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Preparation and characterization of sodium-ion conductive $\text{Na}_3\text{BS}_3$ glass and glass-ceramic electrolytes

Fumika Tsuji, Akira Nasu, Chie Hotehama, Atsushi Sakuda, Masahiro Tatsumisago, and Akitoshi Hayashi

In order to find suitable solid electrolytes for all-solid-state sodium batteries, sulfide electrolytes composed of tetrahedral structural units such as $\text{PS}_4$, $\text{SnS}_4$, and $\text{SB}_4$ have been widely studied. In this paper, the ionic conductivities of $\text{Na}_2\text{BS}_3$ ortho-thioborate electrolytes with triangular $\text{BS}_3$ units are firstly reported. $\text{Na}_2\text{BS}_3$ glass was prepared via a mechanochemical process from crystalline $\text{Na}_2\text{BS}_3$ (monoclinic phase). The crystalline $\text{Na}_2\text{BS}_3$ was pre-synthesized from a mixture of $\text{Na}_3\text{S}$, $\text{B}_2$, and $\text{S}$ due to the instability of the $\text{B}_2\text{S}_3$ compound. A new metastable phase of trigonal $\text{Na}_2\text{BS}_3$ was precipitated as the primary phase by crystallization of the $\text{Na}_2\text{BS}_3$ glass. The prepared glass-ceramic electrolyte showed a higher ionic conductivity than the monoclinic $\text{Na}_2\text{BS}_3$ phase, and the $\text{Na}_2\text{BS}_3$ glass showed the highest conductivity of $1.1\times10^{-4}$ S cm$^{-1}$, which was higher than that of conventional $\text{Na}_2\text{PS}_3$ glass. Furthermore, the $\text{Na}_2\text{BS}_3$ glass showed a superior formability and electrochemical stability to $\text{Na}_3\text{SnS}_4$ negative electrode. An all-solid-state cell with the $\text{Na}_2\text{BS}_3$ glass as an electrolyte successfully operated as a secondary battery at 60 °C. It is concluded that the $\text{Na}_2\text{BS}_3$ glass with triangular structural units has appropriate properties as a solid electrolyte for application to all-solid-state sodium batteries. The results of this study extend research on multi-component sulfide electrolytes with triangular $\text{BS}_3$ structural units and contribute to the development of solid electrolytes for all-solid-state batteries.

1. Introduction

Sodium-ion batteries with their associated low costs and abundant sodium reserves have attracted significant attention as promising next-generation large-scale energy storage systems to replace lithium-ion batteries. Because sodium has a similar electrochemical performance to lithium, such as standard reduction potential, sodium batteries have the potential to exhibit a high performance. As one example of sodium-ion batteries, sodium–sulfur batteries can function as a stationary storage system. However, they require a high temperature of over 300 °C to operate with their molten electrodes, which causes cost and safety concerns. To overcome these issues, all-solid-state sodium–sulfur batteries operated at room temperature are desirable. This requires superior solid electrolytes with high ionic conductivities at room temperature and good formabilities for achieving large contact areas with electrode active materials.

We previously reported that $\text{Na}_3\text{PS}_4$ glass-ceramics in a metastable cubic phase obtained via a mechanochemical process and consecutive heat treatment exhibited a higher ionic conductivity than crystalline $\text{Na}_3\text{PS}_4$ in the tetragonal phase. The $\text{Na}_3\text{PS}_4$ sulfide system possesses a better formability than the $\text{Li}_2\text{PS}_4$ system, and its densification and associated sintering behavior are easily promoted by pressing at room temperature. Subsequently, some sodium sulfides, such as $\text{Na}_3\text{SnS}_4$ and $\text{Na}_2\text{Sn}_3\text{PS}_{12}$, have been found to exhibit high ionic conductivities of over 1 mS cm$^{-1}$ at room temperature. In particular, we reported a $\text{Na}_2\text{S}_8\text{Sb}_{0.18}\text{W}_{0.82}\text{S}_3$ glass-ceramic electrolyte with the highest ionic conductivity of 32 mS cm$^{-1}$ among sulfide Li- and Na-ion conductors reported so far. Studies on solid electrolytes have thus far focused on sulfide systems with tetrahedral structure units, such as $\text{PS}_4^-$ and $\text{SB}_4^-$ in contrast, solid electrolytes composed of triangular structure units have not been extensively studied. Solid electrolytes containing B as a center element are known to have triangular boron units in the systems of $\text{Na}_2\text{O}_2\text{B}_2\text{O}_3$ and $\text{Na}_2\text{S}_2\text{B}_2\text{S}_3$. We reported the preparation of $\text{Na}_2\text{BO}_3$ orthoborate glass with a triangular $\text{BO}_3$ unit via a mechanochemical process, and its ionic conductivity was over $10^{-8}$ S cm$^{-1}$. In general, the Na$^+$ conductivity of glassy electrolytes increases with increasing Na content. The conductivities of $\text{Na}_3\text{S}_2\text{B}_2\text{S}_3$ glasses prepared by conventional melt quenching have only been investigated for compositions with less than 67 mol% $\text{Na}_3\text{S}$. While the conductivities of $\text{Na}_2\text{BS}_3$ ortho-thioborate glasses with Na contents higher than 75 mol% $\text{Na}_3\text{S}$ have not been reported. Another challenge for developing the sodium thioborate system is the difficulty in obtaining pure $\text{B}_2\text{S}_3$, which is not commercially available. Although the synthesis of $\text{B}_2\text{S}_3$ has been reported, it...
is generally difficult to obtain pure B₃S₃ due to its low chemical stability and tendency to easily oxidation.

