Light absorption and photocatalysis of flake-like titanate nanosheets chemically modified by organic ligands

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The application of titanate nanosheets chemically modified by organic ligands to a photocatalyst was examined. Titanate nanosheets have very wide band gap, because of quantum size effect. Ultraviolet light with very short wavelength is required for photocatalysis of titanate nanosheets. In order to circumvent this problem, titanate nanosheets were modified by organic ligands, and the charge transfer from the organic ligands to titanate nanosheets was utilized for photocatalysis. Titanate nanosheets were synthesized by bottom-up process in aqueous solution. Catechol, hydrogen peroxide (H₂O₂), and 2,5-dihydroxyterephthalic acid (DHTP) were used as an organic ligand. Upon adding organic ligands to titanate nanosheet sols, the ligands were adsorbed preferentially on the edge of nanosheets. The adsorption of ligands enabled the absorption of light with a long wavelength. In the case using catechol and H₂O₂, the charge transfer from the Highest Occupied Molecular Orbital (HOMO) level of ligands to the conduction band of nanosheets occurred by photo-irradiation. On the other hand, the adsorbed DHTP caused photo-sensitization, that is, the charge transfer from HOMO through Lowest Unoccupied Molecular Orbital (LUMO) to metallic Ag nanoparticles. The titanate nanosheets modified by H₂O₂ did not exhibit photocatalytic reactions, while in the case using DHTP, the formation of Ag nanoparticles by photocatalysis was observed. Probably, this difference was attributed to the rate of the recombination of electrons and holes formed by photo-irradiation, which was likely dependent on the mechanism of the charge transfer caused by photo-irradiation.

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1. Introduction

Two-dimensional materials have highly anisotropic shapes, which can provide interesting properties. Metalate nanosheets are one of two-dimensional materials, and have been synthesized by exfoliating layered metalates. For such exfoliation, the intercalation of bulky cations, such as N(CH₃)₄⁺ and N(C₄H₉)₄⁺, into the interlayer of layered metalates is useful. Conventionally, the intercalation by two-step ion-exchange has been conducted.¹⁻⁴ On the other hand, we reported the bottom-up synthesis of layered metalates with bulky interlayer cations in aqueous sols, which bring about the exfoliation of the layered metalates, resulting in the formation of metalate nanosheets.⁵⁻¹¹

The metalate nanosheets obtained by this synthetic method are so highly water-dispersible that the aqueous sols of the metalate nanosheets are transparent. So, we envisaged that the titanate nanosheets can be applied to the photocatalysis of reactions in aqueous solutions. However, the titanate nanosheets have very wide band gap, because of quantum size effect. The band gap of layered titanates becomes large by exfoliation.¹²,¹³ Moreover, the lateral size of titanate nanosheets synthesized by bottom-up process is smaller, compared to nanosheets synthesized by conventional method, and thereby leads to further wider band gap. Thus, the modification of titanate nanosheets is required for the absorption of light with a long wavelength. As such a modification, the adsorption of organic ligands is useful. As the absorption of light with a long wavelength, there are two mechanisms¹⁴⁻¹⁶ (Fig. 1): One is photosensitization, which has been utilized for dyesensitized solar cells. Photo-irradiation causes an electron to be excited from Highest Occupied Molecular Orbital (HOMO) level to Lowest Unoccupied Molecular Orbital (LUMO) of adsorbed organic ligand. A subsequent charge transfer occurs from the LUMO of ligand to the conduction band of metal oxides. The other is an interfacial charge transfer from the HOMO of adsorbed ligand to the conduction band to metal oxides, and is similar to ligand-to-metal charge transfer (LMCT) transition observed in metal complexes. This charge transfer is observed for the adsorption of catechol, salicylic acid, and their derivatives on

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The objectives of this study are to examine the adsorption of some organic ligands on titanate nanosheets, and the light absorption and photocatalysis of the resulting titanate nanosheets chemically modified by organic ligands.

