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The introduction of a base component to porous organic salts and their CO₂ storage capability[†]

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Porous organic salts (POSs) are constructed by charge-assisted hydrogen bonding between amino and sulfonic groups, and can be used to design a variety of porous structures based on molecular design. In particular, triphenylmethylamine (TPMA) and aromatic sulfonic acids form robust POSs with a rigid diamond structure (*d*-POSs). In this study, by replacing one of the three phenyl rings of TPMA with a pyrimidine ring, we succeeded in constructing a *d*-POS with high porosity (43.8%) and with a base component (pyrimidine) on the void surface. In addition, the weak basicity of the pyrimidine did not interfere with the formation of *d*-POSs. This *d*-POS adsorbed CO₂ over the primary air components (N₂ and O₂) and also exhibited CO₂ storage capability: It retained CO₂ at a relatively low pressure of $P_e/P_0 = 0.05$, and readily desorbed CO₂ below $P_e/P_0 = 0.05$.

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Introduction

Based on molecular design, the pore size, morphology, and function of porous materials fabricated from organic molecules can be precisely and easily controlled. Therefore, these materials have been extensively investigated for gas separation applications.¹⁻³ Typical examples of extremely designable porous organic materials are metal-organic frameworks (MOFs), in which organic linkers and metal elements are connected by coordination bonds,^{2,4-6} and covalent-organic frameworks (COFs), in which organic molecules are linked by covalent bonds.7-10 However, the fabrication of robust porous structures such as MOFs and COFs usually requires harsh and/or complicated synthesis routes (e.g., microwave, voltage application, high pressure, and high temperature), and/or the use of metal elements obtained from limited resources. On the other hand, porous materials fabricated with non-covalent bonds are prepared by simple recrystallization under ambient conditions.11,12 In particular, all-organic porous materials constructed by



We previously reported that ammonium sulfonate salts, composed of bulky TPMA and aromatic sulfonic acids, such as tetrahedral tetrasulfonic acid (MTBPS), form diamondoid porous organic salts (d-POSs) (Fig. 1a).¹⁵⁻²⁰ In detail, four TPMA molecules and four sulfonic acid molecules form a [4 + 4] supramolecular cluster (Fig. 1a, center) by selfassembly via rigid charge-assisted hydrogen bonding. Subsequently, these clusters are self-assembled to form the diamond network, and the interpenetration of some of the diamond networks hierarchically results in the formation of d-POSs (Fig. 1a, right).¹⁵ The diamond network is composed of sulfonic acid molecules and the amino groups in TPMA; however, it does not include the triphenylmethyl group in TPMA. The bulky triphenylmethyl group suppresses the number of interpenetrations of the diamond network, and therefore d-POSs generally possess a relatively higher porosity than organic porous materials that contain complete amine structures.²¹ Furthermore, we previously found that the phenyl rings of TPMA were exposed on the void surface of *d*-POSs, and the introduction of halogen-

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Fig. 1 Formation of diamondoid porous organic salts (*d*-POSs) using tetrahedral tetrasulfonic acid (MTBPS) and triphenylmethylamine derivatives (TPMA or DPPMA). (a) Schematic images of diamond network formation from MTBPS and TPMA by charge-assisted hydrogen bonding, and of the porous structures hierarchically constructed by the interpenetration of two diamond networks. (b) Schematic image of the construction and characterization of the porous and void structures of TPMA/MTBPS and DPPMA/MTBPS.

substituents such as fluorine (F), chlorine (Cl), bromine (Br), and iodine (I) into the *para*-positions of the phenyl rings of **TPMA** enabled *d*-**POSs** to have a variety of void structures and environments. In addition, we demonstrated that their gas adsorption properties were drastically changed depending on their void structures and environments.²⁰

