**Abstract**—In this study, Li$_4$SiO$_4$ powder was successfully synthesized via sol gel method followed by drying at 150°C. Lithium oxide, Li$_2$O and silicon oxide, SiO$_2$ were used as the starting materials with citric acid as the chelating agent. The obtained powder was then sintered at various temperatures. Crystallographic phase analysis, morphology and ionic conductivity were investigated systematically employing X-ray diffraction, Fourier Transform Infrared, Scanning Electron Microscopy and AC impedance spectroscopy. XRD result showed the formation of pure monoclinic Li$_4$SiO$_4$ crystal structure with lattice parameters $a = 5.140$ Å, $b = 6.094$ Å, $c = 5.293$ Å, $\beta = 90^\circ$ in the sample sintered at 750°C. This observation was confirmed by FTIR analysis. The bulk conductivity of this sample at room temperature was $3.35 \times 10^{-6}$ S cm$^{-1}$ and the highest bulk conductivity of $1.16 \times 10^{-4}$ S cm$^{-1}$ was obtained at 100°C. The results indicated that, the Li$_4$SiO$_4$ compound has potential to be used as a host for LISICON structured solid electrolyte for low temperature application.

**Keywords**— Conductivity, LISICON, Li$_4$SiO$_4$, Solid electrolyte, Structure.

**I. INTRODUCTION**

Crystalline as well as glassy Li$_4$SiO$_4$-based compounds have been investigated with regard to their use as solid electrolytes in secondary lithium batteries. The structure of Li$_4$SiO$_4$ has moderately good Li$^+$ conductivity and is a versatile host structure for doping to form LISICON (Lithium Super Ionic) structure. Both Li$^+$ interstitials and Li$^+$ vacancies can be created resulting in high conductivities [1]. For example, when Si$^{4+}$ ions are substituted by Al$^{3+}$ ions, the Al$^{3+}$ ions occupy Si$^{4+}$ sites with Li$^+$ ion entering interstitial sites, (Si$^{4+} + $ Li$^+$) to give a compound with a general formula, Li$_{4+x}$Al$_x$Si$_{1-x}$O$_4$ and when Si$^{4+}$ ions are substituted by V$^{5+}$ ions, Li$^+$ vacancies are created, (Si$^{4+} + $ Li$^+$ = V$^{5+}$) to give a compound with a general formula, Li$_{4-x}$V$_x$Si$_{1-x}$O$_4$[2].

LISICON structured solid electrolytes based on Li$_4$SiO$_4$ have been reported to show high conductivity at high temperatures (200°C – 500°C) [3]. These compounds are commonly synthesized by conventional solid state reaction method. This method is lead to many problems such as its use of high firing temperature, contamination with impurities, volatilization, lack of control of the microstructure and composition and suffer to obtaining good ceramics free of grain boundary resistances.

In order to overcome this problem, the sol gel method was used to prepare ion conductor materials. The sol gel technique has the advantages of lowering the synthesis temperature and can improving grain boundary conductivity and is a high purity process which leads to good homogeneity [4]. Recently Wu et al. reported the synthesis of Li$_4$SiO$_4$ employing sol gel technique [5-6]. In the former paper, the conductivity behavior of the compound was reported for the temperature range from 250 to 400°C. In the present study, Li$_4$SiO$_4$ compound was synthesized using a similar method. However, its conductivity behavior was studied at low temperatures ranging from 25 to 100°C in order to study the potential of this compound to be used as a host in LISICON structured solid electrolytes for low temperature electrochemical devices.

**II. EXPERIMENTAL PROCEDURE**

**A. Synthesis of Li$_4$SiO$_4$**

Li$_4$SiO$_4$ powder was prepared by sol gel method. Li$_2$O and SiO$_2$ were used as the starting materials and citric acid ($C_6H_8O_7$) was used as the chelating agent. The molar ratio of Li$_2$O: SiO$_2$ was fixed at 4:1. Li$_2$O was dissolved in distilled water before mixing with SiO$_2$ and citric acid. Citric acid was used to adjust the pH value of the solution to alkali (pH = 8.5). After that, the mixture was stirred under continuous reflux process for 1 hour until a colloidal solution was obtained. The colloidal solution was vaporized at 80°C and a gel was formed ultimately. The gel was dried at 150°C for 24 hours to remove H$_2$O particle, resistance organic group and also to avoid ceramic cracks. The flowchart of the synthesis procedure is shown in Figure 1. The obtained powder was palletized and the pallets formed were later sintered at temperatures from 600 – 750°C for four hours.

**B. Characterization Techniques.**

Crystallographic phases present in the prepared samples were identified by XRD using Bruker AXS, with CuK$\alpha$ radiation. To confirm the formation of the phases, FTIR was done on the samples employing Perkin Elmer FTIR Spectrum RX1 Spectrometer. The FTIR spectra were recorded at a resolution of 1 cm$^{-1}$. The morphology of the samples was observed by the Energy Dispersive Xray (EDX) technique. The AC impedance measurements were carried out using impedance analyzer, SOLATRON 1260 with platinum as the blocking electrode in the temperature range from 25 to 300°C over a frequency range from 0.1 to 10$^6$ Hz.

