

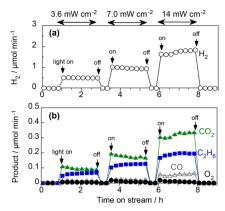


Fig. 6 Effect of light intensity on the activation of humidified CH₄ using the WO₃ photoanode under 453 nm irradiation at 1.2 V; (a) the H₂ evolution rate on the cathode side and (b) the rates of product formation on the photoanode side.

molecule. From the viewpoint of selectivity, the production rate of C₂H₆ was comparable to that of CO₂ at high CH₄ concentrations and low light intensities. The C2H6 selectivity on a carbon basis reached 57.4%, whereas the selectivities for CO₂ and CO were 37.0% and 5.6%, respectively (Table S3 in the ESI†). This indicates that more than half of the PEC process can be explained by the coupling dehydrogenative of methane, similar photocatalytic NOCM.7

The high C₂H₆ selectivity implies the efficient formation of 'CH₃ by the photogenerated holes of WO₃. When the concentration of the generated 'CH₃ is high, homocoupling should easily occur to produce C2H6. In contrast, other side reactions of 'CH₃ are promoted, thereby decreasing C₂H₆ selectivity at low CH4 concentrations.

The production rates of CO₂, CO, and C₂H₆ increased with the incident light intensity (Fig. 6). This indicated that the products were formed via the photoexcitation mechanism. The C₂H₆ selectivity gradually decreased from 57.4% to 49.1% when the irradiance intensity was changed from 3.6 to 14 mW cm⁻², implying that overoxidation is promoted when the concentration of holes is high at the semiconductor surface. Although the photocurrent fluctuated over time, which may have been affected by humidity, the WO3 photoanode repeatedly exhibited sufficient stability for several hours. We also did not confirm the degradation of the crystallinity of WO₃ or the structure of the ionomer coated on the photoanode surface, as shown in X-ray diffraction patterns (Fig. S2†) and Fourier transform infrared spectra (Fig. S3†).

PEC reaction mechanism

To further investigate the radical mechanism of the PEC process, we tested the PEC oxidation of C₂H₆.³⁴ Fig. 7 shows the time course of the C₂H₆ activation on the WO₃ photoanode. We detected n-butane as the product. The formation of *n*-butane suggests the occurrence of the

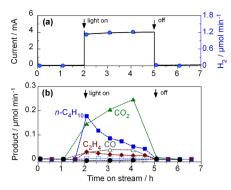


Fig. 7 PEC activation of C₂H₆ using WO₃ photoanode under visiblelight irradiation (6.8 mW cm⁻² at 453 nm) at 1.2 V; (a) the overall current and H₂ evolution rate on the cathode side, and (b) the rates of product formation on the photoanode side.

homocoupling of ethyl radicals (${}^{\cdot}C_2H_5 + {}^{\cdot}C_2H_5 \rightarrow CH_3-CH_2-$ CH₂-CH₃). We also detected the formation of ethylene, which could have been generated through intermolecular dehydrogenation ($C_2H_6 + 2 h^+ \rightarrow CH_2 = CH_2 + 2H^+$). The FE of *n*-butane was 4.4%, and its selectivity was 39.7% (C-basis), as shown in Table S4 in the ESI.†

To investigate the radical intermediates involved in the activation of CH4, we conducted electron paramagnetic resonance (EPR) experiments using 5,5-dimethyl-1-pyrroline-N-oxide (DMPO) as a spin-trapping agent. 35 Photoirradiation was performed for WO₃ powder dispersed in a 50 mM AgNO₃ aqueous solution with CH4 gas. The silver cation acted as an electron acceptor for the photoexcited WO3.36 We observed four-line EPR signals (g = 2.0056, $A_N = 1.49$ mT, $A_H = 1.49$ mT), which were consistent with the 'DMPO-OH spin adduct, in the WO₃ suspension after irradiation (Fig. 8). This implied that hydroxyl radical (OH) could form on the WO3 photoanode in the presence of water vapour. Therefore, 'OH would be the active species for CH4 activation in the PEM-PEC system. In contrast, we could not detect a signal corresponding to the 'DMPO-CH₃ spin adduct, even in the presence of acetic acid and dimethyl sulfoxide. This suggests that spin trapping of 'CH3 with DMPO is difficult in liquid water under our experimental conditions.