In this study, Na₃B₃S₃ sulfide electrolytes with three-coordinated borons were synthesized directly from a starting mixture of Na₂S, B, and S reagents. Crystalline Na₃B₃S₃ (monoclinic phase) was prepared by a solid-phase reaction in advance, which was then used to prepare glassy Na₃B₃S₃ via a mechanochemical process. A metastable crystalline phase was precipitated by crystallization of the prepared glassy Na₃B₃S₃. The structure and ionic conductivity of the prepared Na₃B₃S₃ electrolytes were examined, and their application to all-solid-state sodium cells was investigated.

2. Experimental

A mixture of Na₂S (> 99.1%; Nagao), crystalline B (> 99%; Kojundo Chem.), and S (> 99.99%; Kojundo Chem.) was pelletized and placed into a carbon crucible, then heated at 700 °C for 10 h in a quartz ampoule sealed under vacuum. After cooling to room temperature slowly, crystalline Na₃B₃S₃ was obtained. The Na₃B₃S₃ glass was prepared from the crystalline Na₃B₃S₃ by a mechanochemical technique at an ambient temperature using a planetary ball mill (Pulverisette 7; Fritsch) with zirconia pots (45 mL in volume) and zirconia temperature using a planetary ball mill (Pulverisette 7; Fritsch). The milled sample powders were then heated in an electric furnace at 200 or 300 °C for 1 h. The heating temperatures were determined via differential thermal analysis (DTA). All processes were performed in a dry Ar atmosphere.

X-ray diffraction (XRD) measurements of the prepared materials were performed using CuKα radiation with a diffractometer (SmartLab; Rigaku). The diffraction data were collected in steps of 0.01° in the 2θ range of 10.0°–80.0°. The XRD measurements were performed using an airtight vessel with a beryllium window to prevent exposure of the sample to the air. The crystalline structures were refined using the SLS2 software (Rigaku), and the heated sample patterns were refined using the Rietveld method in the software package RIETAN-FP. ¹⁶

Solid-state NMR experiments were performed using an NMR spectrometer (JNM-ECX 400; JEOL). The sample powders were packed into zirconia spacers in a dry Ar atmosphere. The observation frequency was 128.3 MHz. The spectra were acquired using a single pulse with a pulse width of 1.17 µs (1/3 of 90° pulse width), a recycle pulse delay of 0.5 s, and an MAS rate of 12 kHz. The chemical shifts were calibrated using BPO₄ (=−3.6 ppm.

Raman spectra of the samples were measured using a Raman spectrophotometer (LabRAM HR-800; Horiba) with a 532 nm solid-state laser to identify the structural units. The electrolyte samples were placed in an airtight vessel with a quartz window. The process was performed in a dry Ar atmosphere.

DTA was performed using a thermal analyzer (Thermo Plus TG8110; Rigaku) at a heating rate of 10 °C min⁻¹ under N₂ gas. The milled samples were sealed in Al pans in a dry Ar atmosphere.