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III. RESULT AND DISCUSSION

A. X-ray Diffraction.

Figure 2 shows XRD spectra of Li$_4$SiO$_4$ sintered at different temperatures for four hours. As can be seen in the figure, the samples sintered at 600-700°C exhibit sharp diffraction peaks attributed to Li$_4$SiO$_4$ and Li$_2$CO$_3$ indicated the presence of both Li$_4$SiO$_4$ and Li$_2$CO$_3$ in the samples. The XRD spectrum of the sample sintered at 750°C shows peaks attributed only to Li$_4$SiO$_4$ demonstrating that pure Li$_4$SiO$_4$ has been obtained. The crystal structure of Li$_4$SiO$_4$ is monoclinic with space group \( P2_1/m \) and lattice parameters are \( a = 5.140 \ \text{Å}, \ b = 6.094 \ \text{Å}, \ c = 5.293 \ \text{Å}, \ \beta = 90^\circ \) which are close to those of West et al.\[7\].

B. Fourier Transform Infrared

Figure 3 depicts the FTIR spectra of the Li$_4$SiO$_4$ sample, sintered at 700°C and 750°C. The sample sintered at 700°C show strong bands in the regions of 726-1071 cm$^{-1}$ and 1366-1588 cm$^{-1}$. This may be attributed to stretching and bending vibrational modes of Si-O (800 cm$^{-1}$) in SiO$_4$ tetrahedral [8-9], stretching and bending vibrational modes of C=O (1550-1650 cm$^{-1}$) in CO$_2$ of Li$_2$CO$_3$ [10].

The Li$_4$SiO$_4$ sample sintered at 750°C does not show the bands between 1366 and 1588 cm$^{-1}$ which is due to the disappearance of C=O from Li$_2$CO$_3$. This observation is consistent with the result of XRD study and hence, confirms the formation of pure Li$_4$SiO$_4$ phase in the sample sintered at 750°C.

C. SEM and EDX analysis

The SEM micrograph of the sample sintered at 750°C is shown in Figure 4 (a) and its EDX analysis is presented in Figure 4 (b). The atomic ratio of Si:O is determined to be 1:4. Since Li$^+$ ion is not detectable by EDX, the concept of charge neutrality is employed [11]. Using this concept it is found that the stoichiometry of EDX analysis is in good agreement with the designated stoichiometry. This observation is consistent with the result of XRD analysis. Carbon detected in this analysis may come from citric acid.
Fig. 4 a) SEM micrograph and (b) EDX analysis of Li$_4$SiO$_4$ sample sintered at 750°C

D. Ionic Conductivity

Figures 5(a) and 5(b) display impedance spectra of the sample sintered at 750°C recorded at 27°C and 100°C. The conductivity value of the bulk conductivity was calculated using (1):

\[ \sigma_b = \frac{d}{AR_b} \]  

(1)

where \( d \) is the sample thickness, \( A \) is the area of the electrode and \( R_b \) is the bulk resistance. The bulk conductivity of this sample at 27°C is found to be \( 3.35 \times 10^{-6} \) S cm\(^{-1}\). The conductivity is observed to increase with increase in temperature. The increase in conductivity could be attributed to the greater movement of ionic point defect and the creation of greater ions movement due to an increase in thermal of energy [12]. The conductivity of the sample is determined to be \( 1.16 \times 10^{-4} \) S cm\(^{-1}\) at 100°C. The value is an order of magnitude higher compared to the Li$_{4-3x}$GaxSiO$_4$ (a modified Li$_4$SiO$_4$) system reported by Smith et al. measured at the same temperature [13].

The temperature dependence of the bulk conductivity is illustrated in Fig. 6 is found to be linear and well fits the Arrhenius equation (2),

\[ \sigma_b T = A \exp \left( \frac{-E_a}{kT} \right) \]  

(2)

where \( A \) is the pre-exponential factor, \( E_a \) the activation energy for conduction and \( k \) the gas constant. This indicates that there are no structure and phase changes in the sample for the studied temperature range.

Activation energy normally includes energy for formation and migration of ions. The Li$_4$SiO$_4$ structure is in the extrinsic regime below 200°C [14]. In this extrinsic regime, the activation energy is dominated by the migration energy. In this case, the activation energy can be represented by the migration energy for the doped oxide ionic conductors [15]. The activation energy; \( E_a \) determined from Figure 6 is 0.19 eV. The low value of activation energy is evidence for high mobility of ions in the sample.
IV. CONCLUSIONS

A pure Li$_4$SiO$_4$ sample was successfully prepared by sol gel method followed by sintering at 750°C. The conductivity of the Li$_4$SiO$_4$ compound obtained in this study showed conductivity in the order of 10$^{-4}$ S cm$^{-1}$ at 100°C and is higher compared to the modified Li$_4$SiO$_4$ compound reported by other researchers. This gives an indication of its potential to be used as a host for low temperature LISICON structured solid electrolytes.

REFERENCES


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