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Proton-conductive coordination polymer glass for solid-state anhydrous proton batteries†

Nattapol Ma,^a Soracha Kosasang,^b Atsushi Yoshida^a and Satoshi Horike^{a,c,d,e}

Designing solid-state electrolytes for proton batteries at moderate temperatures is challenging as most solid-state proton conductors suffer from poor moldability and thermal stability. Crystal–glass transformation of coordination polymers (CPs) and metal–organic frameworks (MOFs) *via* melt-quenching offers diverse accessibility to unique properties as well as processing abilities. Here, we synthesized a glassy-state CP, [Zn₃(H₂PO₄)₆(H₂O)₃](1,2,3-benzotriazole), that exhibited a low melting temperature (114 °C) and a high anhydrous single-ion proton conductivity (8.0 × 10^{−3} S cm^{−1} at 120 °C). Converting crystalline CPs to their glassy-state counterparts *via* melt-quenching not only initiated an isotropic disordered domain that enhanced H⁺ dynamics, but also generated an immersive interface that was beneficial for solid electrolyte applications. Finally, we demonstrated the first example of a rechargeable all-solid-state H⁺ battery utilizing the new glassy-state CP, which exhibited a wide operating-temperature range of 25 to 110 °C.

Introduction

The proton (H⁺) has a diameter of 0.84 fm and is easily localized in the solid state.¹ Fast-moving protons in solids are difficult to achieve, whereas solid-state H⁺ conductors are widely used in various electrochemical applications, including fuel cells, electrochemical catalysis, and sensors.² Proton batteries are a new class of secondary batteries employing protons instead of metal ions as charge carriers.^{3,4} They consist of faradaic electrodes and acidic electrolytes. Since the H⁺ charge radius is significantly smaller than that of other ions, faster ion migration and negligible volume changes upon H⁺ insertion/desertion are expected. Additionally, replacing high-cost Li⁺ with cheaper and

more abundant H⁺ provides a promising platform for environmentally benign and intrinsically safe energy storage.^{5–7} Redox-active organic molecules, such as quinone-functionalized conductive polymers,^{4,8} and metal oxides, including MoO₃, WO₃, and H_xIrO₄, are available as H⁺ electrodes.^{9–11} Though proton batteries show a smaller specific capacity with a limited number of applications, as compared to their metallic counterparts, diffusion-free charge transport *via* the Grotthuss mechanism in a defective, Prussian blue analog establishes a high-rate capability (380 A g^{−1}) and extends cycling stability to over 0.5 million charge–discharge cycles, which is a unique advantage of aqueous proton batteries.^{6,12,13} In spite of various choices of electrodes, electrolytes are mostly limited to aqueous H₂SO₄ or H₃PO₄, which dictates the operating-temperature window and selection of usable electrodes.^{8,13–15}

Safely extending the operating-temperature window to ~100 °C is essential for H⁺ batteries to tolerate internal/external heat generation so that they can be used in various high-temperature applications, such as rescue/inspection robots, space exploration, and measure-while-drilling (MWD) equipment in the oil and gas industries.¹⁶ As employing a conventional aqueous electrolyte is not possible at these high temperatures, solid-state H⁺ batteries with anhydrous solid electrolytes would be more suitable. There are no reports of solid-state H⁺ batteries working near or above 100 °C due to the difficulties in achieving high anhydrous H⁺ conductivity, high-temperature stability, and moldability required for H⁺ conductors.¹⁷ Apart from achieving a high H⁺ conductivity value (near 10^{−2} S cm^{−1}), high thermal/chemical stability, processing ability, and ion selectivity are also needed to expand the practicality of solid-state electrolytes. Single-ion conductivity in

^aDepartment of Synthetic Chemistry and Biological Chemistry, Graduate School of Engineering, Kyoto University, Katsura, Nishikyo-ku, Kyoto 615-8510, Japan. E-mail: horike@icems.kyoto-u.ac.jp

^bDepartment of Chemical and Biomolecular Engineering, School of Energy Science and Engineering, Vidyasirimedhi Institute of Science and Technology, Rayong, 21210, Thailand

^cAIST-Kyoto University Chemical Energy Materials Open Innovation Laboratory (ChEM-OIL), National Institute of Advanced Industrial Science and Technology (AIST), Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan

^dInstitute for Integrated Cell-Material Sciences, Institute for Advanced Study, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan

^eDepartment of Materials Science and Engineering, School of Molecular Science and Engineering, Vidyasirimedhi Institute of Science and Technology, Rayong, 21210, Thailand

