

## IMPEDANCE, DIELECTRIC AND MODULUS STUDY OF Ti-doped $\text{LiSn}_2(\text{PO}_4)_3$

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### ABSTRACT

$\text{LiSn}_2(\text{PO}_4)_3$  of composition  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  with NASICON structure was prepared by solidstate synthesis. XRD results show the formation of stable phase material of rhombohedral structure with the 3c space group. Traces of unreacted  $\text{SnO}_2$  and minor impurity of  $\text{SnP}_2\text{O}_7$  were detected. Impedance and dielectric study in the microwave range show conductivity enhancement in bulk and grain boundary. The room temperature ionic conductivity is  $4.74 \times 10^{-5}$  S/cm and the conductivity at 740 K is  $2.37 \times 10^{-3}$  S/cm. The highest value of dielectric constant ' obtained is 2000 and the lowest value is 500. Imaginary modulus vs temperature plot indicates the presence of temperature relaxation in the material. The plot of relaxation frequency at different temperatures was used to calculate the activation energy which was found to be 0.23 eV. These imply that the material could be applied as solid electrolyte at high temperatures.

**Keywords:** Impedance; conductivity; dielectric permittivity; modulus; relaxation

### INTRODUCTION

Solid electrolytes have many advantages over liquid electrolytes such as stability, ruggedness, miniaturization, wide range of operating temperature [1], simplicity of design, absence of leakage and pollution and better resistance to shocks and vibrations [2, 3]. In addition, solid electrolytes suffer from relatively low ionic conductivity, amongst others [4, 5].

The discovery of NASICON (Na-Super-Ionic Conductor) [6] was a major breakthrough in the tailored making of fast ion conductors (Super-Ionic Conductors) with a covalent framework structure. Apart from their potentials as solid electrolytes they find applications in conversion systems, super capacitors [7,8] sensors, displays, nuclear waste disposal, expansion ceramics, thermal shock resistant materials and exhibit promising catalytic properties [2,9]. They have potential applications as Li ion conductors for rechargeable lithium ion batteries due their high ionic conductivity, temperature stability, amongst others. Different systems such as  $\text{LiM}_2(\text{PO}_4)_3$  (M=Ti, Zr, Hf, Ge and Sn) have been reported [10,11] with the Ti-based system probably the most studied due to the smaller tunnels formed with  $\text{Ti}^{4+}$  cations which make better fit for the lithium conductors. The Li conductivity of  $\text{Li}_{1+x}\text{Ti}_{2-x}\text{Al}_x(\text{PO}_4)_3$  is up to  $10^{-3}$  S/cm at room temperature. However  $\text{LiSn}_2(\text{PO}_4)_3$ , an outstanding example, has been prepared via solid state reaction [12] with the sintering temperature reported to be very important. It is the least studied among members of the NASICON family [13] and has two crystallographic phases: a high temperature rhombohedral 3 symmetry phase with high ionic conductivity and a low temperature phase with triclinic *P1* symmetry, or monoclinic *Cc* symmetry with low conductivity. Stability of the compound has been an issue [14] with teflon having been used as binder to improve the stability against breakage due to the structural transition from monoclinic to rhombohedral. But the value of the conductivity obtained was very low ( $10^{-5}$  S/m) at room temperature. Nevertheless, some authors [15] succeeded in obtaining stable



pellets of  $\text{LiSn}_2(\text{PO}_4)_3$  using mechano-chemical milling without binder and the ionic conductivity improved to  $10^{-7}$  S/m at room temperature. Meanwhile, the sol-gel method has been used to overcome some of these problems due to its lower sintering temperature, shorter reaction time, good homogeneity and high specific area of the material [12, 16, 17]. Synthesis of  $\text{LiSn}_2(\text{PO}_4)_3$  using low sintering temperature citric acid-assisted sol-gel method resulted in a minor phase of impurity compared with samples prepared by mechanical ball-milling. X-ray diffraction study confirmed the formation of rhombohedral phase  $\text{LiSn}_2(\text{PO}_4)_3$  after sintering at 873 and 923 K for 48 h and conductivity attained at 873 K was  $1.38 \times 10^{-5}$  S/m, which is higher [17].

In the current work  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  has been synthesized using solid state reaction based on a sintering regime that is expected to enhance stability and electrical conductivity in order to resolve some of the above problems. The results of TGA/DTA, X-ray diffraction, impedance spectroscopy, modulus and dielectric studies are presented to elucidate these properties.

### EXPERIMENTAL PROCEDURE

$\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  was prepared by solid state reaction using agate mortar and pestle using stoichiometric amounts of analytical grade  $\text{Li}_2\text{CO}_3$  (India > 99%),  $\text{SnO}_2$  (99.99%),  $\text{TiO}_2$  (BDH, 99.99%), Methanol  $\text{CH}_3\text{OH}$  (BDH, 99.99%), and  $\text{NH}_4\text{H}_2\text{PO}_4$  (BDH, 99.99%). Appropriate amounts of the sample were properly mixed in agate mortar and pestle along with appropriate quantity of methanol to get a homogenous semisolid paste. The homogenous paste was initially calcined at 1173 K for 4 h in order to decompose  $\text{NH}_4\text{H}_2\text{PO}_4$  and initiate the reaction with the carbonate [14]. This led to the emission of carbon dioxide, ammonia and water vapour. The mixture was reground to micron size and pressed into a pellet. The dimensions of the pellet was measured and inserted into a steel mould of 16.8 mm diameter by 12 mm thickness in a pelletizing machine. The powder was then pressed in a cold press for 5 min under a hydraulic pressure of 5 N/m<sup>2</sup> with the formation of pellets of 16 mm diameter by 1.7 mm thickness. This was sintered at room temperature in alumina crucible at 1173, 1273 and 1373 K for 3 h, successively. 0.5g of sample specimen was used for thermal analysis using DTA/TGA on a TG-DTA machine (Perkin Elmer TGA 400). The data was taken from room temperature to 1113 K. XRD machine (D8 advance, Bruker AXS, 40 kV, 40 mA) with monochromatic  $\text{Cu-K}\alpha_1$  ( $\lambda = 1.54060\text{\AA}$ ) was used to characterise the structure and phase composition in the  $2\Theta$  range 12 to  $40^\circ$  and step size  $0.034^\circ$ . The counts were accumulated for 96 s for each step. Bragg's law ( $n\lambda = 2d \sin \Theta$ ) was used to calculate the peak positions for diffraction experimentally, where  $n$  is an integer,  $\lambda$  is the wavelength of the incident X-rays,  $d$  is the inter planer spacing and  $\Theta$  is the diffraction angle. The lattice parameters of the sample were calculated using equation (1).

$$\frac{1}{d^2} = \frac{4}{3} \left( \frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2} \quad (1)$$

where  $d$  is the inter planer spacing,  $h$ ,  $k$  and  $l$  are Miller indices and  $a$  and  $c$  are the lattice parameters.

The crystallite size was calculated using equation (2)

$$D = \frac{k\lambda}{\beta \cos \Theta} \quad (2)$$



where  $D$  is the crystallite size,  $k$  the Scherer constant (0.94),  $\lambda$  the wavelength,  $\beta$  is the Width at Half Maximum (FWHM) in radians and  $\Theta$  the Bragg's angle in radians.

Microstructure of surface of sample was determined by High Resolution Scanning Electron Microscope (HRSEM, Zeiss) operated at 20 kV and image captured at 5 kV. The ceramic was

positioned on an aluminium stage with the aid of carbon adhesive tape and coated with AuPd (Gold-Palladium) using a sputter coater. Impedance measurements were carried out by measurement of the complex impedance ( $Z = Z' - iZ''$ ) and the complex electrical conductivity ( $\sigma = \sigma' - \sigma''$ ) of the samples using coaxial impedance spectrometer [18] set in the frequency range 300 kHz to 3 GHz. Measurements were taken every 10 K on heating the sample at 1 K per min using a fixed voltage of 200 mV in air atmosphere. The samples were covered with platinum electrode paste and heated to 1073 K. The control and acquisition of data were carried out using Origin graphing software. Temperature range 300 to 740 K was used for all measurements.

### RESULTS AND DISCUSSION

The differential thermal analysis (DTA) and the corresponding thermo-gravimetric (TG) curves are prepared for  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  from 302 to 1113 K as shown in figure 1.