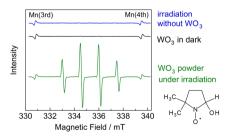


Fig. 8 EPR spectra of an aqueous solution of DMPO and AgNO₃ after 405 nm irradiation for 5 min without WO₃ powder, aging in the dark with WO₃ powder, and 405 nm irradiation for 5 min with WO₃ powder. The standard Mn^{2+} marker shows signals at g = 2.0337 (third line) and g = 1.9803 (fourth line).

We also attempted a photo-Kolbe reaction using WO₃ powder, 5 vol% acetic acid, and 50 mM AgNO₃. 33,36 The gaseous products obtained were CO2, CH4, and O2 (Fig. S4 in ESI†). A trace amount of methanol was also formed in the aqueous solution. However, C2H6 was not formed in the aqueous system, indicating the importance of the vapour-fed conditions in C₂H₆ production.

The advantage of the gas-fed type reactor was also revealed by the gas flow rate dependence of C₂H₆ formation (Fig. S5 in ESI†). The production rate of C₂H₆ was very low at a gas flow rate of 1 mL min⁻¹. We realised that gas diffusion plays an important role in C₂H₆ production in the PEM-PEC system because productivity increased at higher flow rates. The proposed reaction mechanism for the catalytic oxidative coupling of methane involves the coupling of 'CH3 in the gas phase to form C₂H₆.^{2,37} Similar to this mechanism, continuous flow facilitates the desorption of 'CH3 from the surface of the WO₃ photoanode and the formation of C₂H₆.

Zero-bias PEC oxidation of methane

The photocatalytic oxidation of atmospheric CH₄ to CO₂ is another attractive reaction because the greenhouse gas effect of CH₄ is over 30 times greater than that of CO₂. The complete oxidation of methane is an exergonic reaction (CH₄ $+ 2O_2 \rightarrow CO_2 + 2H_2O(g), \Delta G_{298K} = -801 \text{ kJ mol}^{-1}, ^{15,16} \text{ but its}$ high activation energy prevents the catalytic reaction at room temperature.

Fig. 9 shows the PEC oxidation of CH₄ in the PEM-PEC reactor using the WO3 photoanode under blue-light irradiation at 25 °C. CO2 formation by CH4 oxidation was confirmed without an external bias voltage. During the exergonic reaction, the oxygen reduction reaction (O₂ + 4H⁺ + $4e^{-}$ = $H_{2}O$, 1.23 V vs. SHE) was promoted over the Pt/ carbon catalyst in humidified air (Fig. 2a). The IPCE at zero bias was 2.5% at 453 nm, which was much higher than the quantum efficiency previously reported for photocatalytic systems.38,39

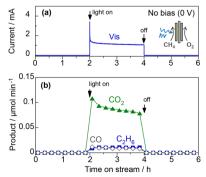


Fig. 9 PEC oxidation of CH₄ by the PEM-PEC reactor using the WO₃ photoanode and Pt/carbon catalyst: (a) the overall current at zero bias, and (b) the rate of products formation on the photoanode side under 453 nm light irradiation (6.8 mW cm⁻²).

Experimental

Preparation of photoanodes

Ti felt was used as the conductive substrate for the gasdiffusion photoanodes. The WO₃ electrode was prepared by dip coating with an aqueous solution of (NH₄)₆H₂W₁₂O₄₀ and polyethylene glycol; the electrode was then calcined at 923 K for 2 h.7,28,40 The TiO2 electrode was prepared by the anodization of Ti felt in ethylene glycol with 0.25 wt% NH₄F and 10 vol% H₂O at 50 V for 3 h.^{29,41,42} The anodized Ti felt was calcined at 823 K for 1 h to crystallize into anatase TiO2. The photoanodes were modified using a Nafion ionomer dispersion (Sigma-Aldrich).