† Electronic supplementary information (ESI) available: Experimental details, PXRD, solid PXRD, ³¹P MAS NMR, TG, and FTIR results, Nyquist plots, long-term conductivity measurements, transport number measurements, cross-sectional SEM images, and a solid state H⁺ battery. CCDC 2044808. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d1sc00392e



solid-state electrolytes is a core factor that promotes charge-transport efficiency and prevents anion polarization.^{18,19} Discontinuities along the electrode–electrolyte interfaces and grain boundaries are primary bottlenecks for efficient utilization of solid electrolytes.^{17,20,21} H⁺ conductivity at the grain boundary of most crystalline compounds requires a higher migration activation energy than that required by H⁺ conductivity through the bulk crystal (grain boundaries contribute up to 40–50% of the overall resistance for Li⁺ conductors).^{22–25}

Coordination polymers (CPs) and metal–organic frameworks (MOFs) exhibiting high H⁺ conductivity over a wide temperature regime (~200 °C) represent a new class of solid-state H⁺ conductors.^{26–29} Despite their remarkable H⁺ conductivity, their crystalline nature hinders their processing ability, thus limiting their practicality.³⁰ The glassy state of CP/MOFs is a strong platform to tackle these issues, and there have been increasing numbers of glassy-state CPs recently made from crystalline-state CPs.^{31–34} Some of these glassy-state CPs show anhydrous H⁺ conductivity superior to that of their crystalline counterparts by several orders of magnitude.^{35,36} Moreover, the vitrifying/melting behavior provides these CPs with processing capabilities and forms a grain-boundary free monolith and a flawless heterogeneous interface.^{31–34,37–41}

To address this issue, we have developed a new H⁺-conductive CP glass suitable for high-temperature anhydrous solid-state H⁺ batteries. By optimizing the pK_a value of the component with 1,2,3-benzotriazole (BTA, pK_a 1.6) and the extended hydrogen-bonding network in Zn²⁺-based CPs, the material demonstrated high anhydrous H⁺ conductivity (8.0 × 10^{−3} S cm^{−1} at 120 °C), relatively low melting point (114 °C), and mechanical softness (42.8 Pa s at 120 °C), which are suitable for electrolytes. The structure and properties were characterized by single-crystal X-ray diffraction (SC-XRD), thermal gravimetric analysis (TGA), differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA), impedance spectroscopy, electromotive force measurements, and solid-state NMR. We also demonstrated a full-cell evaluation of the anhydrous solid-state H⁺ batteries at 25, 100, and 110 °C.

Results and discussion

Crystal structure of [Zn₃(H₂PO₄)₆(H₂O)₃](BTA) (**1a**)

Zinc oxide, phosphoric acid, and BTA were subjected to mechanical milling to form the CP (**1a**) as a white crystalline powder. SC-XRD analysis of **1a** provided its chemical formula, [Zn₃(H₂PO₄)₆(H₂O)₃](BTA), and it was found to exist as a one-dimensional (1D) chain along the *a*-axis (Fig. 1). Three crystallographically independent octahedral Zn²⁺ ions were identified, each with six bridging H₂PO₄[−] anions and one water molecule coordinated to them (Fig. 1A). BTA was stacked in a 1D fashion along the *a*-axis and surrounded by six chains of ZnO₆ octahedra, which orderly arranged in the *bc* plane due to hydrogen-bonding interactions (Fig. 1B and C). Furthermore, **1a** is an isostructure of previously reported [Zn₃(H₂PO₄)₆(H₂O)₃](benzimidazole),³⁸ and it is expected that the dynamics of the phosphates bridging the Zn²⁺ ions (through a single

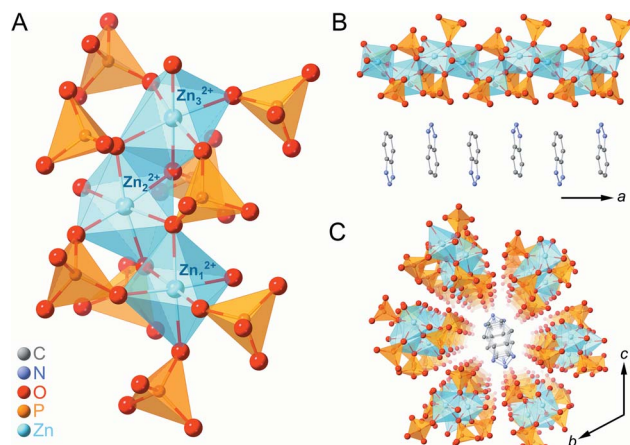


Fig. 1 (A) Local coordination geometry in **1a**. (B) Crystal structure of the one-dimensional (1D) chain along the *a*-axis. (C) Packing structure of **1a** on the *bc*-plane. Zn, P, O, C, and N atoms are represented by light blue, orange, red, grey, and blue spheres, respectively. H atoms are omitted for clarity.