The ionic conductivities were determined via AC impedance measurements using an impedance analyzer (Solartron, 1260) in the frequency range from 10 Hz to 1 MHz with an applied AC voltage of 50 mV. The measurements were carried out using compressed powder pellets (diameter of 10 mm and thickness of 1 mm). Gold thin films (diameter of 10 mm) as ion-blocking electrodes were deposited on both faces of the pellets with a quick coater (Quick coater SC-701; Sanyu Electron). Each pellet was sealed in a laminate-type pouch cell to prevent air exposure.

The electronic conductivity was measured using the DC polarization technique. The sample powders were pressed at 360 MPa, and gold current collectors were used to cover the surfaces of the pellets. Each pellet was sealed in a laminate-type pouch cell. The data were collected using a potentio/galvanostat (1287, Solartron) with the applied DC voltage of 0.16V at room temperature.

The densities of the powder-compressed pellets (d₁) were calculated from the weight and volume of the pellets, and those of the powders (d₂) were measured using a gas pycnometer (Accupyc II 1340; Shimadzu). The relative density was defined as d₁/d₂. The microstructures of the cross-sections of the pellets were observed via scanning electron microscopy (SEM) (JSM-6610A; JEOL).

Cyclic voltammetry was conducted to investigate the electrochemical properties of the prepared Na₃B₃S₃ glass electrolyte. A composite electrode (80 mg) with Na₃B₃S₃ (80 wt.%) and Ketjen Black (KB, 20 wt.%) was used as a counter electrode, and a stainless-steel rod was used as a working electrode. The potential sweep was performed between −0.5 V and 5.0 V with a scanning rate of 5.0 mV min⁻¹ at 60 °C.

All-solid-state cells were constructed as follows. The Na₃B₃S₃ glass powder (80 mg) was used as the solid electrolyte. A composite electrode (2.7 mg) of TiS₂ (99%; Kojundo Chem., 40 wt.%) and the electrolyte (60 wt.%) was used as the positive electrode, and the composite of NaₓS–KB (30 mg) was used as the negative electrode. The prepared all-solid-state cells were charged and discharged at 60 °C in the voltage range from 1.2 to 2.4 V at 0.038 mA cm⁻² under an Ar atmosphere. CV and charge-discharge measurement for the all-solid-state cells were using a potentio/galvanostat device (Bio-logic, VMP-3).

3. Results

Figure 1 shows the XRD patterns of the Na₃B₃S₃ crystalline, glass, and ceramic-samples. The XRD pattern of crystalline Na₃B₃S₃ was the same as that reported for Na₃B₃S₃ (ICSD: 411608, monoclinic structure). From Na₂S, B, and S as starting materials, crystalline Na₃B₃S₃ was successfully synthesized by a conventional solid-phase reaction. The crystal was then mechanochemically treated, and the obtained sample showed a halo XRD pattern and an endothermic change attributable to the glass transition at 175 °C (Tg) on the DTA curve, as shown in Figure 2. The glassy Na₃B₃S₃ electrolyte was then obtained by a two-step process: synthesis of crystalline Na₃B₃S₃ from Na₂S, B, and S and amorphization of the crystal. By using this two-step process, the glass-forming region of sodium thioborates was
determined. As shown in Figure 5(a), the XRD pattern attributable to Na$_3$S as a starting reagent was observed at compositions of $x = 0.76$ and higher for the $x$Na$_3$S$_3$(1-x)B$_2$S$_3$$_3$ samples. Glassy electrolytes were prepared in the range of 0.33 $x$ 0.75 in this study. The glass composition with the highest Na content, $x = 0.75$, corresponds to the ortho-thioborate Na$_3$B$_2$S$_3$.

Figure 1. XRD patterns of Na$_3$B$_2$S$_3$ solid electrolytes.

Figure 2. DTA curve of Na$_3$B$_2$S$_3$ glass. The orange arrow shows the glass transition temperature, and the two black arrows show the heat-treatment temperatures employed to prepare the glass-ceramics.

The Na$_3$B$_2$S$_3$ glass was heated at 200 or 300 °C corresponding to the exothermic peaks in the DTA curve, as shown in Figure 2. After heating at 200 °C, a new metastable phase was observed. The XRD pattern was similar to that of the reported monoclinic Na$_3$B$_2$S$_3$ phase, which is thermodynamically stable, but the new phase was indexed to a higher symmetry. The detailed structural analysis is discussed later. After heating at 300 °C, the glass-ceramic showed almost the same XRD pattern as that of the monoclinic Na$_3$B$_2$S$_3$ phase.