PEM-PEC reaction

The PEC measurements were performed at 25 °C and 1 bar using an AMETEK VersaSTAT3 workstation. For the proposed all-solid-state cells, a Nafion N117 film (DuPont) was sandwiched between the photoanode and the cathode, which was composed of Pt/carbon (Tanaka Kikinzoku Kogyo) and Toray carbon paper (Fuel Cell Store). The photoanode side was supplied with 20 mL min⁻¹ of humidified CH₄/Ar or humidified CH₄ gas. The relative humidity was approximately 90% without liquid condensation. The cathode side was supplied with 20 mL min⁻¹ of humidified Ar gas. The geometric surface areas of the two electrodes were 25 cm², whereas the irradiation area of the photoanode was 16 cm². Photoirradiation was performed through a glass window using light-emitting diodes (LED). The peak wavelengths were 365 and 453 nm for the UV (Nitride Semiconductor) and blue LED (OptoSupply), respectively. The IPCE was calculated as follows:

$$IPCE = \frac{1240 j_{photo}}{\lambda I_0} \times 100\%$$

Here, $j_{\rm photo}$ is the photocurrent density, λ is the wavelength (nm), and I_0 is the intensity of incident light.

Product analysis

The gas products of the PEC reaction were analysed using gas chromatography (Shimadzu GC-8A and GC-2014). A thermal conductivity detector (TCD) equipped with a molecular sieve 5A column in an Ar carrier was used to quantify H2 and O2. A TCD with a Shincarbon ST column in an He carrier was used to quantify CO and CO2. A flame ionisation detector with a GS-CarbonPLOT was used to detect

The C₂H₆ selectivity in carbon basis was calculated using the below equation:

$$S_{\rm C_2H_6} = \frac{2r_{\rm C_2H_6}}{r_{\rm CO_2} + r_{\rm CO} + 2r_{\rm C_2H_6}} \times 100\%$$

Here, r_i is the production rate of each carbon-containing product determined by online GC and is referenced to the calibration curves from the standard gas sample. The corresponding FE values are calculated as follows:

$$FE = \frac{n_i F r_i}{j_{\text{photo}}} \times 100\%$$

Here, n_i is the number of electrons involved, and F is the Faradaic constant. The n_i values for C_2H_6 , O_2 , CO, and CO_2 are 2, 4, 6, and 8, respectively.

Characterization

X-ray diffraction patterns were recorded by a Rigaku SmartLab diffractometer using Cu Kα radiation. Fourier transform infrared spectroscopy was performed on a Shimadzu IR Affinity-1 spectrometer in the attenuated total reflection mode. Electron paramagnetic resonance (EPR) spectra were recorded using a JES-X310 spectrometer (JEOL, Japan) at room temperature. The sample suspension was taken out by a quartz capillary tube with the two ends sealed by sealing compound for the EPR measurement.

Conclusions

We studied the PEC activation of CH₄ over TiO₂ and WO₃ photoanodes in a gas-flow PEM-PEC system. We demonstrated that a WO₃ photoanode excited by visible light converts CH₄ into CO₂ and C₂H₆. At high CH₄ concentrations, the C₂H₆ selectivity was above 50% on a carbon basis. Moreover, we found that WO3 and visible light were more suitable than TiO₂ and UV light to form C₂H₆. When C₂H₆ was used as the reactant, n-butane was formed, suggesting a radical coupling mechanism. The WO3 photoanode showed an IPCE of 7.6% at 453 nm with an applied voltage of 1.2 V. The current efficiency of H2 was nearly 100% in the cathode compartment, demonstrating that the PEM-PEC system is useful for steam reforming of methane and dehydrogenative methane Surprisingly, visible-light induced CH₄ oxidation was also efficiently promoted in the PEM-PEC system using humidified air, even under zero bias.

Author contributions

Fumiaki Amano: conceptualisation, methodology, validation, visualisation, writing - review & editing, and supervision. Ayami Shintani: investigation visualisation, and writing original draft. Tatsuya Sakakura and Yoshiyuki Takatsuji: investigation. Tetsuya Haruyama: validation and resources.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Japan Science and Technology Agency (JST) PRESTO [grant number JPMJPR18T1] and the Japan Society for the Promotion of Science (JSPS) KAKENHI [Grant No. JP20H02525].

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