bridging oxygen atom (μ_2) and the non-coordinating BTA could facilitate an anhydrous H⁺ migration.^{2,38,42,43}

The gram-scale synthesis of **1a** was feasible *via* mechanical milling for 1 h followed by vacuum drying for 3.5 h to remove excess water molecules. Powder X-ray diffraction (PXRD) of **1a** (Fig. S1†) demonstrated a pattern identical to the simulated SC-XRD pattern. The absence of residual free phosphoric acid in **1a** was confirmed using both inductively coupled plasma emission spectroscopy (ICP-ES) and ³¹P magic-angle spinning (MAS) solid-state NMR (Fig. S2†).⁴⁴ A P to Zn ratio (1 : 1.97) slightly lower than the theoretical ratio (1 : 2) suggested the presence of a small amount of structural defects. All peaks in ³¹P NMR were located in the range of orthophosphate, suggesting that no condensation occurs during the mechanical synthesis.^{45–47} TGA of **1a** showed a gradual weight loss due to the release of coordinated water at 100 °C (Fig. S4†). The total weight loss of dehydrated **1a** is equivalent to the release of three coordinated water molecules (5.7 wt%). This dehydrated state is henceforth denoted as **1**. A reversible structural change between **1a** and **1** upon water adsorption and desorption was observed by PXRD (Fig. S5†).^{48–50} The release of each water molecule from the octahedral (*O_h*) coordination sphere caused the 1D chain structure to deform around the Zn²⁺ ion. Under ambient air, **1** converted to **1a** by capturing atmospheric moisture.³⁸

Crystal melting and glass formation

Differential thermal analysis of **1a** by TGA (Fig. S4†) showed two endothermic peaks due to the release of coordinated water and crystal-to-liquid transformation and only the latter peak was observed in **1**. DSC of **1** (Fig. 2A) showed an endothermic peak with an onset melting point (*T_m*) of 114 °C. Two minor endothermic peaks before that of the *T_m* were assigned to the dehydration of adsorbed water during the measurement setup.³³ The *T_m* of **1** was 50 °C lower than that of the isostructure, [Zn₃(H₂PO₄)₆(H₂O)₃](benzimidazole), as BTA exhibits





Fig. 2 (A) First- (blue) and second-cycle (red) DSC profiles of **1** from -10 to 140 °C (begin with a heating step from 30 °C). The inset shows a photo of **1m** at 140 °C. (B) Temperature-dependent viscosity of **1g**. (C) DMA of **1g** from -30 to 120 °C (heating rate of 2 °C min^{-1}). The storage (G') and loss (G'') moduli were marked as (\blacktriangle) and (\bullet), respectively. (D) Arrhenius plots of the anhydrous conductivity of **1** (\bullet) and **1g** (\blacktriangle) under an Ar atmosphere. The inset shows the Nyquist plot of **1** (\bullet) and **1g** (\blacktriangle) at 50 °C.

lower T_m and pK_a values than those of benzimidazole.^{31,33} Additionally, no significant weight loss was seen at 120 °C after 12 h, confirming a stable liquid state (Fig. S6†). The liquid/molten state of **1** is henceforth referred to as **1m**. The first cooling process in DSC confirmed the vitrification of **1m** to a glassy state of **1** (denoted as **1g**) that demonstrated a glass transition temperature (T_g) of 7.6 °C, exhibiting no Bragg diffraction, and was categorized as melt-quenched glass (MGQ) (Fig. S7†).³⁴

DMA and viscosity evaluation of **1g** further determined its processing ability, where its viscosity (Fig. 2B) was observed above the Littleton softening point ($10^{6.6}$ Pa s) from -30 to 90 °C until it sharply decreased below the working point regime (10^3 Pa s) above 100 °C. The working point defines the viscosity regime in which the viscosity of a substance is equivalent to that of soda-lime-silica glass above 1100 °C (suitable for industrial forming processes).⁵¹ The storage modulus (G') dominated the loss modulus (G'') from -30 to 90 °C, verifying the solid character of **1g** (Fig. 2C). Immediate reduction of G' at 100 °C represents the softening of **1g**, and the G'/G'' crossover indicates the range in which **1g** starts to behave like a viscous liquid.^{31,52}