In this study, we found that not only the para-positions but also meta-positions of the phenyl rings of TPMA were exposed on the void surface. Therefore, for introducing the base component into the void surface of the d-POSs, we focused on pyrimidine, which has more base components (e.g., lone pair of nitrogen), and is a weaker base than primary amines. The diphenyl(pyrimidine-5-yl)methylamine (DPPMA) is synthesized by replacing one of the three phenyl rings of TPMA with a pyrimidine ring, where two nitrogen atoms are substituted at the meta-positions of the phenyl ring.²² A facile recrystallization method is used to combine DPPMA and MTBPS for the fabrication of a d-POS (DPPMA/ MTBPS) with two nitrogen atoms, with their lone pairs exposed on the void surface. In the crystal structure of DPPMA/MTBPS, the base component of the pyrimidine rings (lone pairs of the nitrogen atoms) do not interfere with the charge-assisted hydrogen bonding between amino and sulfonic groups, and therefore DPPMA/MTBPS forms a diamond network identical to that of TPMA/MTBPS. DPPMA/ MTBPS adsorbed CO_2 over the primary air components (N₂

and O₂). Moreover, the adsorbed CO₂ (49.9 mL (STP)/g at $P_e/P_0 = 1$) was stabilized in the void *via* interactions with the pyrimidine ring.^{23,24} DPPMA/MTBPS retained CO₂ down to a reasonably low pressure of $P_e/P_0 = 0.05$, and subsequently CO₂ was desorbed by decreasing the pressure to below $P_e/P_0 = 0.05$.

Experimental section

Preparation of organic salts composed of DPPMA and MTBPS

DPPMA (5 eq) and **MTBPS** (1 eq) were separately dissolved in methanol, and then mixed. After solvent evaporation, the residue was washed with diethyl ether, and the organic salts were obtained as a pale-yellow powder.

Preparation of the single-crystal of DPPMA/MTBPS.

The organic salt (2.0 mg) was recrystallized with benzonitrile (200 μ L) in *N*,*N*-dimethylacetamide (400 μ L) by gradually evaporating the solvent at 70 °C. The single crystals of **DPPMA/MTBPS** were obtained as colorless prisms. By repeating this process, a sufficient amount of **DPPMA/MTBPS** was collected for the gas adsorption experiments.

Results and discussion

An organic salt with an exact **TPMA: MTBPS** molecular ratio of 4:1 was produced by simply mixing **TPMA** and **MTBPS** in

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a polar organic solvent. Subsequently, the facile recrystallization of the organic salt in N,Ndimethylformamide with 1,2,4-trichlorobenzene (a template molecule that facilitates the formation of porous structures) resulted in TPMA/MTBPS§ (Fig. 1b, center and S1;† for details of the preparation processes, please see the experimental section). MTBPS has a tetrahedral structure, which is consistent with the diamondoid structure, and therefore TPMA/MTBPS was selectively formed without crystal polymorphism. The single-crystal structure of TPMA/MTBPS indicated that the two diamond networks are deeply interlocked in opposite directions, forming а thermodynamically stable structure (Fig. 1b, center).

Additionally, the PLATON/VOID routine calculation showed that **TPMA/MTBPS** has a high porosity of 40.7%. After the evacuation of a template molecule using the supercritical fluid carbon dioxide process (**SCFCO**₂),²⁶ **TPMA/ MTBPS** (Fig. S2a†) adsorbed CO₂ over the primary air components, such as N₂ and O₂ (Fig. S2b†). This was ascribed to the quadrupole–quadrupole interactions^{27,28} between CO₂ (with a strong quadrupole moment)²⁹ and the phenyl rings exposed on the void surface, and the smaller kinetic diameter of CO₂ (3.30 Å³⁰) than those of N₂ (3.64 Å³⁰) and O₂ (3.46 Å³⁰).

This study aimed to introduce the base component into the void surface of the d-POSs. In TPMA/MTBPS, the para-positions and meta-positions of the phenyl rings of TPMA are exposed on the void surface (Fig. 1b, void surface). Thus, we hypothesized that the incorporation or substitution of base functional groups at the para-positions or meta-positions of phenyl rings would introduce the base component into the void surface. Therefore, a TPMA derivative (DPPMA) was synthesized by replacing one of the phenyl rings of TPMA with a pyrimidine ring, where two nitrogen atoms and their lone pairs were substituted at the meta-positions of the phenyl ring. Nitrogen atoms and their lone pairs on the pyrimidine ring are known showing weak basicity.^{23,24} Subsequently, by combining DPPMA with MTBPS, DPPMA/MTBPS similar to TPMA/MTBPS (Fig. 1b, right and S3;† for details of the synthesis processes, please see the experimental section) was successfully prepared. Notably, the single-crystal X-ray structure analysis revealed that the base component (lone pairs of the nitrogen atoms) of the pyrimidine ring do not interfere with the charge-assisted hydrogen bonding between the amino and sulfonic groups. DPPMA/MTBPS forms a diamond network identical to that of TPMA/MTBPS (Fig. 1b, right and S4[†]). This indicates that pyrimidine is less likely to interact with the sulfonic acid than with the amino group of TPMA because of the weaker basicity of pyrimidine than primary amines.^{31,32} The porosity of DPPMA/MTBPS is exhibited a slightly higher porosity of 43.8% compared to that of TPMA/MTBPS (Table S2⁺),