2. Experimental procedure

2.1 Materials

Titanate nanosheets were synthesized as follows: Titanium iso-proxide \{\text{Ti(OCH(CH\text{3})\text{2})\text{4}, 20 mmol}\} and 25\% tetramethylammonium hydroxide [\text{N(CH\text{3})\text{4}OH (TMAOH), 10 mmol}] aqueous solution was mixed for 2 h. The mixture was diluted with distilled water to 40 mL. The thus-obtained sol was stirred for 2 h under the ambient condition, and then was heated at 80 °C for 1 day in a closed vessel for complete crystallization of titanate nanosheets. The titanate nanosheet sols had a Ti\(^{4+}\) concentration of 0.5 M and a TMAOH/Ti\(^{4+}\) molar ratio of 0.5.

Organic ligands were adsorbed on titanate nanosheets. Catechol [C\(_6\)H\(_4\)(OH)\(_2\)], hydrogen peroxide (H\(_2\)O\(_2\)), and 2,5-dihydroxyterephthalic acid [C\(_6\)H\(_2\)(OH)\(_2\)(COOH)\(_2\) (DHTP)] were used as an organic ligand (Fig. 2). Since the crystallinity of titanate nanosheets is decreased in acid or neutral sols and the organic ligands are weak acid, the organic ligands were neutralized by TMAOH at molar ratios of TMAOH/catechol = 1, TMAOH/H\(_2\)O\(_2\) = 2, and TMAOH/DHTP = 3. Then, the aqueous solutions (10 mL) were mixed with 0.5 mol-Ti\(^{4+}\) L\(^{-1}\) titanate nanosheet sols (5 mL). The molar ratio of organic ligands to Ti\(^{4+}\) was adjusted by changing the concentration of organic ligands in the mixture solutions of organic ligands and TMAOH.

The titanate nanosheet sols used for photocatalysis measurements were prepared in the same way. The molar ratios of organic ligands to Ti\(^{4+}\) in titanate nanosheets were fixed at H\(_2\)O\(_2\)/Ti\(^{4+}\) = 0.1 and DHTP/Ti\(^{4+}\) = 0.03. The photocatalytic activities of titanate nanosheets chemically modified by organic ligands were evaluated by the reduction of [Ag(NH\(_3\))\(_2\)]\(^{+}\) to metallic Ag. An aqueous solution of [Ag(NH\(_3\))\(_2\)]\(^{+}\) was prepared by mixing AgNO\(_3\) aqueous solution and 30\% NH\(_3\) aqueous solution at NH\(_3\)/Ag\(^{+}\) molar ratio of 4 or 6, and then was added to titanate nanosheet sols including organic ligands. The Ti\(^{4+}\) and Ag\(^{+}\) concentrations of the used sols were 0.5 M and 0.5 or 1.5 mM, respectively.

The above-mentioned sol (15 mL) was transferred to a quartz glass test tube. For photocatalysis measurements, light was irradiated to the sols for 1 or 2 h under N\(_2\) gas bubbling and agitation. The light from a super high pressure Hg lamp was used through water filter and ultraviolet (UV)-cut filter, which passes light with a wavelength longer than 340 nm.

![Fig. 1. Charge transfer from organic ligand to titanate nanosheets (a) like LMCT transition and (b) by photosensitization. (c) Spatial separation of oxidation and reduction sites of photocatalysis by charge transfer (a) and (b).](image)

![Fig. 2. Molecular structures of the used organic ligands. (a) catechol, (b) hydrogen peroxide, (c) 2,5-dihydroxyterephthalic acid.](image)
2.2 Measurements

Ultraviolet visible (UV–vis) measurement (Hitachi, U-4100 model) was conducted in a transmittance mode using a dual beam. Spectra were recorded in the wavelength range from 1500 to 200 nm at a rate of 300 nm min⁻¹ for the sol transferred in a quartz glass cell (10 × 10 × 45 mm³).