Anhydrous H^+ conductivity

We measured the H^+ conductivity of **1** and **1g** via variable-temperature alternating current (AC) impedance under an Ar atmosphere to exclude the influence of water molecules (Fig. 2D and S9†). The Nyquist plots were fitted with a single impedance response corresponding to the bulk resistance without the grain-boundary region.^{52,53} The conductivity of **1** was measured from 30 to 100 °C, where the crystalline phase of **1** was preserved. We observed conductivity values of 3.3×10^{-7} S cm^{-1} and 9.0×10^{-5} S cm^{-1} at 30 and 60 °C, respectively. The conductivity value increased rapidly upon heating, reaching 1.2×10^{-3} S cm^{-1} at 100 °C. The activation energy of **1** from 30 to 60 °C was 1.22 eV. Above 60 °C, the Arrhenius plot flattened and the activation energy reduced to 0.57 eV. Utilizing BTA with its low pK_a in **1** provided higher conductivity values than those of the isostructure $[\text{Zn}_3(\text{H}_2\text{PO}_4)_6](\text{HBim})$ at 30 °C (1.2×10^{-7} S cm^{-1}) and 60 °C (1.5×10^{-5} S cm^{-1}).³⁸

To highlight the advantage of glass transformation on ionic conductivity, we prepared a monolith (**1g**) via melt-quenching directly into the electrochemical cell for impedance analysis. Upon the crystalline-to-glassy state transformation, only the



bulk impedance response pattern was obtained (Fig. S9†) and it was identical to that of **1a** in the higher temperature range. The Arrhenius plot (Fig. 2D) shows two different activation energy regimes: 0.59 eV between 30 and 60 °C and 0.39 eV from 60 to 120 °C. At 30 °C, **1g** exhibited a conductivity value of $3.3 \times 10^{-4} \text{ S cm}^{-1}$, which increased to $4.9 \times 10^{-3} \text{ S cm}^{-1}$ and $6.5 \times 10^{-3} \text{ S cm}^{-1}$ at 100 and 110 °C, respectively. A conductivity value of 8.0×10^{-3} was achieved at 120 °C (molten state, **1m**). Long-term conductivity retention was also evaluated. After 12 h, less than 4% and 10% loss in conductivity was observed at 100 and 120 °C, respectively (Fig. S10†). The contribution of the ions of interest to the total current can be distinguished *via* the H^+ transport number (transference number) measurements.^{52,54} The transport numbers of most aqueous and ionic liquid electrolytes are lower than 0.6.^{54–56} The transport number of **1m** was elucidated *via* electromotive force (EMF) measurements, which were conducted for different hydrogen partial pressure ($-\ln(P_1/P_2)$) values of 0.22, 0.51, 0.69, 0.92, and 1.61) at 120 °C (Fig. S11†).⁵⁷ According to eqn S1 (ESI),† the H^+ transference number of **1g** is 1.0, indicating an ideal single-ion H^+ conductivity. The absence of anion mobility suggests that the coordination networks are retained even in the molten state.^{31,58}

Proton dynamics in **1** and **1g**

The H^+ conductivity would be dominated by either the phosphate or BTA dynamics; therefore, we utilized variable-temperature ^1H MAS solid-state NMR to study their mobilities (Fig. 3). The peaks from 8.1–8.5 and 5.8–6.1 ppm were assigned to the phosphate and BTA H^+ , respectively.^{44,52} The substantial narrowing and intensifying of the peaks between 50 and 75 °C suggested a significant increase in both the phosphate and BTA dynamics. The molecular motion of BTA initiates at the temperature above 50 °C as the BTA peaks are barely distinguishable at 25 and 50 °C (Fig. 3A).³⁸ The H^+ mobilities of **1g** and **1** were compared at 25 and 50 °C as well as at 50 and 75 °C,

where the narrower and more intense peaks of **1g** demonstrated its higher H^+ mobility than that of **1** (Fig. 3B). This higher degree of H^+ mobility was promoted by a disordered structure formed in **1g**. Furthermore, the BTA dynamics were observable in **1g** even at temperatures lower than 60 °C, which agrees with the impedance response and lower activation energy of **1g**. Additionally, hydrogen-bond formations are indicated by downfield shifts.⁵⁹

Electrode–electrolyte interface

Discontinuities along the heterogeneous interface inhibit practical applications of solid-state electrolytes.¹⁷ Therefore, we are interested in the H^+ -conductivity integration and moldability of **1g** as a grain boundary-free immersive solid electrolyte (Fig. 4A). Additionally, the lower T_m of **1** would prevent the anode/cathode materials from degrading during the fabrication process.^{8,9,12,13} A carbon fiber (CF) electrode was pressed to **1m** at 120 °C and quenched to room temperature to provide the electrode–electrolyte interface (CF–**1g**). Cross-sectional scanning electron microscopy (SEM) images of CF–**1g** were collected (Fig. 4B, S12A, and B†), where neither a distinguishable solid–electrolyte interface nor grain boundaries were observed.⁶⁰ Optimum contact between the CF layer and **1g** domain was achieved as **1m** can penetrate the CF, generating a fully immersed environment. Fig. 4C shows a cross-sectional SEM reference image of the pristine CF. Energy-dispersive X-ray (EDX) mapping (Fig. 4D–G) further elucidated the position of the CF electrode (intense C) with homogeneously distributed Zn, P, and O signals. To amplify the benefits of melt-quenching glass, we re-examined the morphological alteration of CF–**1g** after recrystallization. **1g** undergoes the recrystallization process upon humidity exposure and transforms back to **1a**. As confirmed by PXRD (Fig. S13†), atmospheric humidity (65% relative humidity) at room temperature (25 °C) is sufficient for the recrystallization to occur within 4 h. Fig. S12C and D† revealed grain boundaries and fractures formed throughout the recrystallized **1g** matrix, especially in the region where the CF and **1g** co-exist.