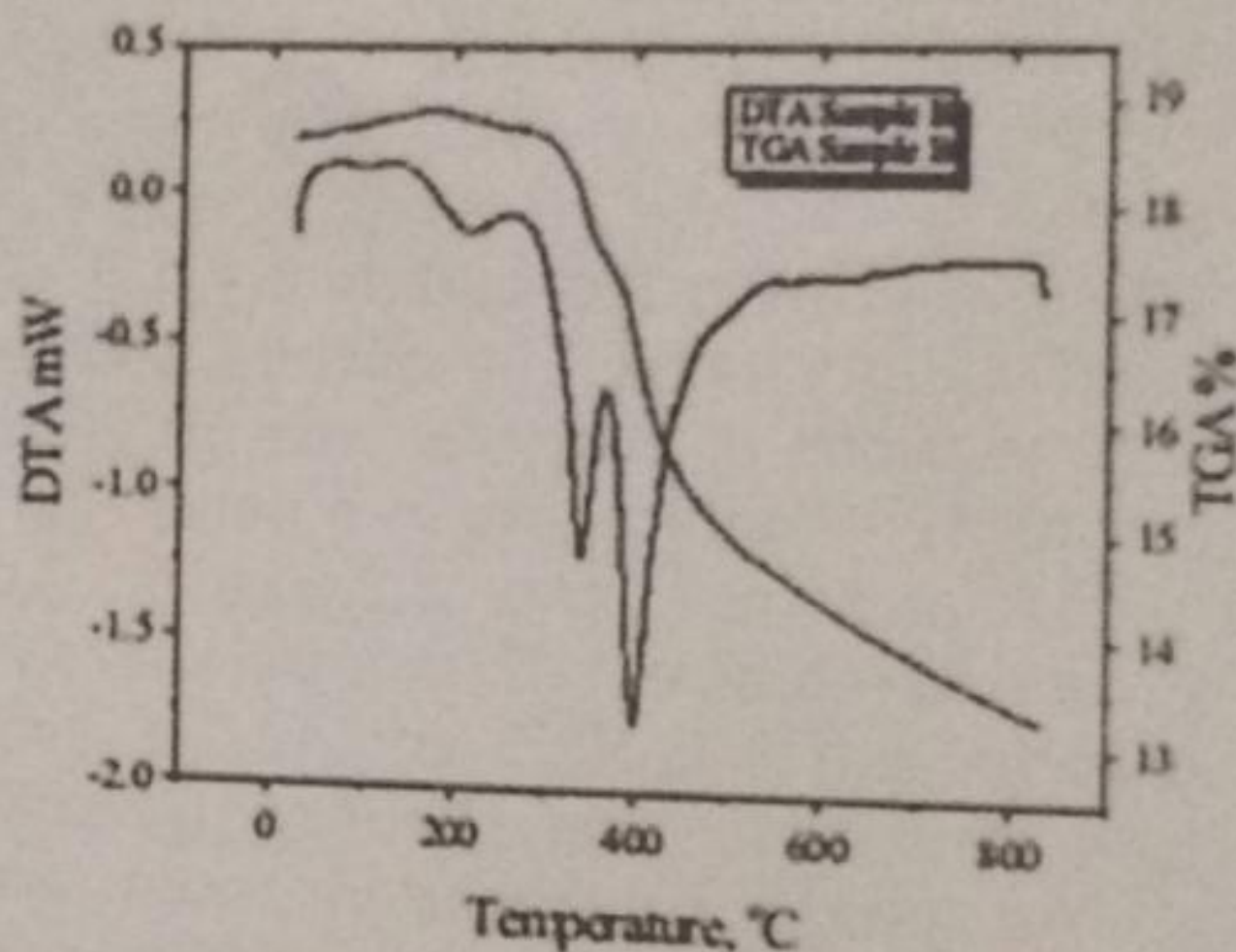


Figure 1: Simultaneous DTA-TG Plot for  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  showing Exothermic and Endothermic Peaks.

NASICON precursors show a slow rate of water losses up to about 220°C. These are the first endothermic processes which are due to the evolution of water molecules. A large endothermic peak appeared at 330°C and 410°C in the DTA plot of figure 1 with exothermic peak at 370°C in between them which may be attributed to thermal effects of decomposition of the sample precursors. The temperature 370°C is expected to be crystallization temperature of the material. The entire thermal effect was accompanied by the evolution of various gases such as,  $\text{CO}_2$ ,  $\text{NH}_3$  and water vapour which manifests as single step weight loss as shown in the TG curves.

Table 1 shows the variation of density with sintering temperature for  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  measured using Archimedes' principle. The unit cell volume of the sample was calculated from its structure and the lattice parameters,  $a$  and  $c$  were found to be 8.6122 and 21.4 Å, respectively. The density of the sample is 3.5945 g/cm<sup>3</sup> (that is more than 70% of theoretical value).



**X-ray powder diffraction (XRD) analysis**

XRD pattern of  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  sintered at 1100°C for 3 h is shown in figure 2. The spectrum clearly indicates the presence of rhombohedral  $\text{LiSn}_2(\text{PO}_4)_3$  crystalline NASICON of  $R3c$  symmetry obtained together with unreacted  $\text{SnO}_2$  and  $\text{SnP}_2\text{O}_7$  peaks [17]. Other authors [19] found minor phase of  $\text{SnO}_2$  and attributed it to Li loss during high temperature sintering. The peaks around  $20.9^\circ$  and  $21.9^\circ 2\theta$  correspond to triclinic structure (phase II) and  $P1$  symmetry along with rhombohedral NASICON-type structure (phase I) symmetry and  $\text{SnP}_2\text{O}_7$  [20]. The remaining peaks can be indexed in accordance with ICSD card no. 202157.

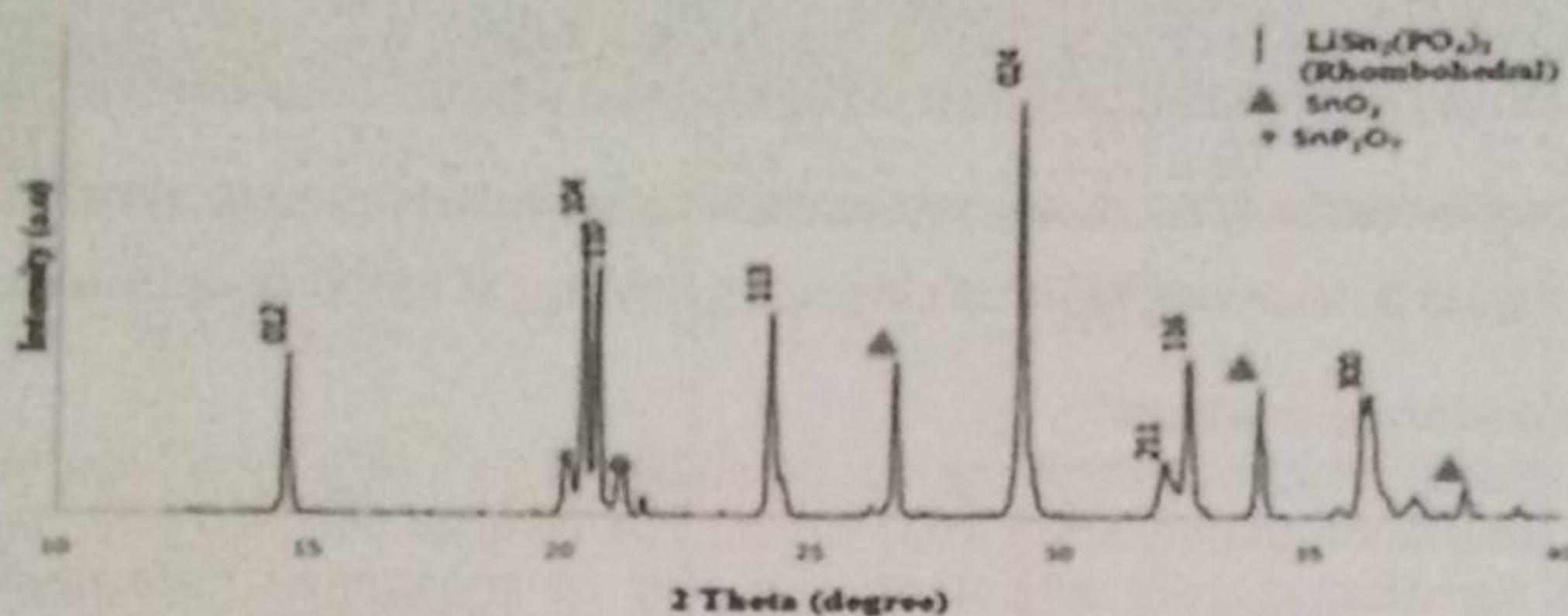


Figure 2: XRD Pattern of Sintered  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  with Peaks of Unreacted  $\text{SnO}_2$  and  $\text{SnP}_2\text{O}_7$ .

The lattice parameters, unit cell volume, experimental and theoretical density are presented in table 1.

Table 1: Calculated Lattice Parameters, Unit Cell Volume and Densities of  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  Compared with Reference Sample.

Sample	a(Å)	c(Å)	V(Å <sup>3</sup> )	Experimental Density (g/cm <sup>3</sup> )	Theoretical Density (g/cm <sup>3</sup> )	% Difference
$\text{LiSn}^{1.85}\text{Ti}^{0.15}(\text{PO}_4)_3$	8.5281	21.6492	1363.57	2.7568	3.5975	76.70
$\text{LiSn}^2(\text{PO}_4)_3$	8.4048	21.9621	1288.51	2.7027	3.5788	75.52

Table 1 shows the lattice parameters, where the cell volume, experimental and theoretical densities of the Ti-doped  $\text{LiSn}_2(\text{PO}_4)_3$  are in close agreement with literature [12] and those calculated from ICSD card no. 202157. The average crystallite size was found to be  $9.32\mu\text{m}$ .

**SEM analysis**

SEM micrograph image of  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  for the cross-sectional surface shown in figure 3 with some agglomeration of grains of different sizes. Estimation of average grain size showed a value of  $5.07\mu\text{m}$ . The sample has small grains in the  $\mu$ .