X-ray diffraction (XRD) measurements were performed on a Rigaku Ultima IV diffractometer with a monochromatic Cu Kα irradiation. XRD patterns were recorded at a scan rate of 2° min⁻¹ in the 2θ range of 2 to 70°. The samples were thin films fabricated by evaporating sols (200 µL) on a glass substrate (35 × 12 mm², Corning #1737) or powders prepared by evaporating sols in a rotary evaporator.

3. Results and discussion

3.1 Light absorption of titanate nanosheets modified by organic ligands

The light absorption of the titanate nanosheets modified by organic ligands is examined. Catechol, hydrogen peroxide, and DHTP were used (Fig. 2). First, the use of catechol as an organic ligand was investigated. Titanate nanosheet sols absorbed UV light with wavelength shorter than about 310 nm (Fig. 3). For aqueous solutions of catechol, absorption was observed at 275 nm. Upon adding TMAOH to catechol solution, the absorption around 320 nm also appeared due to the oxidation of catechol. Moreover, upon adding catechol aqueous solution to titanate nanosheet sols, the color of the sols was changed from colorless to brown or black [Fig. 3(a)]. The aqueous mixtures of catechol and titanate nanosheet sols provided absorption around 370 nm [Fig. 3(a)], which was longer than the wavelength of the absorption of catechol or titanate nanosheets. This new light absorption is probably attributed to the charge transfer from the HOMO level of the adsorbed catechol to the conduction band of titanate nanosheets [Fig. 1(a)]. The same phenomena is reported for the TiO₂ nanoparticles chemically modified by catechol and its derivatives.¹⁷⁻²²) Thus, the titanate nanosheets chemically modified by catechol absorbed a light with longer wavelength, compared to pristine titanate nanosheets.

The influence of the chemical modification by hydrogen peroxide on the light absorption was also investigated. Aqueous solution of hydrogen peroxide showed weak light absorption at wavelength shorter than 300 nm. However, upon adding hydrogen peroxide to titanate nanosheet sols, the sols became yellowish, and absorption around 350 nm appeared [Fig. 3(b)]. It is well known that the reaction of peroxide ion with Ti⁴⁺ species yields peroxotitanium complexes, which provide yellow or orange color.²³,²⁴) Probably, in this study, peroxide ion was adsorbed on titanate nanosheets in the same way as peroxotitanium complexes. The light absorption was attributed to the charge transfer from the HOMO level of adsorbed peroxide ion to the conduction band of titanate nanosheets [Fig. 1(a)], and had a longer wavelength than the absorption of pristine titanate nanosheets.

DHTP was also used as a ligand. Upon adding DHTP to titanate nanosheet sols, the sols became reddish. However, both of DHTP aqueous solution and the mixtures of DHTP and titanate nanosheet sols exhibited light absorption at 350 nm [Fig. 3(c)]. Likely, intramolecular light absorption occurred in the DHTP ligand adsorbed on titanate nanosheets [Fig. 1(b)], and causes the charge transfer from the HOMO level through the LUMO level of adsorbed DHTP to the conduction band of titanate nanosheets. However, it is hard to distinguish the adsorbed DHTP molecules from free DHTP. So, the change of the absorption of DHTP by the basicity of aqueous solutions was investigated. For DHTP aqueous solution, with increasing the basicity with the addition of TMAOH, the absorption at 350 nm faded away, and another absorption appeared at 310–330 nm [Fig. 4(a)], indicating the change in molecular structure of DHTP. On the other hand, for aqueous mixture sols of DHTP and titanate nanosheets, the absorption at 350 nm was present even after the addition of strong base TMAOH [Fig. 4(b)], though the absorbance at 350 nm was slightly decreased and the one at 320 nm increased. This indicated that the adsorption onto titanate nanosheets caused DHTP
to acquire a resistance to basicity, and confirmed the presence of DHTP adsorbed to titanate nanosheets, though a small amount of free DHTP molecules co-existed.