Solid-state H^+ battery under anhydrous conditions

Adequately high H^+ conductivity, single-ion conductivity, low processing temperatures, and thermal/electrochemical stabilities motivated us to apply **1g** as a solid electrolyte for H^+ batteries. MoO_3 and $\text{Cu}^{\text{II}}[\text{Fe}^{\text{III}}(\text{CN})_6]_{2/3} \cdot 4\text{H}_2\text{O}$ (CuFe-TBA) were selected as a model cathode and anode, respectively.^{10,12} As a reference, we also evaluated a full-cell configuration in 2 M H_2SO_4 solution at 25 °C. It exhibited a discharge capacity of 35.8 mA h g^{-1} at 100 mA g^{-1} (Fig. S14†). The specific capacity was calculated based on the cathode mass. The distance between the electrodes was *ca.* 1 cm.¹² The solid-state H^+ battery was prepared by immersing both electrodes (1 cm separations) in **1m** at 120 °C under an Ar atmosphere, where subsequent quenching to room temperature gave the **1g** electrolyte. Fig. 4H and S15A† show the charge–discharge profiles (from 0 to 1.2 V) and rate performance evaluation of solid-state H^+ batteries under an Ar atmosphere utilizing the **1g** electrolyte at 25 °C. The

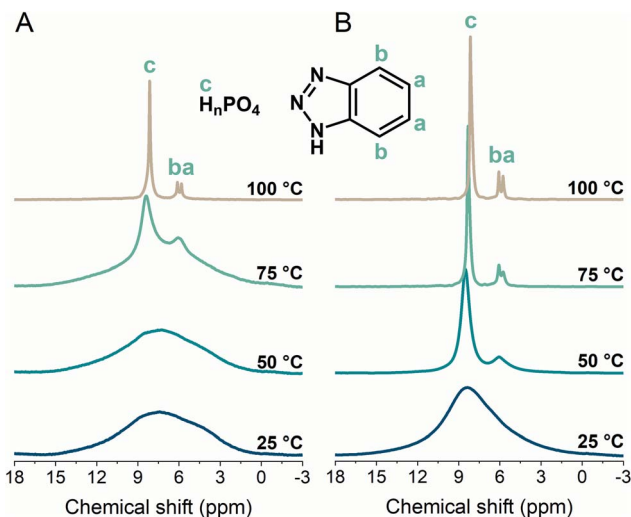


Fig. 3 Variable-temperature ^1H magic-angle spinning (MAS) solid-state NMR spectra (MAS 8 kHz) of (A) **1** and (B) **1g** from 25 to 100 °C.





Fig. 4 (A) Schematic representation of the interfaces/flaws within the polycrystalline solid electrolyte (left) and MQG solid electrolyte proposed in this work (**1g**). Cross-sectional scanning electron microscopy (SEM) images ($\times 150$ magnification) of (B) the electrode–solid-state electrolyte interface (CF–**1g**) and (C) CF electrode. Scale bar = 150 μm . Energy-dispersive X-ray (EDX) mapping for (D) C, (E) P, (F) Zn, and (G) O. Scale bar = 100 μm . Full-cell charge–discharge profiles utilizing **1g** as a solid-state electrolyte at (H) 25 $^\circ\text{C}$ and (I) 100 $^\circ\text{C}$.

highest discharge capacity was 55.4 mA h g^{-1} at 10 mA g^{-1} . Another advantage the **1g**-electrolyte system has over the aqueous system is its large operating-temperature range. The elevated-temperature H^+ battery was evaluated at 100 and 110 $^\circ\text{C}$ under an Ar atmosphere (Fig. 4I and S15C†) and the redox potentials of both electrodes reduced, corresponding to the change in free energy.^{61,62} As shown in Fig. S15B and D,† rate performances improved significantly as the ionic conductivity of **1g** was enhanced.² In a high-temperature regime, electrodes would show an excessive self-discharge as well as a thermal structural distortion limiting the protonation/deprotonation processes, causing a net loss of capacity. For instance, in a Li-ion battery, capacity fading was observed in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ as

elevated temperature promotes a larger structural distortion between $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ and $\text{V}_2(\text{PO}_4)_3$ limiting the re-insertion of Li^+ .⁶³ Additionally, 76% of the original capacity was retained after 1000 cycles of the charge–discharge process at 110 $^\circ\text{C}$ (Fig. S16†). We also attempted to demonstrate a solid-state H^+ battery using crystalline **1** with a similar configuration and an identical anode and cathode. However, charging and discharging processes were not possible at 25 $^\circ\text{C}$ nor under low-current (10 mA g^{-1}) conditions, even though the thickness of this electrolyte was ten times smaller than that of the **1g** electrolyte. This emphasizes the importance of interface engineering that endows soft glass materials with high H^+ conductivity and moldability.^{17,20,21}