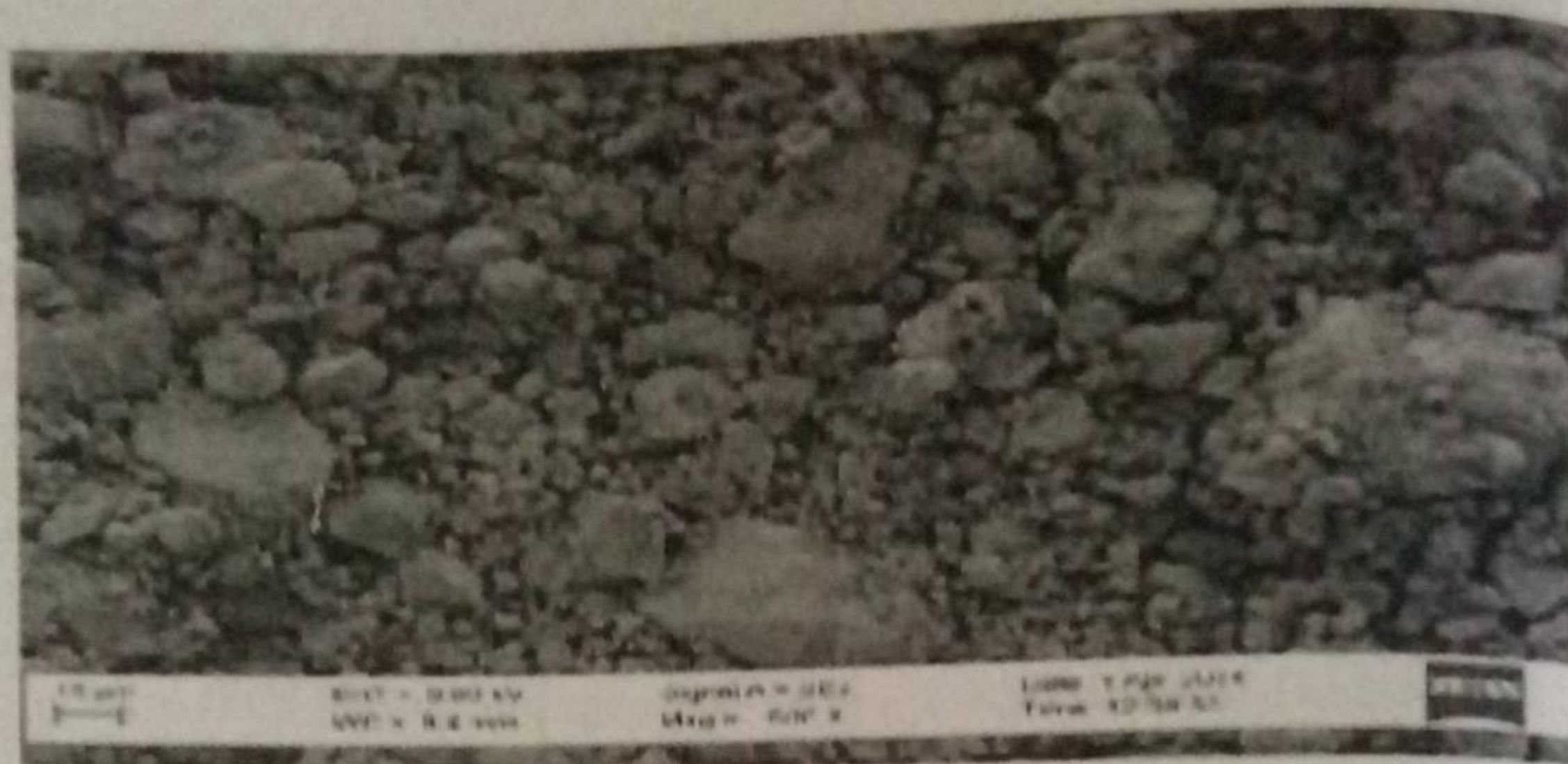


Figure 3: Microstructure of  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  at x1000 Magnification

**Complex impedance analysis**

Electrode /ceramic/ electrode interface can be analysed generally by an equivalent circuit of two parallel resistance-capacitance (RC) circuit. The Nyquist plot is a complex impedance plot for the variation of real and imaginary part of impedance measured at different temperatures and is shown in figure 4(a-d) for  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$ . The characteristic impedance spectrum is displayed by the appearance of the semi-circular arcs with patterns of evolution change with rise in temperature. The shape of these plots at 300 K is almost a straight line indicating the insulating behaviour of the sample. These shapes decrease with increasing temperature up to 400 and 600 K in which the curves bend towards the real axis. With further increase in temperature to 740 K the curves become almost semi-circular (figure 4d) and are indicative of an increase in the conductivity of the sample. It is difficult to determine the values of  $R_g$ (grain resistance) and  $R_{gb}$ (grain boundary) from complex impedance plots due to the overlap of the semicircles [21, 22]. As an alternative, the value of  $b$  (bulk conductivity) was determined by plotting imaginary part of conductivity versus real part  $\sigma'$ . The intercepts of the dispersion curves with the  $\sigma'$ -axis at high and middle frequencies give the values of  $b$  and  $t$  (total conductivity), respectively. The grain boundary conductivity is obtained by subtracting  $\sigma_b$  from  $\sigma_t$ .

Table 2: Shows the Comparison of Conductivity Values at Different Temperatures Determined from Impedance Plots for the Sample

Temp(K)	$R_b(\Omega)$	$R_{gb}(\Omega)$	$b(\text{S/cm})$	$gb(\text{S/cm})$	$t(\text{S/cm})$
300	$3.5 \times 10^3$	$4.1 \times 10^4$	$2.56 \times 10^{-5}$	$2.18 \times 10^{-5}$	$4.74 \times 10^{-5}$
400	$1.50 \times 10^3$	$3.75 \times 10^3$	$5.98 \times 10^{-5}$	$2.11 \times 10^{-5}$	$8.09 \times 10^{-5}$
600	$1.54 \times 10^2$	$3.30 \times 10^3$	$2.99 \times 10^{-4}$	$2.71 \times 10^{-5}$	$3.26 \times 10^{-4}$
740	$4.0 \times 10^1$	$6.80 \times 10^2$	$2.24 \times 10^{-3}$	$1.32 \times 10^{-4}$	$2.37 \times 10^{-3}$



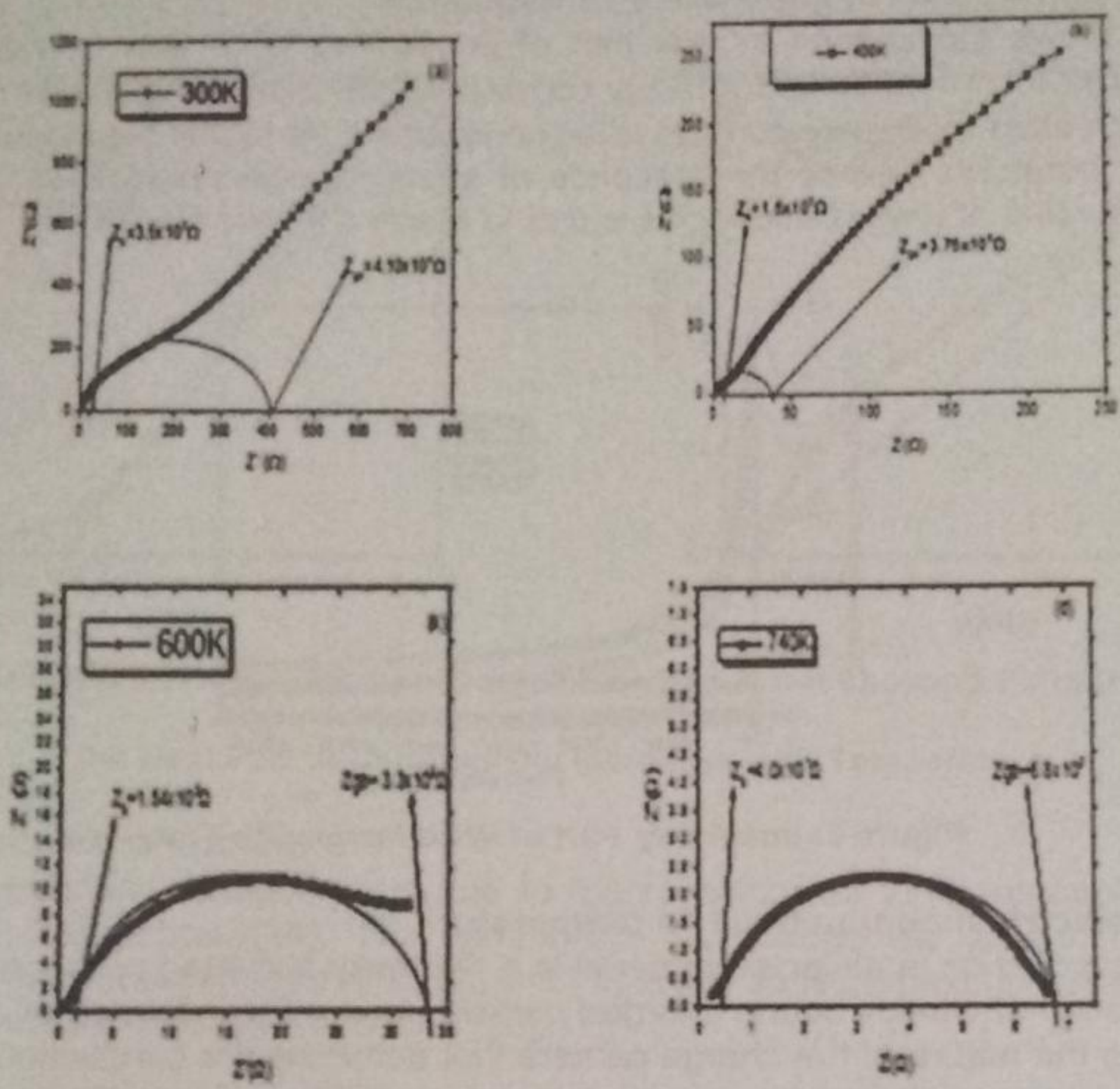


Figure 4: Impedance Plots of  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  (300 to 740 K),  
 (a) Impedance Plot of  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  at Temperatures 300  
 (b) 400 (c) 600 (d) 740 K, showing the Extrapolations for Grain and Grain Boundaries.