### 3.2 The amount of organic ligands adsorbed on titanate nanosheets and their adsorption sites

Next, the change in the amount of organic ligands adsorbed on titanate nanosheets with their added amount and their adsorption sites are examined. For the former, the absorbance of adsorbed organic ligands in UV–vis spectra was investigated. Moreover, for the latter, the basal spacing of layered titanates, which was formed by evaporating the mixture sols of titanate nanosheets and organic ligands on a glass substrate, was investigated. If organic ligands are adsorbed on the edge of titanate nanosheets, the adsorption would have no influence on the basal spacing of the layered titanates. If ligands are adsorbed on the surface of nanosheets, the basal spacing would be increased.

For catechol adsorption, at first, very large amount of catechol was added to titanate nanosheet sols, i.e. catechol/Ti$^{4+}$ = 2.0 and 4.0 in molar. In UV–vis spectra [Fig. 5(a)], the absorption of catechol adsorbed on Ti$^{4+}$ species was stronger than the one of titanate nanosheets, and the absorption of free catechol was also observed at 270 nm. In the XRD patterns of thin films fabricated by evaporating the sols on a substrate, no peaks of layered titanate was observed. The colloidal particles were collected by adding 2-propanol to the sols. Blackish powder was obtained. The powder could not be highly dispersed in water. Thus, these results indicate that the addition of a large amount of catechol to titanate nanosheet sols caused titanate nanosheets to be collapsed, resulting in the formation of amorphous Ti$^{4+}$ species containing catechol.

A small amount of catechol was added to titanate nanosheet sols at catechol/Ti$^{4+}$ = 0.1 to 0.5. In UV–vis spectra, the absorption of catechol adsorbed on Ti$^{4+}$ was observed between 350 and 390 nm [Fig. 5(b)]. With increasing the amount of catechol, the absorption of adsorbed catechol shifted to longer wavelength. Possibly, this absorption shift was due to the collapse of a very small amount of titanate nanosheets. In XRD patterns, only the peaks assigned to layered titanates appeared. The basal spacing of the layered titanates was 1.68 nm, and did not change with the amount of added catechol [Fig. 5(c)]; however, their intensities were steeply decreased at catechol/Ti$^{4+}$ > 0.2 [Fig. 5(d)]. These results indicate that when the

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![Fig. 4. Change of UV–vis spectra of (a) DHTP aqueous solutions and (b) aqueous mixture of titanate nanosheet and DHTP by the addition of base.](image)

![Fig. 5. UV–vis spectra of aqueous mixture of titanate nanosheets and catechol at catechol/Ti = (a) 2, 4, and (b) 0.1 to 0.5. (c) XRD patterns of the thin films fabricated by evaporating the sols. (d) Change in the intensity of the peak at d = 1.68 nm in (c) with catechol/Ti ratio.](image)
amount of added catechol was small, catechol was adsorbed preferentially on the edge of titanate nanosheets; however, excessive addition of catechol collapsed the structure of titanate nanosheets by catechol adsorption.

The adsorption of peroxide ion on titanate nanosheets was investigated. In UV–vis spectra, the absorption of peroxide ion adsorbed on titanate nanosheets, which was observed at 350 nm, became stronger with increasing the amount of added hydrogen peroxide [Fig. 6(a)], and then their strength was levelled off at a H₂O₂/Ti⁴⁺ molar ratio of about 0.4 [Fig. 6(b)]. Furthermore, in XRD patterns, only the peaks assigned to layered titanates was observed, and the basal spacing and peak intensity were unchanged with the amount of added hydrogen peroxide [Fig. 6(c)]. Thus, these results indicate that peroxide ions were adsorbed on the edge of titanate nanosheets by the reaction between the dangling bonds of nanosheet edge and peroxide ion, and excess peroxide ion did not affect the structure of titanate nanosheets.