The local structure of the Na$_3$B$_2$S$_3$ samples was analyzed by $^{11}$B MAS-NMR and Raman spectroscopy. Figure 3 shows the $^{11}$B MAS-NMR spectra of the Na$_3$B$_2$S$_3$ solid electrolytes, where the peaks marked with asterisks are spinning side bands. All the samples showed similar spectra. The two resonance peaks between 50 and 70 ppm are attributable to triangular BS$_3$$_3$ units with three-coordinated boron, and the highly symmetrical peaks at 0 and 10 ppm are attributable to tetrahedral BS$_3$$_3$ units with four-coordinated boron. The peaks corresponding to the tetrahedral units were hardly observed for the Na$_3$B$_2$S$_3$ glass, suggesting that the glass mainly consisted of trigonal BS$_3$$_3$ units.

Figure 3. $^{11}$B MAS-NMR spectra of Na$_3$B$_2$S$_3$ solid electrolytes.

The Raman spectra of the Na$_3$B$_2$S$_3$ samples are shown in Figure 4. The crystal and glass-ceramics showed similar spectra with a sharp band at 435 cm$^{-1}$ and broad bands at 470, 765, and 940 cm$^{-1}$, all of which are attributable to triangular BS$_3$$_3$ units. The residual broad band at 795 cm$^{-1}$ is expected to be attributable to tetrahedral BS$_3$$_3$ units since they were detected by $^{11}$B MAS-NMR. The spectrum of Na$_3$B$_2$S$_3$ glass was broader than that of the Na$_3$B$_2$S$_3$ crystal because of its amorphous nature. Thus, it was concluded that the local structures of all the Na$_3$B$_2$S$_3$ samples were similar.

Figure 4. Raman spectra of Na$_3$B$_2$S$_3$ solid electrolytes.

Figure 5(a) shows the Rietveld refinement profile for the Na$_3$B$_2$S$_3$ glass-ceramic heated at 200 °C. Structural optimization of the new metastable phase resulted in a trigonal crystal structure. The observed and calculated XRD patterns (red and black lines, respectively) were in good agreement, as indicated by their difference spectrum (blue line). Table 1 summarizes the crystallographic parameters including the lattice constants, positions of atoms, thermal factors, and atomic occupancies of the Na$_3$B$_2$S$_3$ glass-ceramic obtained from the Rietveld refinement. The lattice parameters were $a = 3.90\,\text{Å}$, $b = 7.42\,\text{Å}$, $\alpha = \beta = 90^\circ$, and $\gamma = 120^\circ$, and the space group was P 3 (No. 143). The trigonal phase had a higher symmetry than the monoclinic phase of crystalline Na$_3$B$_2$S$_3$ as shown in Table S1.

Table 1 Atomic coordinates of the Na$_3$B$_2$S$_3$ metastable phase.

Figure 5(b) and Figure S2(a) show schematic diagrams of trigonal and monoclinic Na$_3$B$_2$S$_3$, respectively, generated by the VESTA visualization program. The red, green, and yellow spheres are Na, B, and S, respectively. The major difference between the metastable and stable structures is the distortion of the six-membered ring consisting of B and S atoms. For ease of understanding, Figure S2(b) shows an image diagram of the monoclinic structure; the Na layers and B–S layers located at different z-positions are shown on the left. Na sites were added to a selected B–S layer. One-third of the B sites of the B–S layers are occupied, and the vacancy sites are shown as gray spheres. In the trigonal structure, the six-membered rings are not distorted because B atoms randomly occupy 1a or 1b sites. Conversely, in the monoclinic structure, the B atoms are located at only one of the three sites of the six-membered rings, leading to a distorted framework.