**Plot of real part of impedance vs frequency**

Figure 5 shows the change in real part of impedance ( $Z'$ ) with frequency at different temperatures for Ti-doped  $\text{LiSn}_2(\text{PO}_4)_3$  compound. On increasing the temperature the  $Z'$  value decreased indicating increase in ac conductivity as shown in figure 5. At higher frequencies the  $Z'$  values merge for all the temperatures due to the presence of space charge polarization [23]. The higher impedance values at lower frequencies are due to space charge polarization.

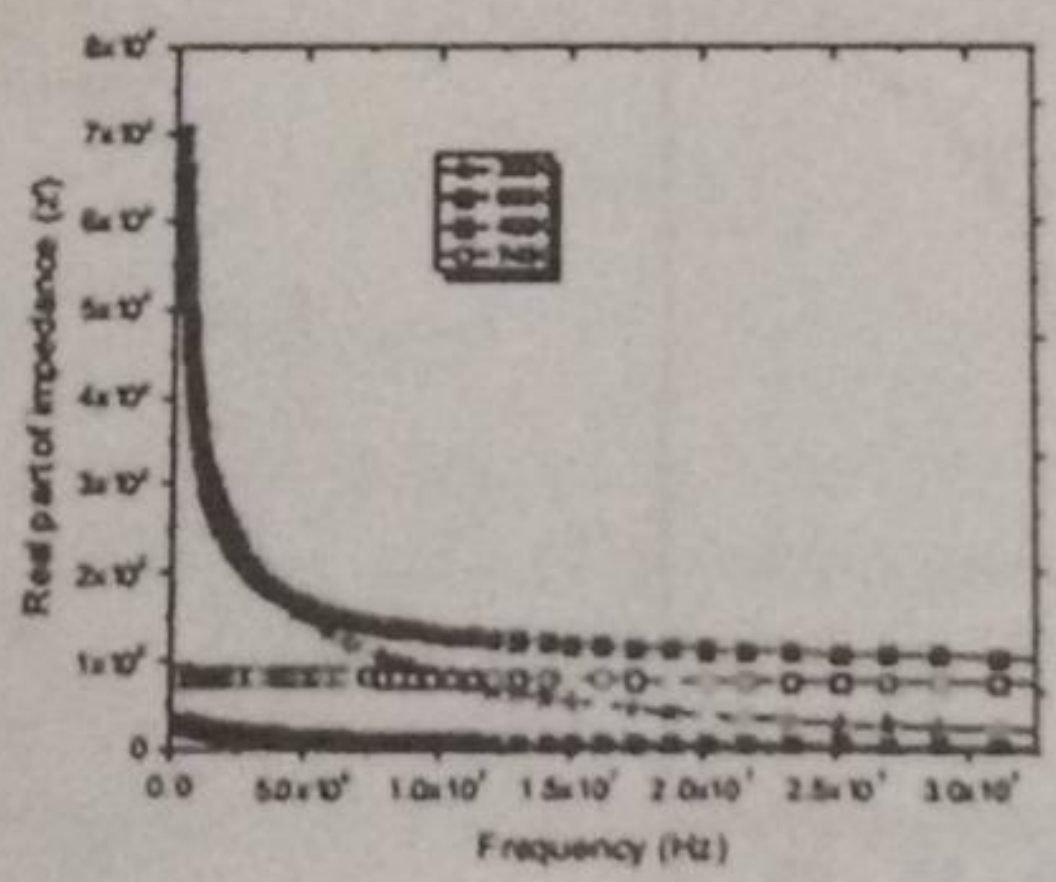


Figure 5: Variation of Real Part of Impedance with Frequency at Different Temperatures



**Plot of imaginary part of impedance vs frequency**

Figure 6 shows the change in real part of impedance ( $Z'$ ) with frequency at different temperatures for Ti-doped  $\text{LiSn}_2(\text{PO}_4)_3$  compound. On increasing the temperature the values decreased indicating increase in ac conductivity. At higher frequencies,  $Z'$  merges all the temperatures due to the presence of space charge polarization [23]. The high impedance value at lower frequencies is due to space charge polarization.

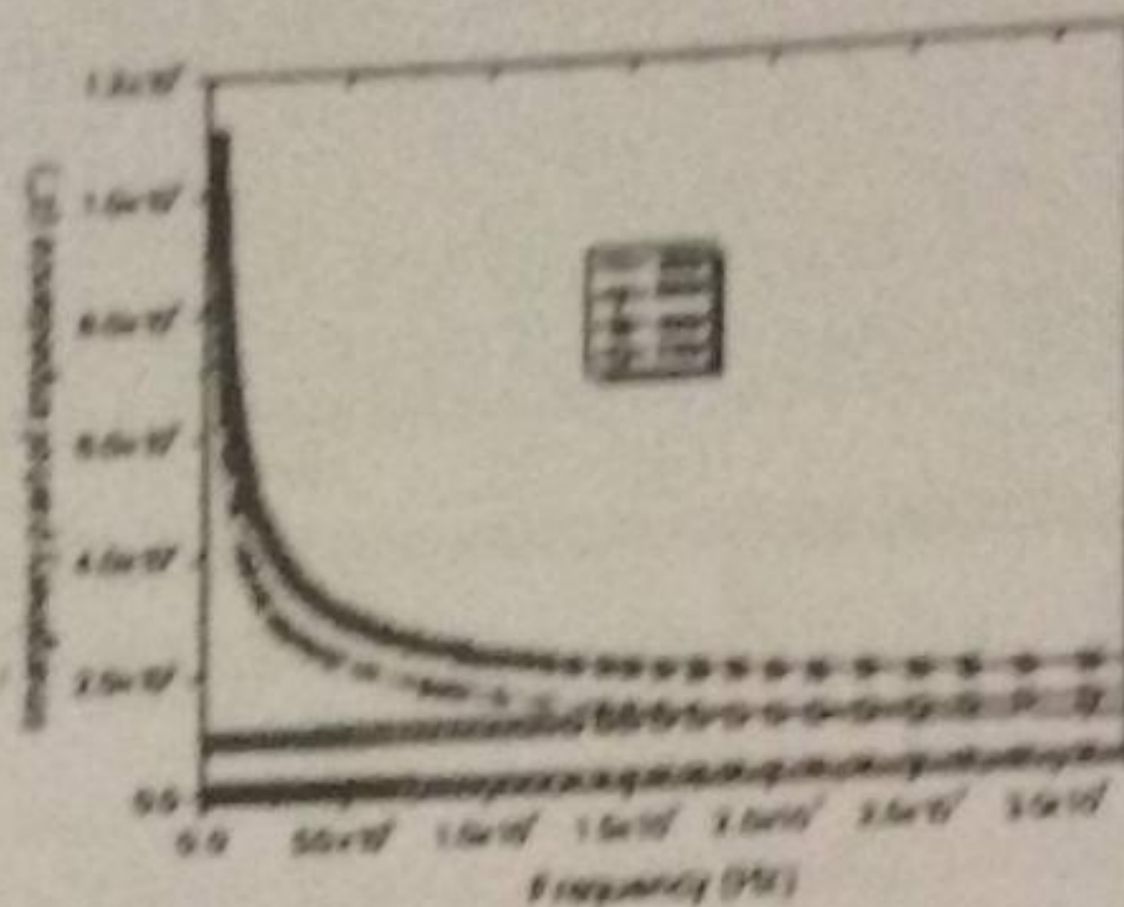
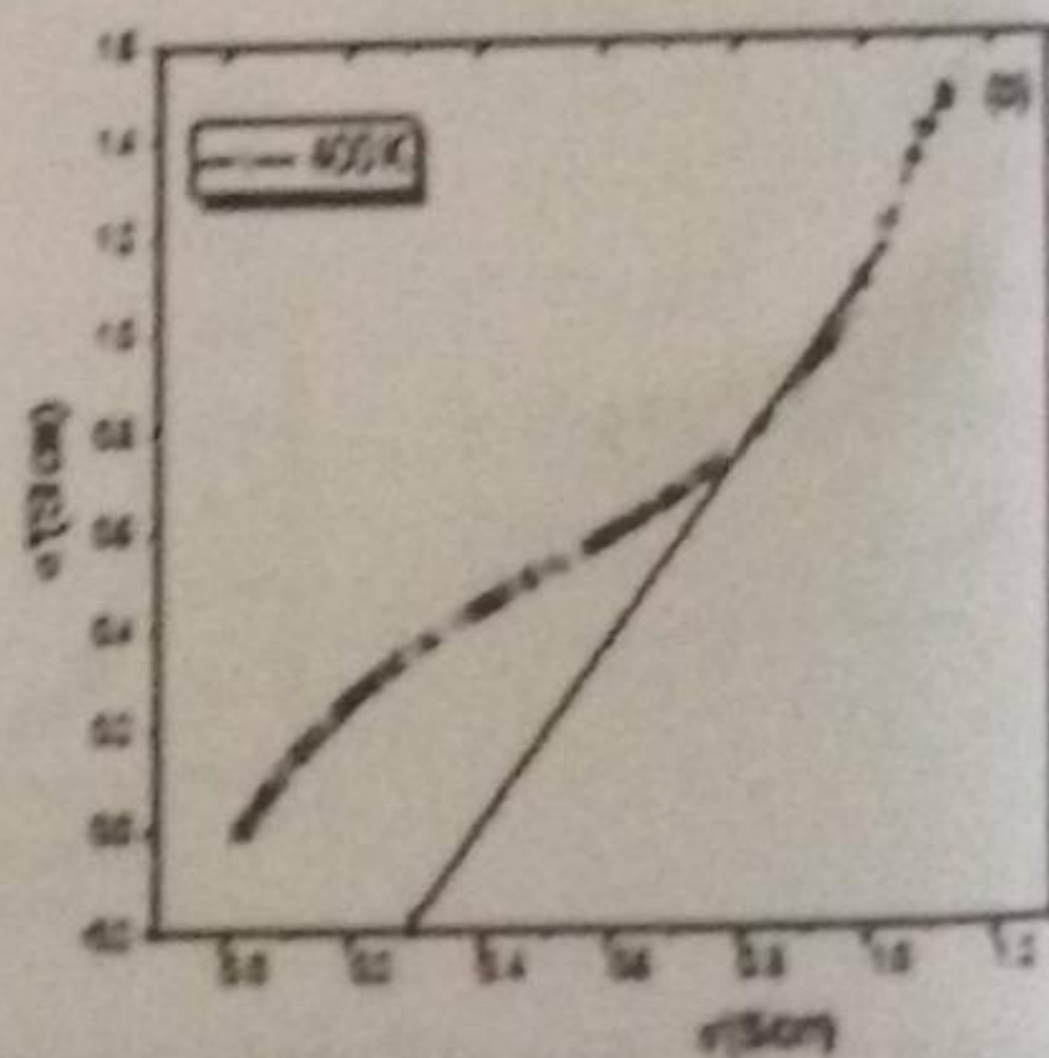
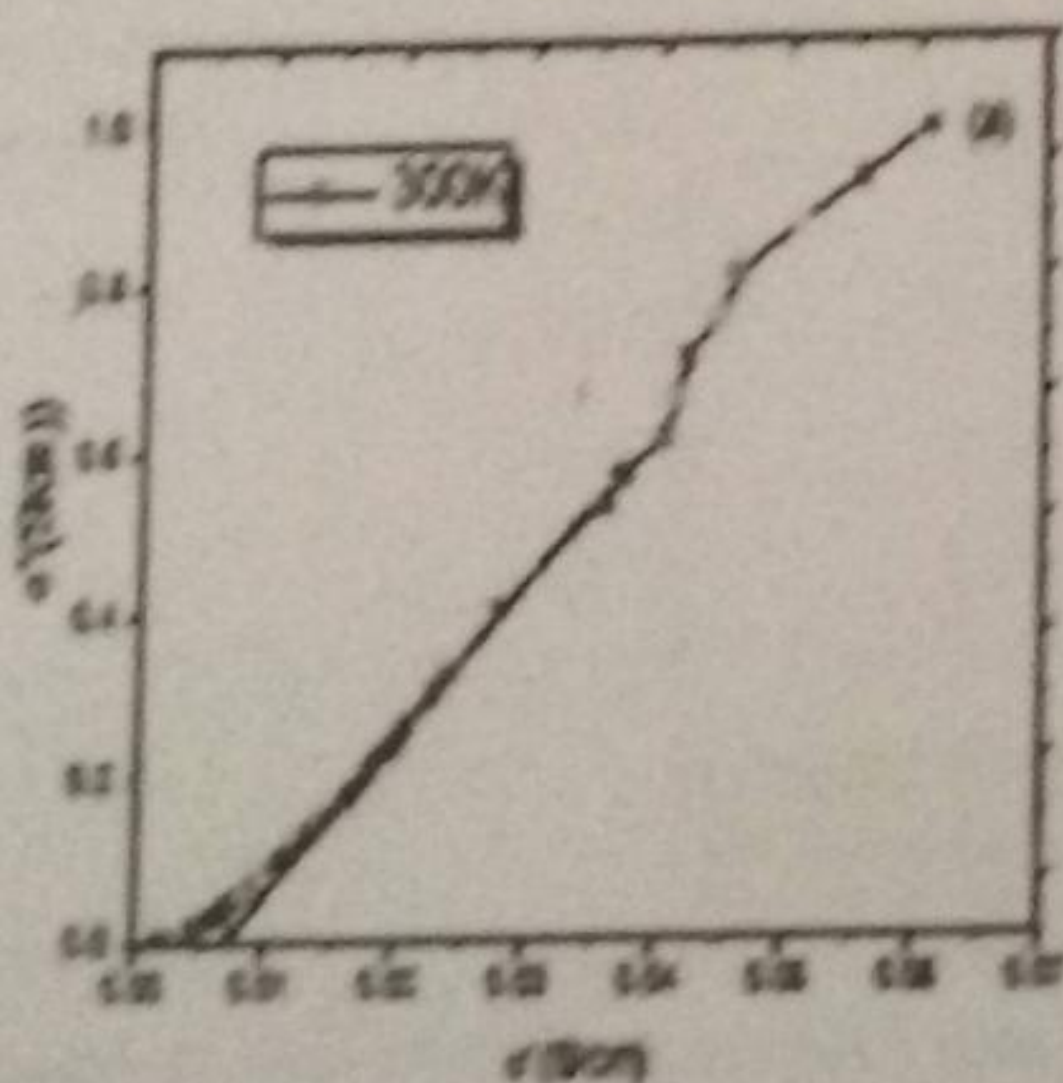