Conclusions

We synthesized a new H⁺ conductive CP, [Zn₃(H₂PO₄)₆(-H₂O)₃](BTA), where the dehydrated state (**1**) integrated promising anhydrous H⁺ conductivity (1.2 × 10⁻³ S cm⁻¹ at 100 °C) and relatively low melting point (114 °C). The melt-quenched glass of **1** (**1g**) enhanced the H⁺ dynamics of both phosphate and BTA, resulting in a H⁺ conductivity value of 8.0 × 10⁻³ S cm⁻¹, a H⁺ transference number of 1.0, and a viscosity of 42.8 Pa s at 120 °C. The coexistence of high conductivity, transport number, and moldability of **1g**, as well as its flawless interface, encouraged us to implement it in solid-state H⁺ battery applications. A solid-state H⁺ battery with an operating temperature range above room temperature (25–110 °C) was demonstrated for the first time. The tuning capability of the CP glass H⁺ conductivity, working temperature, and softness could provide H⁺ batteries with wider applications.

Author contributions

S. H. designed the project, and N. M. and A. Y. synthesized the compounds. S. K. collected and analyzed solid-state NMR measurements. N. M. collected and analyzed SC-XRD, PXRD, TGA, SEM, DSC, ICP-ES, DMA, FTIR, conductivity and transport number measurements and battery evaluation. S. H. and N. M. wrote the paper.

Conflicts of interest

There are no conflicts to declare.