because the replacement of the phenyl ring with a pyrimidine ring increases the void volume owing to the loss of the hydrogen atoms. Additionally, the porosity of DPPMA/MTBPS is the highest in the other reported *d*-POSs^{15,16,18,20} and organic porous structures with diamond networks (Table S3[†]).³³⁻³⁶ Thermogravimetric analysis (TGA) data (Fig. S5[†]) and the number of electrons found in the masking routine revealed that the crystals of DPPMA/MTBPS immediately following formation via crystallization included six N,Ndimethylacetamide molecules and three benzonitrile molecules per one MTBPS molecule and four DPPMA molecules, which were equivalent to 29.5% of total weight. Furthermore, as designed, the nitrogen atoms and their lone pairs on the pyrimidine rings are exposed on the void surface of DPPMA/MTBPS (Fig. 1b, right), and, per unit cell, 48 nitrogen atoms are exposed on the void surface. It is noteworthy that changing the meta-positions of the phenyl rings of TPMA successfully tuned the void environment, while maintaining the void shape of TPMA/MTBPS. Variable temperature powder X-ray diffraction (VT-PXRD) (Fig. S6†) of DPPMA/MTBPS revealed that the porous structure of DPPMA/ MTBPS was maintained up to approximately 100 °C. Furthermore, DPPMA/MTBPS shows high stability for nonpolar solvents such as diethyl ether and benzene. However, the crystallinity of DPPMA/MTBPS was decreased after soaking in the polar solvents, water, and acidic/basic aqueous solutions (Fig. S7[†]), presumably because of the partial dissolution of DPPMA/MTBPS. Similar to TPMA/ MTBPS, the template molecule in DPPMA/MTBPS was evacuated by SCFCO₂ while maintaining the porous structure (Fig. 2a and S8[†]).

The gas adsorption properties of DPPMA/MTBPS, after the evacuation of the template molecule, for CO2, N2, and O2 were evaluated. The PXRD patterns of TPMA/MTBPS and DPPMA/MTBPS did not change before and after the sorption experiments (Fig. S9[†]). Therefore, these POSs maintained their porous structures after the sorption experiments, and their gas adsorption behavior is highly reproducible even after the second time. DPPMA/MTBPS adsorbed 49.9 mL (STP)/g of CO₂ at $P_e/P_0 = 1.0$, 2.87 mL (STP)/g of N₂ at $P_e/P_0 =$ 0.97, and 1.07 mL (STP)/g of O₂ at $P_e/P_0 = 0.99$ (Fig. 2b). DPPMA/MTBPS exhibited the same selective adsorption behavior for CO₂ as that of TPMA/MTBPS. In addition, the CO2 adsorption isotherm revealed that DPPMA/MTBPS had a CO_2 -BET surface area of 192 m² g⁻¹ (Table S2⁺) and an average pore size of 10.2 Å (Fig. S10[†]). On the other hand, DPPMA/MTBPS did not adsorb N₂ and O₂, therefore the pore size distribution analysis based on the N2 and O2 adsorption isotherms were unable to be performed. The large hysteresis observed in the CO2 adsorption/desorption behavior of DPPMA/MTBPS demonstrates that CO₂ is retained on the void surface by interactions with the pyrimidine rings. DPPMA/MTBPS retains the CO₂ adsorbed at $P_e/P_0 = 1.0$ when the pressure is decreased to $P_e/P_0 = 0.05$ (Fig. 2b and S11⁺), whereas TPMA/MTBPS releases approximately 50% of the adsorbed CO_2 (Fig. S2b^{\dagger}). Furthermore, the strength of

[§] The crystal structure of **TPMA/MTBPS** has been reported in our previous work.²⁰ Deposition Number 2160329 (**DPPMA/MTBPS**) contain the supplementary crystallographic data for this paper.