Figure 6: Imaginary Part of Impedance with Frequency

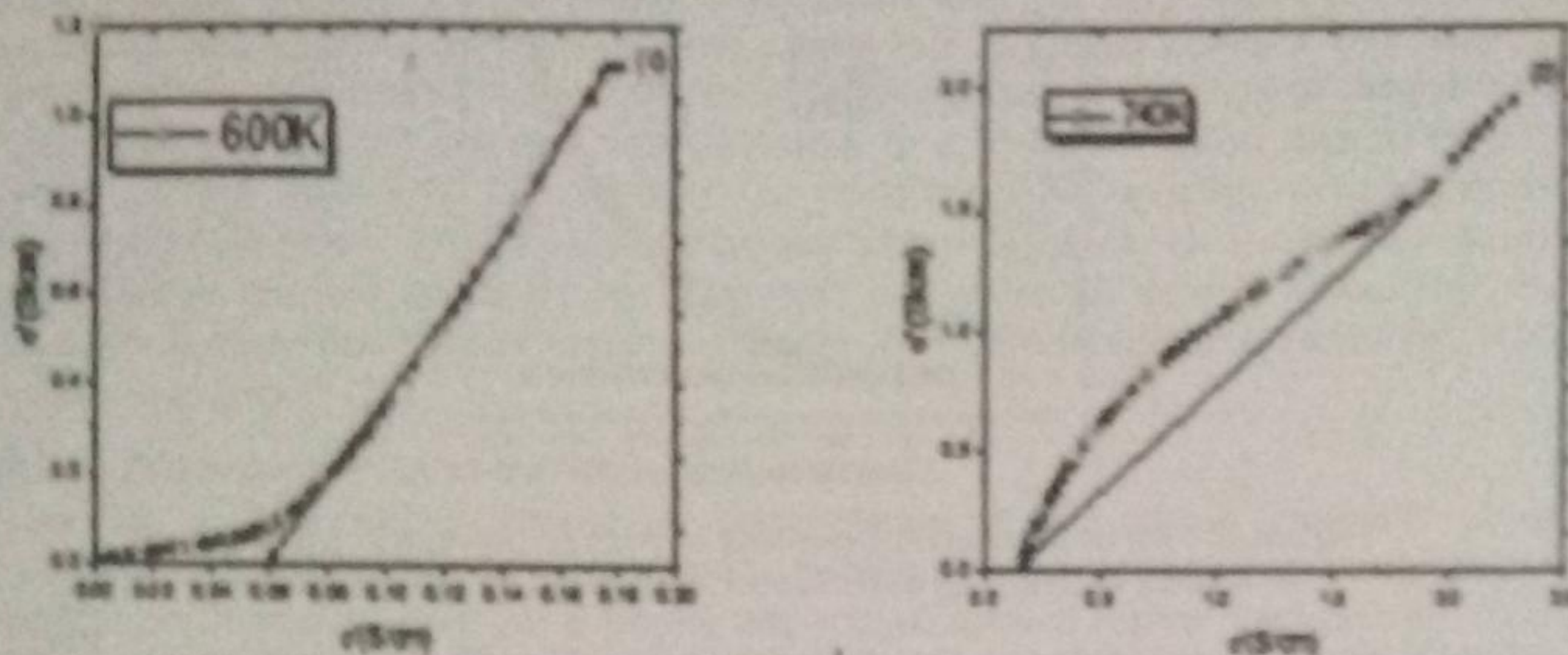
**Complex electrical conductivity vs temperature**

Electrical conduction in dielectric material is a thermally activated process and is due to the ordered motion of weakly bound charged particles under the influence of an electric field. It depends on the nature of the charge carriers that dominate the conduction process such as electrons/holes or cations/anions and follow the Arrhenius law. The  $\sigma_b$  and  $\sigma_{gb}$  of the compound can be evaluated from the impedance data using the relation,  $\sigma_b = \frac{d}{AR_b}$ , where  $R_b$  is the bulk resistance,  $d$  the thickness and  $A$  the area of the electrode deposited on the sample.  $R_b$  is obtained from the value of the low frequency intercept of the semicircle on the real axis ( $Z'$ ) on the complex impedance plot.

The conductivity plots shown in figure 7 consist of a semicircle and two dispersion curves in the low and high  $\sigma'$  regions at the same time. The point of intersection of the dispersion curve with  $\sigma'$  axis at high frequency gives the bulk conductivity value,  $\sigma_b$ .







Different Temperatures: (a) 300 (b) 400 (c) 600 and (d) 740 K showing Extrapolations for Real Part of Conductivity.

The Real Part of Conductivity Increases with Temperature.