The temperature dependence of the ionic conductivities of the Na$_3$B$_2$S$_3$ samples is shown in Figure 6(a), and the Nyquist plot of Na$_3$B$_2$S$_3$ glass at room temperature is shown in Figure S3. A semicircle in the higher-frequency region and spike in the lower-frequency region were observed in the Nyquist plot. The insert figure in the Fig. S3 is an equivalent circuit consisting of resistance and constant phase element (CPE). The CPE of the equivalent circuit reflects the capacitance from the Au current collector. The bulk and grain-boundary contributions were not reliably separated and thus the herein reported conductivities were calculated from total resistance $R$. The glass-ceramic heated at 300 °C had a low ionic conductivity, and thus it was measured only at 106 °C. For the other samples, the temperature dependence of the ionic conductivities obeyed the Arrhenius equation, and thus the activation energies were calculated from the Arrhenius plots. Their ionic conductivities at 25 °C (calculated from the Arrhenius equation) and activation energies are summarized in Table 2; for the glass-ceramic heated at 300 °C, the experimental conductivity determined at 106 °C is listed. The room-temperature ionic conductivity and activation energy of the Na$_3$B$_2$S$_3$ glass were 1.1x10$^{-5}$ S cm$^{-1}$ and 39 kJ mol$^{-1}$, respectively. This conductivity is higher than those of Na$_3$BO$_3$ glass$^4$ and Na$_3$PS$_3$ glass$^5$, as shown in Figure 6(b). The ionic conductivities at 25 °C and activation energies of other reported sodium-ion conducting glass electrolytes are summarized in Table S2. The electronic conductivity at room
temperature measured via DC polarization was $\text{7.6} \times 10^{-10} \text{ S cm}^{-1}$, which is five orders of magnitude lower than the ionic conductivity. Thus, the sodium-ion transport number of the Na$_3$BS$_4$ glass was almost unity. Figure S4 shows the room-temperature ionic conductivities and activation energies of the xNa$_3$S–(1−x)Na$_2$S$_2$O$_3$ (0.33 ≤ x ≤ 0.75) glasses. In the glass-forming region, Na$_3$BS$_4$ glass showed the highest ionic conductivity and the lowest activation energy because of its highest Na content.

**Figure 6.** Temperature dependence of conductivity for (a) Na$_3$BS$_4$ glass, glass-ceramics, and crystal electrolytes and (b) Na$_3$BS$_4$, Na$_3$BO$_2$, and Na$_3$PS$_4$ glass electrolytes.

Table 2 Ionic conductivities at room temperature ($\sigma_0$), activation energies ($E_A$), densities of pellets ($d$) and powders ($d$), and relative density ($d/d_0$) of Na$_3$BS$_4$ solid electrolytes.

| Electrolyte          | $\sigma_0$ (S cm$^{-1}$) | $E_A$ (kJ mol$^{-1}$) | $d$ (g cm$^{-3}$) | $d_0$ (g cm$^{-3}$) | $d/d_0$ |
|----------------------|---------------------------|-----------------------|-------------------|---------------------|---------|
| Na$_3$BS$_4$ glass   | 1.1×10$^{-1}$             | 55                    | 3.2               | 3.7                 | 0.86    |
| Na$_3$BO$_2$ glass   | 1.0×10$^{-1}$             | 32                    | 3.2               | 3.7                 | 0.86    |
| Na$_3$PS$_4$ glass   | 1.0×10$^{-1}$             | 32                    | 3.2               | 3.7                 | 0.86    |

The glass showed the highest ionic conductivity among the prepared Na$_3$BS$_4$ solid electrolytes. Between the glass-ceramics heated at 200 and 300 °C, the former showed a higher ionic conductivity. Table 2 lists the densities of the powder-pressed pellets ($d$) and powders ($d$) and the relative densities ($d/d_0$) of the Na$_3$BS$_4$ solid electrolytes. After heat treatment, the glass-ceramics showed lower relative densities than the glass because of crystal precipitation. The Na$_3$BS$_4$ glass pressed at 360 MPa showed the highest relative density of 94%, which is higher than that of Na$_3$BO$_2$ glass (88%) pressed at 720 MPa. This is related to the fact that the sulfide ion has a larger polarizability than the oxide ion. The high relative density means that the Na$_3$BS$_4$ glass has a favorable formability. Of other sulfide-based solid electrolytes, the relative density of Na$_3$PS$_4$ glass pressed at 360 MPa was 94%, indicating that the Na$_3$BS$_4$ glass has a similar formability. Figure 7 shows an SEM image of the fractured cross-section of the powder-pressed pellet of the Na$_3$BS$_4$ glass, indicating that the glass showed good formability.