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References

- R. Pohl, A. Antognini, F. Nez, F. D. Amaro, F. Biraben, J. M. R. Cardoso, D. S. Covita, A. Dax, S. Dhawan, L. M. P. Fernandes, A. Giesen, T. Graf, T. W. Hänsch, P. Indelicato, L. Julien, C.-Y. Kao, P. Knowles, E.-O. Le Bigot, Y.-W. Liu, J. A. M. Lopes, L. Ludhova, C. M. B. Monteiro, F. Mulhauser, T. Nebel, P. Rabinowitz, J. M. F. dos Santos, L. A. Schaller, K. Schuhmann, C. Schwob, D. Taqqu, J. F. C. A. Veloso and F. Kottmann, *Nature*, 2010, **466**, 213–216.
- K.-D. Kreuer, *Chem. Mater.*, 1996, **8**, 610–641.
- K. Nueangnoraj, T. Tomai, H. Nishihara, T. Kyotani and C.-J. Cai, *Carbon*, 2016, **107**, 831–836.
- R. Emanuelsson, M. Sterby, M. Strømme and M. Sjödin, *J. Am. Chem. Soc.*, 2017, **139**, 4828–4834.
- M. Armand and J. M. Tarascon, *Nature*, 2008, **451**, 652–657.
- X. Ji, *Energy Environ. Sci.*, 2019, **12**, 3203–3224.
- G. Liang, F. Mo, X. Ji and C. Zhi, *Nat. Rev. Mater.*, 2021, **6**, 109–123.
- C. Strietzel, M. Sterby, H. Huang, M. Strømme, R. Emanuelsson and M. Sjödin, *Angew. Chem., Int. Ed.*, 2020, **59**, 9631–9638.
- H. Jiang, J. J. Hong, X. Wu, T. W. Surta, Y. Qi, S. Dong, Z. Li, D. P. Leonard, J. J. Holoubek, J. C. Wong, J. J. Razink, X. Zhang and X. Ji, *J. Am. Chem. Soc.*, 2018, **140**, 11556–11559.
- X. Wang, Y. Xie, K. Tang, C. Wang and C. Yan, *Angew. Chem., Int. Ed.*, 2018, **57**, 11569–11573.
- P. Lemaire, O. Sel, D. Alves Dalla Corte, A. Iadecola, H. Perrot and J.-M. Tarascon, *ACS Appl. Mater. Interfaces*, 2020, **12**, 4510–4519.
- X. Wu, J. J. Hong, W. Shin, L. Ma, T. Liu, X. Bi, Y. Yuan, Y. Qi, T. W. Surta, W. Huang, J. Neufeind, T. Wu, P. A. Greaney, J. Lu and X. Ji, *Nat. Energy*, 2019, **4**, 123–130.
- X. Wu, S. Qiu, Y. Xu, L. Ma, X. Bi, Y. Yuan, T. Wu, R. Shahbazian-Yassar, J. Lu and X. Ji, *ACS Appl. Mater. Interfaces*, 2020, **12**, 9201–9208.
- L. Yan, J. Huang, Z. Guo, X. Dong, Z. Wang and Y. Wang, *ACS Energy Lett.*, 2020, **5**, 685–691.
- H. Jiang, W. Shin, L. Ma, J. J. Hong, Z. Wei, Y. Liu, S. Zhang, X. Wu, Y. Xu, Q. Guo, M. A. Subramanian, W. F. Stickle, T. Wu, J. Lu and X. Ji, *Adv. Energy Mater.*, 2020, **10**, 2000968.
- X. Lin, M. Salari, L. M. R. Arava, P. M. Ajayan and M. W. Grinstaff, *Chem. Soc. Rev.*, 2016, **45**, 5848–5887.
- Q. Zhao, S. Stalin, C.-Z. Zhao and L. A. Archer, *Nat. Rev. Mater.*, 2020, **5**, 229–252.
- J. Evans, C. A. Vincent and P. G. Bruce, *Polymer*, 1987, **28**, 2324–2328.
- S. S. Park, Y. Tulchinsky and M. Dincă, *J. Am. Chem. Soc.*, 2017, **139**, 13260–13263.
- J. van den Broek, S. Afyon and J. L. M. Rupp, *Adv. Energy Mater.*, 2016, **6**, 1600736.
- X. Han, Y. Gong, K. Fu, X. He, G. T. Hitz, J. Dai, A. Pearse, B. Liu, H. Wang, G. Rubloff, Y. Mo, V. Thangadurai, E. D. Wachsman and L. Hu, *Nat. Mater.*, 2017, **16**, 572–579.
- P. G. Bruce and A. West, *J. Electrochem. Soc.*, 1983, **130**, 662.
- Y. Inaguma, C. Liqun, M. Itoh, T. Nakamura, T. Uchida, H. Ikuta and M. Wakihara, *Solid State Commun.*, 1993, **86**, 689–693.
- R. Murugan, V. Thangadurai and W. Weppner, *Angew. Chem., Int. Ed.*, 2007, **46**, 7778–7781.
- J. A. Dawson, P. Canepa, T. Famprikis, C. Masquelier and M. S. Islam, *J. Am. Chem. Soc.*, 2018, **140**, 362–368.
- S. Horike, D. Umeyama and S. Kitagawa, *Acc. Chem. Res.*, 2013, **46**, 2376–2384.
- T. Yamada, K. Otsubo, R. Makiura and H. Kitagawa, *Chem. Soc. Rev.*, 2013, **42**, 6655–6669.
- P. Ramaswamy, N. E. Wong and G. K. H. Shimizu, *Chem. Soc. Rev.*, 2014, **43**, 5913–5932.
- D.-W. Lim and H. Kitagawa, *Chem. Rev.*, 2020, **120**, 8416–8467.