**Ac conductivity vs temperature**

Frequency dependent conductivity is due to the relaxation of ionic atmosphere after the movement of the particle [24]. The variation of ac conductivity as function of log of frequency at different temperatures is shown in figure 8. Jonscher explained ac conductivity using the Universal Power Law equation [25]:

$$\sigma(\omega) = \sigma(0) + A\sigma\omega^n \tag{3}$$

where  $\sigma(0)$  is the dc or frequency-independent part related to dc conductivity and the second term is of constant phase element (CPE) type;  $n$  is a frequency exponent in the range  $0 \leq n \leq 1$ . The correlation exponent  $n$  can be determined from the slope of  $\ln \sigma$  versus  $\ln \omega$  [26]. The ac conductivity can be calculated from equation (4).

$$\sigma_{ac} = \omega \epsilon \epsilon_0 \tan \delta \tag{4}$$

The increasing trend of ac conductivity is due to the presence of disordered cations between the neighbouring sites and the presence of space charges that vanish at higher temperatures and frequencies. The change in slope takes place at a particular frequency known as the *hopping frequency*  $\omega_p$  and obeys the relation [27]:

$$\sigma(\omega) = K\omega_p \left[ 1 + \left( \frac{\omega}{\omega_p} \right)^n \right] \tag{5}$$

where all terms have been defined as usual.

**Dielectric vs Temperature and Frequency**

Figure 8 shows the plot of imaginary part of dielectric permittivity  $\epsilon''$  versus real part of dielectric permittivity  $\epsilon'$  which increases with temperature. The value of the imaginary part of dielectric permittivity is very high (2000) while that of real part of dielectric constant is very low (340) due to the effect of space charge polarization and/or motion of conducting ions [23].



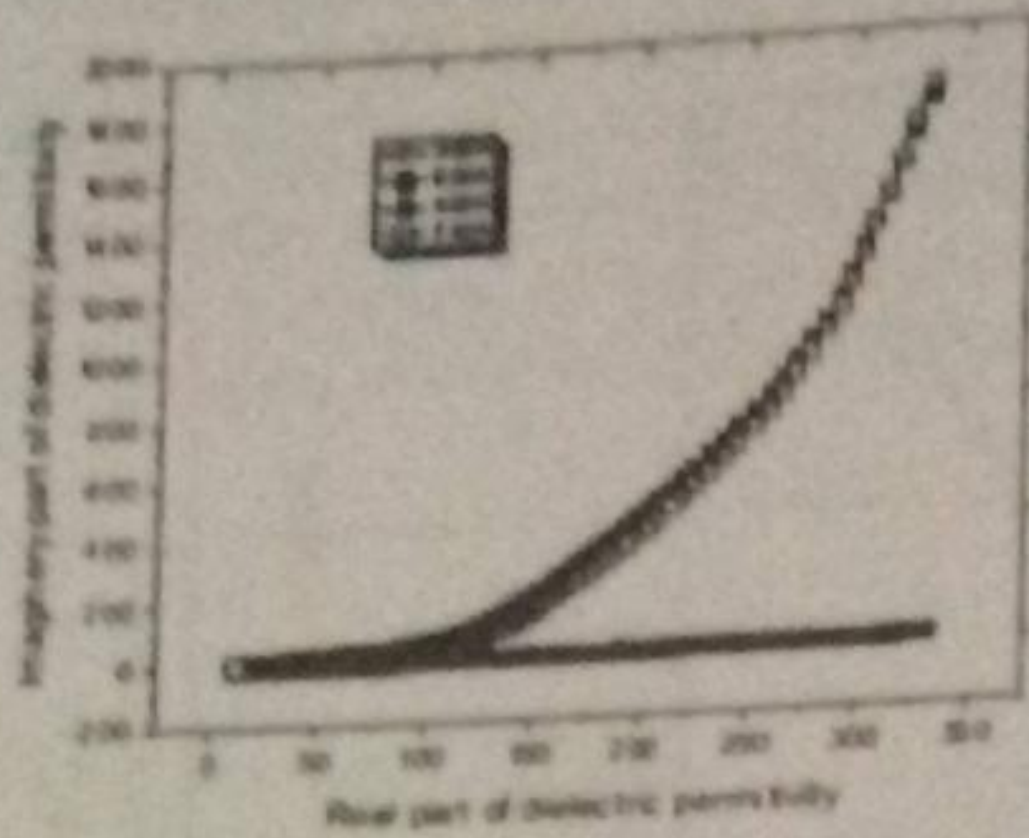


Figure 8. Plot of Dielectric Constant  $\epsilon'$  Versus Dielectric Loss ( $\epsilon''$ ) of Ti-doped  $\text{LiSn}_2(\text{PO}_4)_3$  at Different Temperature (300 to 740 K).

To acquire more information on the dynamic properties of the ion in the material, frequency dependence of the dielectric constant  $\epsilon'$  and dielectric loss  $\epsilon''$  for the  $\text{LiSn}_{1.85}\text{T}(\text{PO}_4)_3$  at different temperatures are depicted in figures 9 and 10.

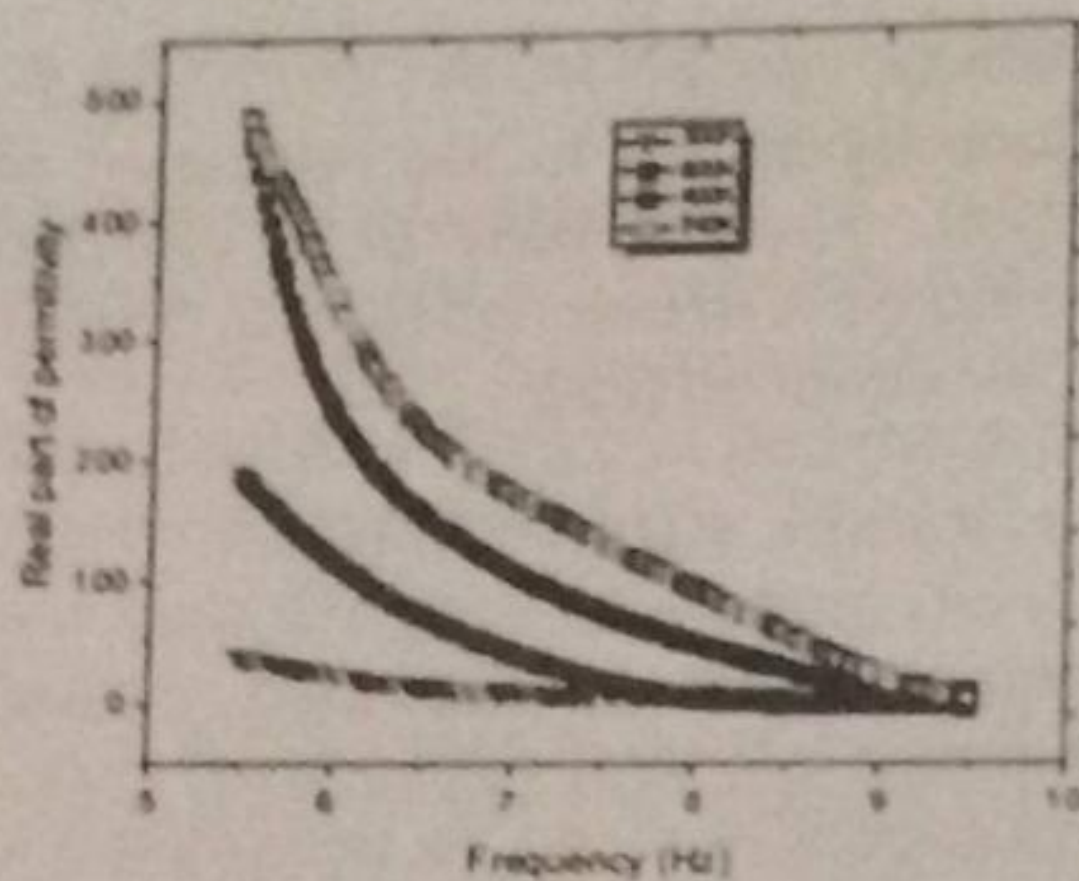


Figure 9: Plot of Relative Dielectric Constant ( $\epsilon'$ ) of Ti-doped  $\text{LiSn}_2(\text{PO}_4)_3$  as a Function of  $\log f$  at Different Temperatures