For the adsorption of DHTP, when very large amount of DHTP was added to titanate nanosheet sols, the absorption at 330 nm was also observed. As mentioned above, free DHTP shows structural change in basic aqueous solutions. This absorption at 330 nm was attributed to the species formed by structural change of free DHTP, and overlapped with the absorption of DHTP adsorbed on titanate nanosheets, which appeared around 350 nm [Fig. 7(a)]. Thus, the change of the amount of adsorbed DHTP with the amount of added DHTP was not elucidated. Moreover, in XRD patterns of the thin films fabricated by evaporating the mixture sols, the basal spacing and peak intensity of layered titanate, which were formed by the stacking of titanate nanosheets, were unchanged by the addition of DHTP [Fig. 7(b)]. Thus, the added DHTP molecules were adsorbed on the edge of titanate nanosheets and did not affect the structure of titanate nanosheets; however, excess addition of DHTP led to the co-existence of the species formed by structural conversion of free DHTP.

3.3 Photocatalysis of titanate nanosheets chemically modified with organic ligands

Photocatalysis of titanate nanosheets modified by ligands was investigated by the reduction of [Ag(NH₃)₂]⁺ to metallic Ag nanoparticles. Since the reduction of dissolved oxygen to superoxide radical •O₂⁻ can be a competitive photocatalytic reduction reaction, photocatalysis was conducted under nitrogen gas bubbling. Moreover, since titanate nanosheet sols included 2-PrOH, which was formed by hydrolysis of Ti[OCH(CH₃)₂]₄ used as a Ti source, and were basic, the oxidation of 2-PrOH to acetone and of OH⁻ to hydroxy radical •OH can be photocatalytic oxidation reactions, other than the oxidative degradation of adsorbed organic ligands.

First, the photocatalysis of titanate nanosheets without organic ligands was examined. The photo-irradiation to the mixture of titanate nanosheet sols and [Ag(NH₃)₂]⁺, which had Ti⁴⁺, Ag⁺, and NH₃ concentrations of 0.5 M, 1.5 and 6 mM, respectively, was conducted for 1 h. Using a filter to cut UV light with a wavelength <340 nm, the sol remained colorless, while without the UV-cut filter, the color of sol became yellowish orange [Fig. 8(a)]. UV–vis spectra showed that the photo-irradiation led to the appearance of absorption at >400 nm, and the use of the UV-cut filter...
decreased the absorption strength [Fig. 8(a)]. Moreover, the colloidal particles in the sols irradiated for a prolonged period without a UV-cut filter were collected by evaporating the sols. The XRD pattern measured for the obtained powder exhibited the peaks assigned to Ag and layered titanates [Fig. 8(b)]. Thus, without the UV-cut filter, the photocatalysis of titanate nanosheets caused the reduction of [Ag(NH$_3$)$_2$]$^+\text{Ti}^{4+}$ to metallic Ag nanoparticles, which provided yellowish orange color, and the use of UV-cut filter inhibited the excitation from the valence band to the conduction band of titanate nanosheets.

Next, the photo-irradiation to the mixture of titanate nanosheet sols and [Ag(NH$_3$)$_2$]$^+$, which had Ti$^{4+}$, Ag$^+$, and NH$_3$ concentrations of 0.5 M, 0.5 and 3 mM, respectively, was conducted for 2 h with the UV-cut filter. The sols including peroxide ion or DHTP as a ligand were also used. They were added at DHTP/Ti$^{4+} = 0.03$ and H$_2$O$_2$/Ti$^{4+} = 0.1$. However, catechol was not used, because the addition of catechol easily formed Ti species other than titanate nanosheets. For titanate nanosheet sols without organic ligands, photo-irradiation did not change the color or UV-vis spectrum of the sols; though without a UV-cut filter, the absorbance was increased a little in the wavelength range of 350 to 400 nm, because of the formation of Ag nanoparticles [Fig. 9(a)].

The sols with H$_2$O$_2$ also remained intact by photo-irradiation. In UV-vis spectra, the absorption of the peroxide ion adsorbed on titanate nanosheets was not changed, and no absorption of Ag nanoparticles appeared [Fig. 9(b)]. Thus, the titanate nanosheets modified by peroxide ions did not exhibit photocatalytic activities. Likely, the recombination of the electrons in the conduction band of nanosheets and the holes in adsorbed peroxide ions was very fast.