**Figure 7.** Cross-sectional SEM image of the Na$_3$BS$_4$ glass.

Cyclic voltammetry was conducted to investigate the electrochemical properties of the Na$_3$BS$_4$ glass. Figure S5(a) shows cyclic voltammogram of an all-solid-state two-electrode cell using the Na$_3$BS$_4$ glass electrolyte. Stainless-steel and Na$_{12}$Sn$_4$–KB were used as working and counter electrodes, respectively. The potential sweep was performed with a scanning rate of 5.0 mV min$^{-1}$ at 60 °C. Reduction and oxidation currents attributable to sodium deposition and dissolution were observed at around 0 V versus the counter electrode, and no remarkable oxidation current was observed up to 5.0 V. This suggests that the Na$_3$BS$_4$ glass has a wide electrochemical window of 5.0 V. Figure S5(b) shows the cross-sectional SEM image of the cell after cyclic voltammetry. The working electrode of stainless steel was removed from the cell and two layers of Na$_3$BS$_4$ / Na$_{12}$Sn$_4$–KB are observed. A close contact at the interface between the two layers was maintained and unfavourable deterioration for the interface was not observed. The Na$_3$BS$_4$ glass was used as an electrolyte in an all-solid-state cell. Figure 8 shows the initial five charge–discharge curves of the all-solid-state Na$_{12}$Sn$_4$/Na$_3$BS$_4$ glass/TiS$_2$ cell. The cell was operated as a sodium secondary battery at 60 °C, where the conductivity of the Na$_3$BS$_4$ glass was $\text{5.8} \times 10^{-10} \text{ S cm}^{-1}$ and showed an initial charge capacity of 190 mA h g$^{-1}$. A capacity of approximately 170 mA h g$^{-1}$ was retained from the second to the fifth cycle, suggesting that Na$_3$BS$_4$ glass is adopted as a solid electrolyte for all-solid-state cells manufactured only by pressing.

**Figure 8.** Charge–discharge curves of the all-solid-state cell Na$_{12}$Sn$_4$/Na$_3$BS$_4$ glass/TiS$_2$ cell at 60 °C and a current density of 0.038 mA cm$^{-2}$ in the potential range of 1.2–2.4 V.

4. Discussion

Compared with the ionic conductivities of the glass-ceramic, the glass-ceramic heated at 200 °C showed higher ionic conductivity than that of heated at 300 °C. This was due to the obtaining of the metastable phase with a higher ionic conductivity than the stable phase. The activation energy of metastable phase was 55 kJ mol$^{-1}$. That of stable phase of glass-ceramic was not measured, but the activation energy of the Na$_3$BS$_4$ crystal which showed the same stable phase was 79 kJ mol$^{-1}$. It suggests that the activation barrier to ion conduction of metastable phase was smaller than that of stable phase due to the higher symmetry of the structure.

The ionic conductivity of the glass was higher than those of the glass-ceramics and crystal because of the random structure and free volume for ion conduction. Moreover, this conductivity is higher than that of Na$_3$PS$_4$ glass. These relative densities were same value (94%). Thus, the difference between these ionic conductivities is not caused by their formabilities. The activation energy of Na$_3$BS$_4$ glass was 39 kJ mol$^{-1}$, which was lower than that of Na$_3$PS$_4$ glass (47 kJ mol$^{-1}$). This suggests that the activation barrier to ion conduction of the Na$_3$BS$_4$ glass with planar triangular BS$_3$ units is smaller than that of Na$_3$PS$_4$ glass with tetrahedral PS$_4$ units. It was also found that the mean atomic volumes of the Na$_3$BS$_4$ glass and Na$_3$PS$_4$ glass were calculated using the powder densities of these glasses (1.932 g cm$^{-3}$ of Na$_3$BS$_4$ glass and 2.002 g cm$^{-3}$ of Na$_3$PS$_4$ glass). The mean atomic volume of the Na$_3$BS$_4$ glass is 13.0 cm$^3$ mol$^{-1}$, which is smaller than that of the Na$_3$PS$_4$ glass (14.2 cm$^3$ mol$^{-1}$). It suggests the high ionic conductivity of Na$_3$BS$_4$ glass is related with its larger packing density compared to the Na$_3$PS$_4$ glass.

5. Conclusions

The Na$_3$BS$_4$ glass electrolyte was prepared and their electrical and electrochemical properties were examined for the first time. The new metastable Na$_3$BS$_4$ phase with a trigonal structure was formed as a primary phase by crystallization of the Na$_3$BS$_4$ glass, and showed a higher ionic conductivity than the previously reported monoclinic Na$_3$BS$_4$ phase. The room-temperature ionic conductivity and activation energy of the Na$_3$BS$_4$ glass were $\text{1.1} \times 10^{-5} \text{ S cm}^{-1}$ and 39 kJ mol$^{-1}$, respectively and its crystallization decreased conductivity. In addition, the Na$_3$BS$_4$ glass showed a favorable formability. The all-solid-state cell operated with the prepared glass as the electrolyte exhibited a reversible capacity of approximately 170 mA h g$^{-1}$.
during five charge–discharge cycles at 60 °C. It is concluded that the Na$_3$BS$_3$ glass with triangular structural units has appropriate properties as a solid electrolyte for application to all-solid-state sodium batteries. The results of this study extend research toward designing multi-component sulfide electrolytes with triangular BS$_3$ structural units and contribute to the development of solid electrolytes for all-solid-state batteries.