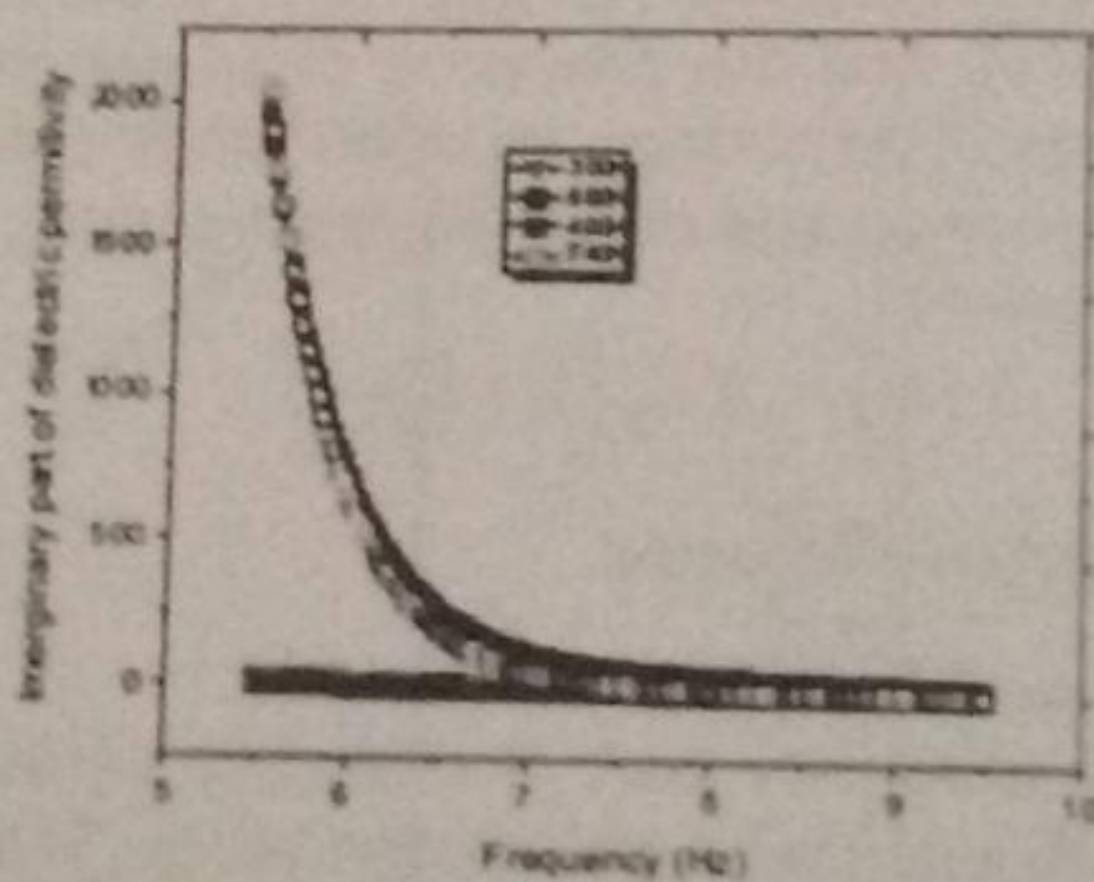


Figure 10: Plot of dielectric constant ( $\epsilon''$ ) of Ti-doped  $\text{LiSn}_2(\text{PO}_4)_3$  as a Function of  $\log f$  at Different Temperatures.

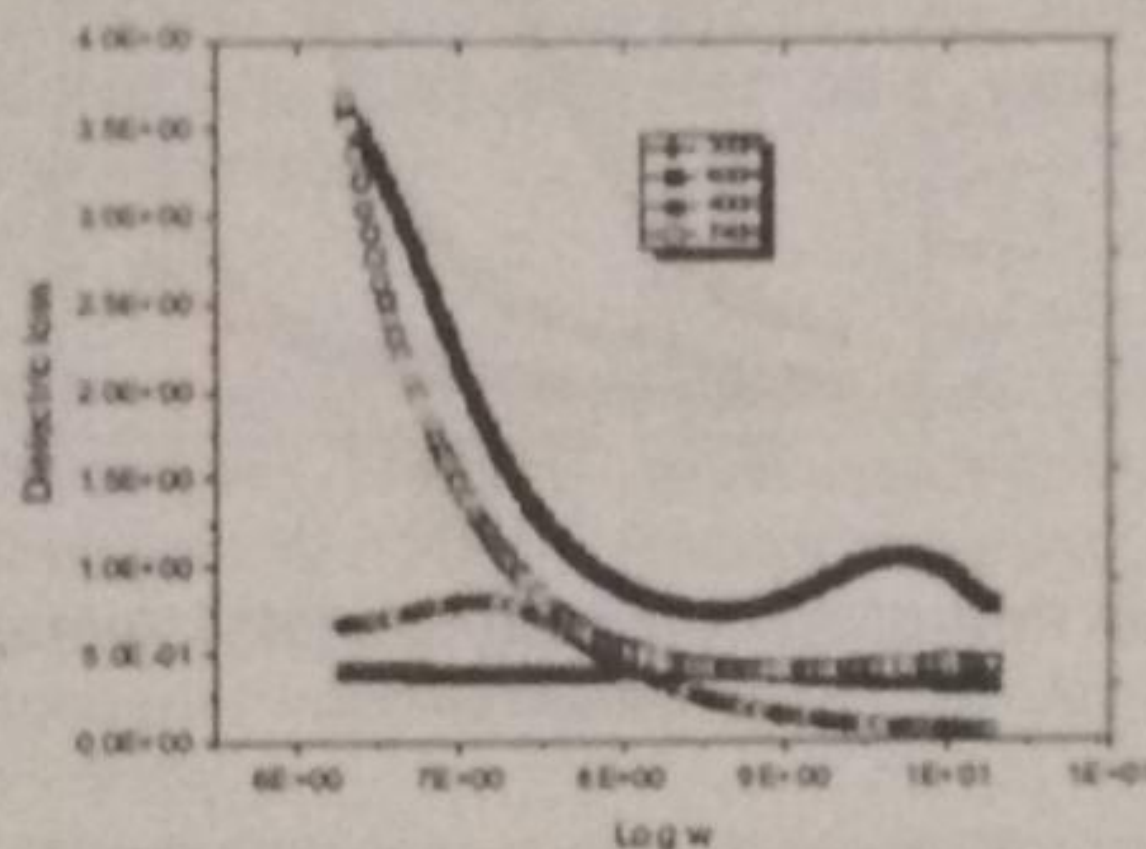
At low frequencies the high value of dielectric constant ( $\epsilon' \sim 500$ ) is due to the contribution of charge carrier accumulation at the interface of electrode and the  $\text{LiSn}_2(\text{PO}_4)_3$  material.



Also at high frequencies the dielectric constant  $\epsilon'$  and dielectric loss  $\epsilon''$  decrease to a constant value. Meanwhile, the values of dielectric loss are very high ( $\epsilon'' \sim 2000$ ) at these frequencies because the electrical energy loss is high because some of their energy is lost to the lattice as heat due to ion motion. At high frequencies the values of dielectric constant  $\epsilon'$  and dielectric loss  $\epsilon''$  are low and decrease to a constant value due to high periodic reversal of the field and to limitations of dielectric loss sources (ion vibration only), respectively [28]. The  $\epsilon'$  and  $\epsilon''$  values increase with increase in temperature indicating that bound charge carriers get sufficient excitation energy to be able to follow the charge in external field more easily. This in turn increases their contribution to polarization resulting in increase in  $\epsilon'$  and  $\epsilon''$  [29].

**Tan $\delta$  vs Frequency Plot at Various Temperatures.**

Figure 11 is the plot of frequency dependence of  $\tan \delta$  (loss tangent) at different temperatures and indicates a peaking behaviour for some temperatures. As the temperature increases, the  $\tan \delta$  peaks are shifted toward higher frequencies. The peaks are expected when the hopping frequency of ions is approximately equal to the external applied electric field. In this, case  $\omega\tau = 1$ , where  $\tau$  is the relaxation time of the hopping process and is the angular frequency of the external field ( $\omega = 2\pi f_{max}$ ).



**Figure 11: The Plot of Frequency Dependence of  $\tan$  vs  $\log w$  at Different Temperatures**

The frequency dependence of imaginary part of modulus  $M''$  at different temperatures has been plotted (figure 12) in order to determine the relaxation frequencies. The imaginary part of electric  $M''$  modulus is indicative of energy loss under electric field [11], while  $M''$  rises smoothly to a peak value, and two of the peaks decrease at high frequency [11]. The low frequency side of the peaks is an indication of long range motion in which the ions drift to a long distance and the position of the peaks can be attributed to a transition from short range to long range mobility as the frequency decreases [11]. The shifts in  $M''$  maxima indicate the presence of temperature relaxation process in the material [11]. When the conductivity plots of frequency are analysed, the shifts in frequency of the  $M''$  peaks correspond to conductivity relaxation phenomenon [30]. The real part of electric modulus ( $M'$ ), on the other hand, represents the ability of a material to store energy and increases with increase in temperature at low frequencies (figure 13). The maxima of  $M'$  falls with increase in temperature in all the plots and  $M'$  tends to lower values, confirming that electrode effects make negligible contribution and may be ignored in the modulus at low frequencies and temperatures [11]. The frequency independent variation of at high frequencies may be attributed to absence of charge effects due to inhomogeneities in composition.



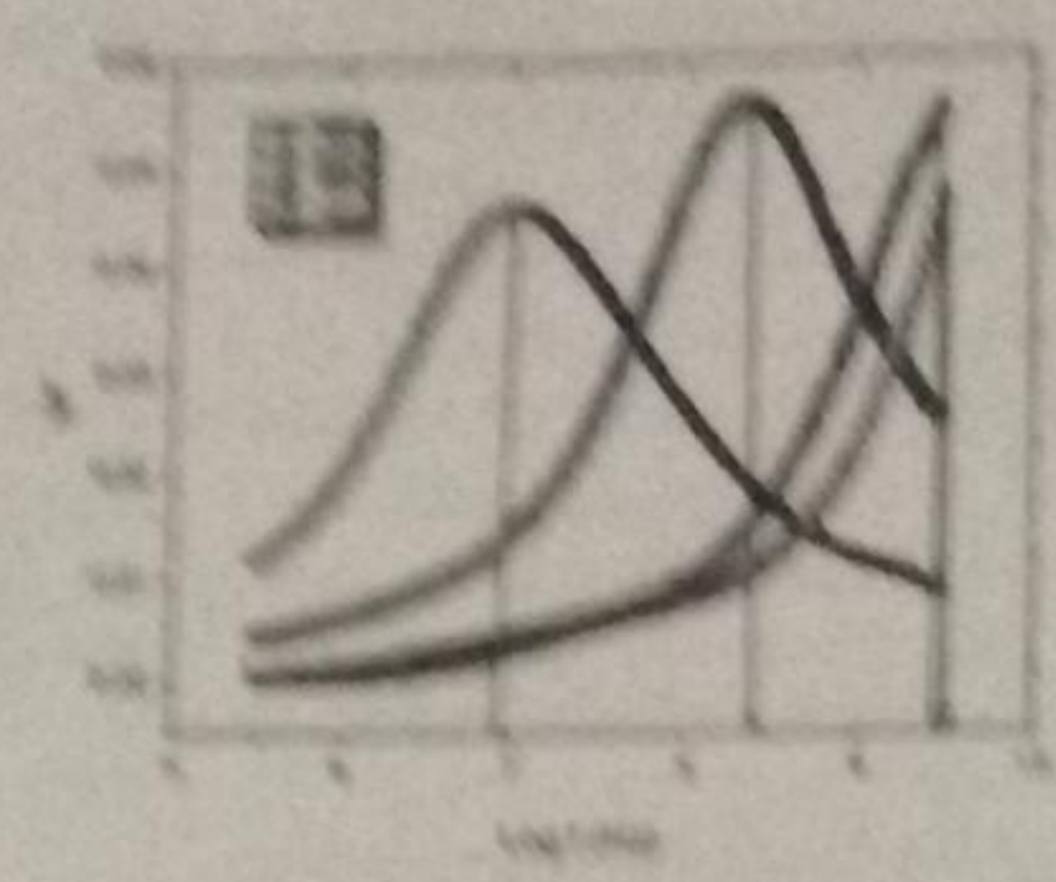


Figure 12: Plot of Frequency Dependence on at Different Temperatures Indicate the Relaxation process