For the sols containing DHTP, the color of the sols became from pale orange to reddish orange by photo-irradiation. The UV-vis spectra showed that the increase in absorbance was observed around 500 nm, which was due to the formation of Ag metal nanoparticles [Fig. 9(c)]. Thus, the titanate nanosheets modified by DHTP exhibited photocatalytic activities. Moreover, the absorption of adsorbed DHTP was decreased a little, and the absorption of the species formed by structural change of free DHTP was increased a little. Thus, the photo-irradiation desorbed DHTP molecules from the edge of titanate nanosheets; however, the reason why such a phenomenon occurred could not be elucidated.

Titanate nanosheets modified by DHTP acted as a photocatalyst, while the modification by peroxide ions did not lead to the photocatalytic activities. Likely, this difference is attributed to the rate of the recombination of the electrons in the conduction band of nanosheets and the holes in the adsorbed ligands. For titanate nanosheets modified by peroxide ions, the charge transfer by photo-irradiation occurs from the HOMO level of adsorbed peroxide ions to the conduction band of nanosheets. On the
other hand, for the modification by DHTP, the adsorbed DHTP acts as a photosensitizer, and the charge transfer from adsorbed ligand to nanosheets occurs via the LUMO level of adsorbed DHTP. Possibly, the mechanism of the charge transfer by photo-irradiation has large influence on the recombination rate.

The increase in absorbance by Ag metal nanoparticle formation by the photo-irradiation to titanate nanosheet sols without a UV-cut filter was similar to the one by the photo-irradiation to the mixture of titanate nanosheets and DHTP with a UV-cut filter, despite the fact that the absorption of more photons by the former occurred, compared to the latter. Likely, the spatial separation of photocatalytic oxidation and reduction sites increased photocatalytic activities.

It is known that the wavelength of plasmon absorption of silver nanoparticles is dependent on the particle size. The photo-irradiation to titanate nanosheet sols without a UV-cut filter [Fig. 8(a)] and to titanate nanosheets modified by DHTP with a UV-cut filter [Fig. 9(c)] yielded silver particles with a diameter of about 70 nm and about 90 nm, respectively. The synthetic conditions employed in this study provide titanate nanosheets with a lateral size of 10–50 nm. Based on the photocatalysis shown in Fig. 1(c), it is expected that the size of silver nanoparticles is smaller than the lateral size of titanate nanosheets. However, the obtained results were different from such a situation. We do not know the reason why the formed silver nanoparticles became large. Further modification may be required for the fabrication of nanocomposites of silver nanoparticles and titanate nanosheets.

4. Conclusions

The metalate nanosheets synthesized by bottom-up are highly water-dispersible. For utilizing this feature, the application of the titanate nanosheets synthesized by bottom-up process to the photocatalysis of reactions in aqueous solutions was envisaged. However, the band gap of titanate nanosheets is very wide, because of quantum size effect. Thereby, UV light with very short wavelength is required for photocatalysis. In this study, titanate nanosheets were chemically modified by organic ligands, and the charge transfer from the organic ligands to titanate nanosheets was utilized for photocatalysis, because some types of organic ligands enable the absorption of light with a long wavelength. In this study, catechol and H2O2 led to the charge transfer from the HOMO level of adsorbed ligands to the conduction band of nanosheets, while for DHTP, photosensitization occurred. In both cases, the adsorption of organic ligands on titanate nanosheets caused the coloration of the sols, resulting in the absorption of light with a long wavelength. Moreover, the organic ligands were adsorbed on the edge of titanate nanosheets by the dangling bonds. The titanate nanosheets had small lateral sizes, that is, a large ratio of edge length to surface area, so that they were useful for the adsorption of organic ligands. Additionally, the oxidation and reduction sites of photocatalysis would be spatially separated by the adsorption of ligands on the edge of nanosheets. Furthermore, the photocatalysis of titanate nanosheets chemically modified by ligands was investigated by utilizing the reduction of [Ag(NH3)2]⁺ to metallic Ag nanoparticles. The titanate nanosheets modified with DHTP exhibited photocatalytic activities, while photocatalytic reactions did not occur for the nanosheets with peroxide ions. Probably, the photocatalytic activities are dependent on recombination rate, which likely has a relation to the mechanism of charge transfer.