Fig. 2 Characterization of the diamondoid porous organic salts (**DPPMA/MTBPS**). (a) Powder X-ray diffraction (**PXRD**) patterns of **DPPMA/MTBPS**, simulation (black), immediately following formation *via* crystallization (blue), after conducting the supercritical fluid carbon dioxide (**SCFCO**₂) process for 5 h (red). (b) Gas adsorption/desorption isotherms of **DPPMA/MTBPS** in the cases of nitrogen (N₂, 77 K), oxygen (O₂, 77 K), and carbon dioxide (CO₂, 195 K). P_e denotes the pressure at gas adsorption and P_0 is the condensation pressure of the adsorbate at the measurement temperature. Green line is $P_e/P_0 = 0.05$. The amount of CO₂ adsorption of **DPPMA/MTBPS** reaches a maximum value at $P_e/P_0 = 0.2$ in the desorption isotherm which is common in porous structures with complicated micropores such as **MOFs** because of the extremely slow diffusion rate of the adsorbent in their void.²⁵

interactions between pyrimidine or phenyl rings and CO₂ molecules was evaluated by Fourier transform infrared (FT-IR) spectroscopy measurements under CO₂ atmospheres. However, as shown in Fig. S12,† no significant differences were found between the spectra measured under vacuum and CO₂ atmospheres. This means that these interactions are weaker than the general chemical interactions. Therefore, although DPPMA/MTBPS retains CO₂ up to $P_e/P_0 = 0.05$, it can readily desorb the adsorbed CO₂ below $P_e/P_0 = 0.05$. The ability to retain CO₂ over a wide pressure range (0.05–1.0 atm) may play a very important role in CO₂ storage and utilization processes.³⁷

Conclusions

In this study, DPPMA, where two nitrogen atoms and their lone pairs are substituted at the meta-positions of the phenyl ring, and MTBPS were combined to form d-POSs. The pyrimidine ring did not interfere with the charge-assisted hydrogen bonding between the sulfonic and primary amino groups, and therefore DPPMA/MTBPS formed the same crystal structure as that of TPMA/MTBPS. Furthermore, as designed, the nitrogen atoms and their lone pairs on the pyrimidine rings were exposed on the void surface of DPPMA/MTBPS, and the base components were successfully introduced into the void surface while maintaining the void shape of TPMA/MTBPS. DPPMA/MTBPS adsorbed CO2 over the primary air components (N_2 and O_2), which was ascribed to strong quadrupole-quadrupole interactions with the phenyl rings on the void surface. DPPMA/MTBPS retained the adsorbed CO₂ in the void down to a reasonably low pressure of $P_e/P_0 = 0.05$ (originally adsorbed at $P_e/P_0 = 1.0$), which was attributed to interactions between the pyrimidine rings and

CO₂. Moreover, when the pressure was decreased to below $P_e/P_0 = 0.05$, **DPPMA/MTBPS** readily desorbed the adsorbed CO₂. Therefore, **DPPMA/MTBPS** captured and retained CO₂ even at a relatively low CO₂ pressure of 0.08–0.13 atm, which is comparable to that of a waste incinerator,³⁸ or 0.05 atm, which is comparable to that of a natural gas combined cycle power station.³⁹ Therefore, the introduction of a functional component (even a base component) into the benzene rings of **TPMA** enables the void environment and the functionalities of **POSs** to be precisely designed.

Author contributions

Takahiro Ami and Kouki Oka contributed equally to this work. Takahiro Ami: conceptualization, methodology, formal analysis, data curation, investigation, and writing - original draft. Kouki Oka: conceptualization, methodology, formal analysis, data curation, project administration, validation, supervision, investigation, and writing - original draft. Keiho Tsuchiya: investigation. Wataru Kosaka: investigation and writing - review & editing. Hitoshi Miyasaka: writing - review Norimitsu Tohnai: conceptualization, & editing. methodology, data curation, project administration, validation, supervision, investigation, writing - review & editing, funding acquisition, and resources.

Conflicts of interest

The authors declare no conflict of interest.

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