- 30 T. Inada, T. Kobayashi, N. Sonoyama, A. Yamada, S. Kondo, M. Nagao and R. Kanno, *J. Power Sources*, 2009, **194**, 1085–1088.
- 31 D. Umeyama, S. Horike, M. Inukai, T. Itakura and S. Kitagawa, *J. Am. Chem. Soc.*, 2015, **137**, 864–870.
- 32 T. D. Bennett, Y. Yue, P. Li, A. Qiao, H. Tao, N. G. Greaves, T. Richards, G. I. Lampronti, S. A. T. Redfern, F. Blanc, O. K. Farha, J. T. Hupp, A. K. Cheetham and D. A. Keen, *J. Am. Chem. Soc.*, 2016, **138**, 3484–3492.
- 33 T. D. Bennett and S. Horike, *Nat. Rev. Mater.*, 2018, **3**, 431–440.
- 34 S. Horike, S. S. Nagarkar, T. Ogawa and S. Kitagawa, *Angew. Chem., Int. Ed.*, 2020, **59**, 2–15.
- 35 W. Chen, S. Horike, D. Umeyama, N. Ogiwara, T. Itakura, C. Tassel, Y. Goto, H. Kageyama and S. Kitagawa, *Angew. Chem., Int. Ed.*, 2016, **55**, 5195–5200.
- 36 Y. Ohara, A. Hinokimoto, W. Chen, T. Kitao, Y. Nishiyama, Y.-I. Hong, S. Kitagawa and S. Horike, *Chem. Commun.*, 2018, **54**, 6859–6862.
- 37 S. Horike, D. Umeyama, M. Inukai, T. Itakura and S. Kitagawa, *J. Am. Chem. Soc.*, 2012, **134**, 7612–7615.
- 38 D. Umeyama, S. Horike, M. Inukai and S. Kitagawa, *J. Am. Chem. Soc.*, 2013, **135**, 11345–11350.
- 39 S. Horike, W. Chen, T. Itakura, M. Inukai, D. Umeyama, H. Asakura and S. Kitagawa, *Chem. Commun.*, 2014, **50**, 10241–10243.
- 40 D. Umeyama, N. P. Funnell, M. J. Cliffe, J. A. Hill, A. L. Goodwin, Y. Hijikata, T. Itakura, T. Okubo, S. Horike and S. Kitagawa, *Chem. Commun.*, 2015, **51**, 12728–12731.
- 41 T. D. Bennett, J.-C. Tan, Y. Yue, E. Baxter, C. Ducati, N. J. Terrill, H. H. M. Yeung, Z. Zhou, W. Chen, S. Henke, A. K. Cheetham and G. N. Greaves, *Nat. Commun.*, 2015, **6**, 8079.
- 42 N. Agmon, *Chem. Phys. Lett.*, 1995, **244**, 456–462.
- 43 D. Umeyama, S. Horike, M. Inukai, T. Itakura and S. Kitagawa, *J. Am. Chem. Soc.*, 2012, **134**, 12780–12785.
- 44 M. Inukai, S. Horike, T. Itakura, R. Shinozaki, N. Ogiwara, D. Umeyama, S. Nagarkar, Y. Nishiyama, M. Malon, A. Hayashi, T. Ohhara, R. Kiyanaagi and S. Kitagawa, *J. Am. Chem. Soc.*, 2016, **138**, 8505–8511.
- 45 S. Hayashi and K. Hayamizu, *Bull. Chem. Soc. Jpn.*, 1989, **62**, 3061–3068.
- 46 P. Reinert, N. Z. Logar, J. Patarin and V. Kaucic, *Eur. J. Solid State Inorg. Chem.*, 1998, **35**, 373–387.
- 47 T. Akamatsu, T. Kasuga and M. Nogami, *Adv. Mater. Res.*, 2007, **15–17**, 327–332.
- 48 S. Horike, S. Shimomura and S. Kitagawa, *Nat. Chem.*, 2009, **1**, 695.
- 49 S. Henke, A. Schneemann, A. Wütscher and R. A. Fischer, *J. Am. Chem. Soc.*, 2012, **134**, 9464–9474.
- 50 J. Canivet, A. Fateeva, Y. Guo, B. Coasne and D. Farrusseng, *Chem. Soc. Rev.*, 2014, **43**, 5594–5617.
- 51 J. E. Shelby, *Introduction to glass science and technology*, Royal Society of Chemistry, Cambridge, UK, 2nd edn, 2005.
- 52 T. Ogawa, K. Takahashi, S. S. Nagarkar, K. Ohara, Y.-I. Hong, Y. Nishiyama and S. Horike, *Chem. Sci.*, 2020, **11**, 5175–5181.
- 53 J. R. M. E. Barsoukov, *Impedance Spectroscopy Theory, Experiment, and Applications*, John Wiley & Sons, NJ, USA, 2nd edn, 2005.
- 54 P. V. Wright, *MRS Bull.*, 2002, **27**, 597–602.
- 55 H. Nakamoto, A. Noda, K. Hayamizu, S. Hayashi, H.-o. Hamaguchi and M. Watanabe, *J. Phys. Chem. C*, 2007, **111**, 1541–1548.
- 56 S.-Y. Lee, T. Yasuda and M. Watanabe, *J. Power Sources*, 2010, **195**, 5909–5914.
- 57 T. Norby, *Solid State Ionics*, 1988, **28–30**, 1586–1591.
- 58 R. Gaillac, P. Pullumbi, K. A. Beyer, K. W. Chapman, D. A. Keen, T. D. Bennett and F.-X. Coudert, *Nat. Mater.*, 2017, **16**, 1149–1154.
- 59 T. L. Greaves and C. J. Drummond, *Chem. Rev.*, 2015, **115**, 11379–11448.
- 60 A. Hayashi, K. Noi, A. Sakuda and M. Tatsumisago, *Nat. Commun.*, 2012, **3**, 856.
- 61 S. G. Bratsch, *J. Phys. Chem. Ref. Data*, 1989, **18**, 1–21.
- 62 A. J. Bard and L. R. Faulkner, *Electrochemical Methods: Fundamentals and Applications*, Wiley, 2nd edn, 2000.
- 63 Y. Q. Qiao, J. P. Tu, X. L. Wang and C. D. Gu, *J. Power Sources*, 2012, **199**, 287–292.