The nanocomposites of titanate nanosheets and Ag nanoparticles are prepared as a sol by the photocatalysis employed in this study. There is possibility that such a sol
can be used for the fabrication of thin films useful for the application to surface enhanced Raman scattering; though further modification is required. Thus, the combination of photocatalysis in this study and the sol–gel method would possibly lead to the fabrication of interesting nanomaterials.

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References
1) T. Sasaki, M. Watanabe, H. Hashizume, H. Yamada and H. Nakagawa, J. Am. Chem. Soc., 118, 8329–8335 (1996).
2) T. Sasaki, M. Watanabe, H. Hashizume, H. Yamada and H. Nakagawa, Chem. Commun., 229–230 (1996).
3) M. Osada and T. Sasaki, Adv. Mater., 24, 210–228 (2012).
4) R. Ma and T. Sasaki, Adv. Mater., 22, 5082–5104 (2010).
5) T. Ohya, A. Nakayama, T. Ban, Y. Ohya and Y. Takahashi, Chem. Mater., 14, 3082–3089 (2002).
6) T. Ban, S. Yoshikawa and Y. Ohya, J. Colloid Interf. Sci., 364, 85–91 (2011).
7) T. Ban, S. Yoshikawa and Y. Ohya, CrystEngComm, 14, 7709–7714 (2012).
8) T. Ban, T. Ito and Y. Ohya, Inorg. Chem., 52, 10520–10524 (2013).
9) T. Ban, S. Iriyama and Y. Ohya, Adv. Powder Technol., 29, 537–542 (2018).
10) T. Ban, T. Wakita, R. Yokoyama, T. Miyake and Y. Ohya, CrystEngComm, 20, 3559–3568 (2018).
11) T. Ban, T. Kaiden and Y. Ohya, Cryst. Growth Des., 19, 6903–6910 (2019).
12) M. Honda, Y. Oaki and H. Imai, Phys. Chem. Chem. Phys., 17, 32498–32504 (2015).
13) N. Sakai, Y. Ebina, K. Takada and T. Sasaki, J. Am. Chem. Soc., 126, 5851–5858 (2004).
14) J. Fujisawa, Phys. Chem. Chem. Phys., 17, 12228–12237 (2015).
15) T. Eda, J. Fujisawa and M. Hanaya, J. Phys. Chem. C, 122, 16216–16220 (2018).
16) E. L. Tae, S. H. Lee, J. K. Lee, S. S. Yoo, E. J. Kang and K. B. Yoon, J. Phys. Chem. B, 109, 22513–22522 (2005).
17) T. Rajh, L. X. Chen, K. Lukas, T. Liu, M. C. Thurmaner and D. M. Tiede, J. Phys. Chem. B, 106, 10543–10552 (2002).
18) J. Fujisawa, R. Muroga and M. Hanaya, Phys. Chem. Chem. Phys., 17, 29867–29873 (2015).
19) S. Manzhos, R. Jono, K. Yamashita, J. Fujisawa, M. Nagata and H. Segawa, J. Phys. Chem. C, 115, 21487–21493 (2011).
20) J. Fujisawa and M. Hanaya, Chem. Phys. Lett., 653, 11–16 (2016).
21) M. Fukui, A. Tanaka, K. Hashimoto and H. Kominami, Chem. Commun., 53, 4215–4218 (2017).
22) W.-X. Mao, X.-J. Lin, W. Zhang, Z.-X. Chi, R.-W. Lyu, A.-M. Cao and L.-J. Wan, Chem. Commun., 52, 7122–7125 (2016).
23) M. Kobayashi, M. Osada, H. Kato and M. Kakihana, Polym. J., 47, 78–83 (2015).
24) M. Kakihana, M. Kobayashi, K. Tomita and V. Petrykin, Bull. Chem. Soc. Jpn., 83, 1285–1308 (2010).