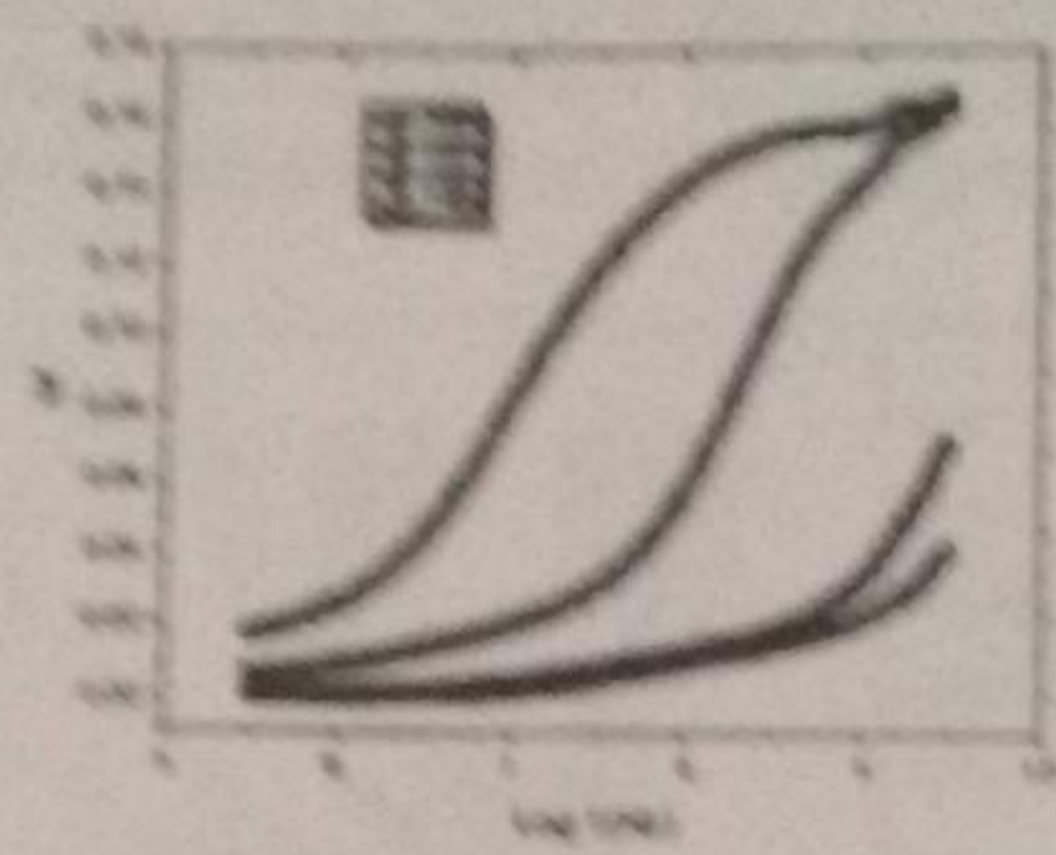


Figure 13. Plot of Real Part of Electric Modulus ( $M'$ ) Versus Frequency at Different Temperatures

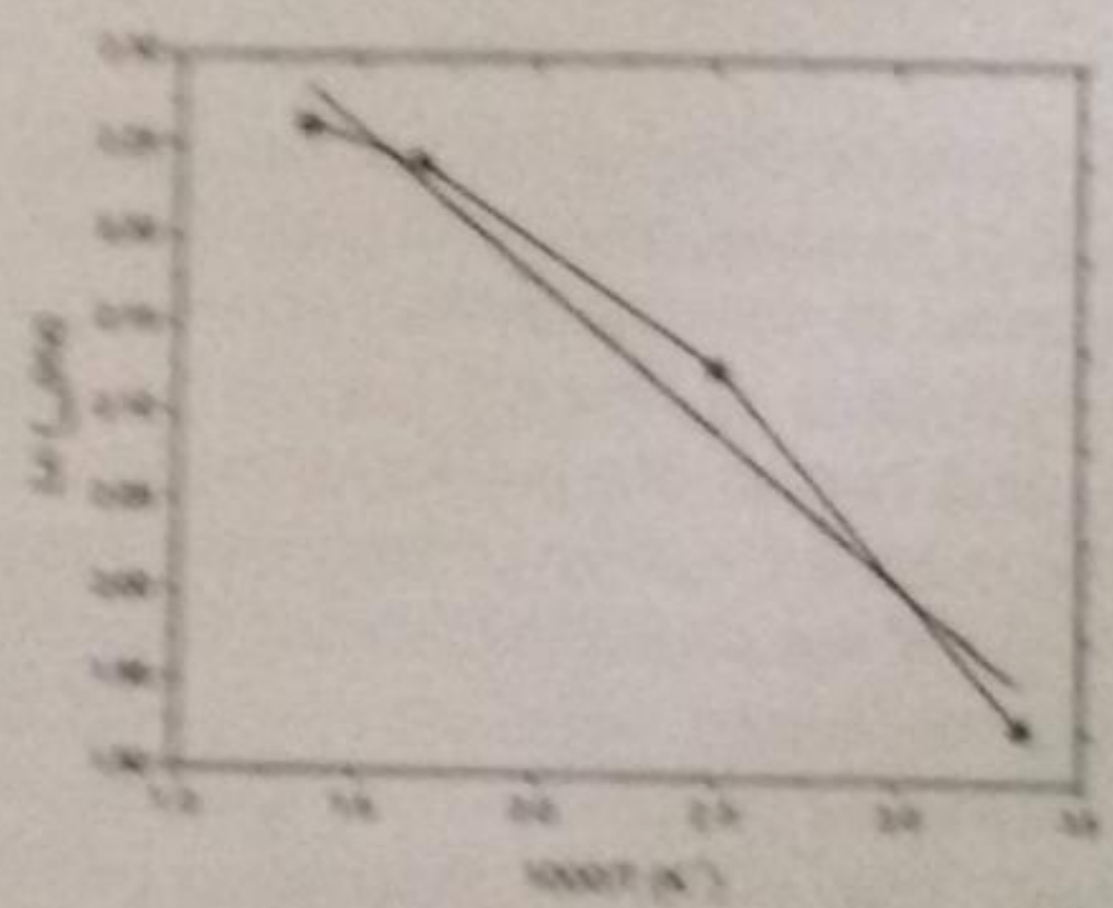


Figure 14. Plot of the Peaks of in  $M''(f_{max})$  vs  $1000/T$

The values of the peaks of  $M''$  (i.e.  $f_{max}$ ) are plotted in figure 14 against  $1000/T$ . The peaks are expected when the hopping frequency of the ions is approximately equal to the external applied electric field. In the case  $\omega\tau = 1$ , where  $\tau$  is the relaxation time of hopping process and  $\omega$  the angular frequency of the external field ( $\omega = 2\pi f_{max}$ ),  $\tau = \sigma_s = \frac{1}{\omega}$ . The natural logarithm of the relaxation frequencies at different temperatures have been plotted against reciprocal temperature. It was fitted to the Arrhenius equation of the form  $\ln f_{max} = \ln f_0 \exp\left(-\frac{E_a}{kT}\right)$ , where  $f_0$  is the pre-exponential factor, the activation energy



relaxation,  $k$  the Boltzmann constant and  $T$  is the absolute temperature. From slope the value of  $E_a \sim 0.23\text{eV}$ .

### CONCLUSION

Powdered  $\text{LiSn}_{1.85}\text{Ti}_{0.15}(\text{PO}_4)_3$  has been prepared by conventional solid-state reaction. XRD patterns of calcined sample showed the formation of rhombohedral symmetry with space group  $R3c$  and unreacted  $\text{SnO}_2$  phase coexisting with triclinic  $\text{SnP}_2\text{O}_7$ . Analysis shows decrease in lattice parameter  $c$ ; while  $a$ , the unit cell volume ( $V$ ) and the densities (both experimental and theoretical) increased compared with reference (pristine). The experimental density is  $\sim 3.6\text{ g/cm}^3$  ( $\sim 77\%$  of theoretical density). The crystallite size and the particle size of the sample decreased comparatively. Electrical conductivity studies show conductivity of order of  $4.74 \times 10^{-5}\text{ S/cm}$  at room temperature, that is, two orders of magnitude higher than those reported in literature. The highest conductivity achieved was  $2.37 \times 10^{-3}\text{ S/cm}$  at  $740\text{ K}$ . The results indicate that the sintering temperature was instrumental in the enhancement in electrical conductivity and thus makes the sample applicable as solid electrolyte at high temperatures.

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