Conflicts of interest
There are no conflicts to declare.

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Table 1 Atomic coordinates of the Na$_3$BS$_3$ metastable phase.

| Phase   | Na$_3$BS$_3$ |
|---------|--------------|
| Crystal System | Trigonal |
| Space Group | $P\ 3$ (No. 143) |

Lattice Parameter, Volume, $Z$

| $a$ | $c$ | $V$ | $\alpha$ | $\beta$ | $\gamma$ | $Z$ |
|-----|-----|-----|---------|--------|--------|-----|
| 3.901(1)Å | 7.422(1)Å | 97.83(1)Å$^3$ | 90° | 90° | 120° | 1 |

$$
\text{Atoms} \quad x \quad y \quad z \quad \text{Site} \quad \text{Occupancy} \quad B
$$

| Na1 | 0.6667 | 0.3333 | 0.2467(1) | 1c | 1.0000 | 1.000 |
|-----|--------|--------|-----------|----|--------|-------|
| Na2 | 0.6667 | 0.3333 | 0.7468(1) | 1c | 1.0000 | 1.000 |
| S1  | 0.0000 | 0.0000 | 0.0000    | 1a | 1.0000 | 1.000 |
| S2  | 0.3333 | 0.6667 | 0.5000    | 1b | 1.0000 | 1.000 |
| B1  | 0.3333 | 0.6667 | 0.0000    | 1b | 0.3333 | 1.000 |
| B2  | 0.0000 | 0.0000 | 0.5000    | 1a | 0.3333 | 1.000 |

Table 2 Ionic conductivities at room temperature ($\sigma_{25}$), activation energy ($E_a$), densities of pellets ($d_1$) and powders ($d_2$), and relative density ($d_1 / d_2$) of Na$_3$BS$_3$ solid electrolytes.

| Phase           | $\sigma_{25}$ / S cm$^{-1}$ | $E_a$ / kJ mol$^{-1}$ | $d_1$ (g cm$^{-3}$) | $d_2$ (g cm$^{-3}$) | Relative density (%) |
|-----------------|-----------------------------|----------------------|---------------------|---------------------|---------------------|
| crystal         | $3.7 \times 10^{-10}$       | 79                   | 1.725               | 1.996               | 86.4                |
| glass           | $1.1 \times 10^{-5}$        | 39                   | 1.824               | 1.932               | 94.4                |
| g.c. (HT200°C)  | $1.2 \times 10^{-8}$        | 55                   | 1.529               | 1.999               | 76.5                |
| g.c. (HT300°C)  | $8.0 \times 10^{-8}$ (at 106°C) | 1.701 | 2.001               | 85.0                |

$d_1$: density calculated from the volume measured by dimension of the pellet.

$d_2$: density calculated from the volume measured by a gas pycnometer.
Fig. 1

Intensity (arb. unit)

Monoclinic Na$_3$BS$_3$ [18] ICSD: 411608

Glass - ceramic HT at 200°C

Glass - ceramic HT at 300°C

Glass

Crystal
**Fig. 2**
**Fig. 3**

The figure shows NMR spectra for different materials:
- **Crystal**
- **Glass**
- **Glass-ceramic HT at 200°C**
- **Glass-ceramic HT at 300°C**

Key features:
- BS₃ and BO₂S₄-x
- Intensity (arb. unit)
- δ / ppm
- * : Spinning side bands
Fig. 4
Fig. 5

(a) Observed, Calculated, Difference, Trigonal Na$_3$BS$_3$

Intensity (arb.unit)

2θ / °(CuKα)

(b) 

Fig. 5
Fig. 6
Fig. 8

Cell voltage / V (vs. Na-Sn)

Capacity / mAh g\(^{-1}\) (TiS\(_2\))

60°C, 0.038 mA cm\(^{-2}\)

1.2 - 2.4 V