Chapter 6

ELECTRICAL PROPERTIES OF NANOCRYSTALLINE Cu₂P₂O₇

6.1. Introduction

For the last few years, nanocrystalline materials have received extensive attention due to their unique physical, chemical, electrical and mechanical properties. Recent advancements in nanocrystalline materials manufacturing and processing enable the production of bulk nanoscale structural materials. The properties of these materials are entirely different from their conventional polycrystalline counterparts, due to their unique structure. Also, the structure-property relationship of nanocrystalline materials differ considerably from those observed for thin-film materials. The differences are mainly attributed to microstructural characters including crystallographic texture, porosity, impurities, grain boundary and triple junctions.

Nanocrystalline materials exhibit enhanced electrical properties compared to their bulk polycrystalline counterparts. The electrical conductivity and dielectric behavior of nanocrystalline materials depend on chemical compositions, preparation conditions and grain size. When nanostructured materials are sintered under special conditions, the valence state of ions change, and the individual cations thus formed in the sample lead to high conductivity. When such a material is cooled in an oxygen atmosphere, it is possible to form films of high resistivity over the constituent grains. Studies on the effect of temperature, grain size and frequency on the dielectric behaviour and a.c. electrical conductivity offer valuable information about conduction phenomenon based on localized electric charge carriers in nanostructured materials.

6.2. Experimental

Nanocrystalline copper pyrophosphate of different grain sizes were prepared by adding stoichiometric amounts of copper nitrate and ammonium dihydrogen phosphate, 10%(w/v) aqueous solution of PVA (the matrix) and the aqueous solution of sucrose (the fuel) and then evaporated to a viscous liquid, as described...
in section 2.2. This fluffy, voluminous, carbonaceous, pyrolysed mass is then thermolysed to get the nanosized powders. The carbonaceous precursor powders are then grounded and annealed at 600 °C for 5 hours. The crystal structure and particle size were determined by X-ray powder diffraction technique.\(^\text{11}\) The nanosized samples were consolidated into pellets of diameter 13 mm and thickness 1-2 mm at a pressure of 0.4 GPa. Capacitance \((C_p)\), dielectric constant \((\varepsilon')\), dielectric loss tangent \((\tan \delta)\) and a.c. conductivity \((\sigma_{ac})\) were obtained using a computer controlled Hewlett-Packard 4192 A impedance analyzer.\(^\text{12}\) The measurements were carried out at different frequencies from 100 Hz to 3 MHz over the temperature range 300 K to 373 K.

For the present study stoichiometric amounts of the reactants are taken such that the concentration of the reactants are \(1.0\ \text{mol} \cdot \text{L}^{-1}\), \(0.5\ \text{mol} \cdot \text{L}^{-1}\) and \(0.1\ \text{mol} \cdot \text{L}^{-1}\) to produce nanosized \(\text{Cu}_2\text{P}_2\text{O}_7\) samples of average grain sizes 34.46 nm, 32.26 nm and 27 nm (samples C1, C2 & C3) respectively, as described in section 2.2. In order to determine the crystal structure of nanocrystalline \(\text{Cu}_2\text{P}_2\text{O}_7\), the calculated ‘d’ values are compared with the standard ICDD-PDF\(^\text{13}\) data of \(\text{Cu}_2\text{P}_2\text{O}_7\). All the samples are found to be of monoclinic structure. The sharp and single X-ray diffraction peaks in the XRD pattern of \(\text{Cu}_2\text{P}_2\text{O}_7\) powder samples suggest the formation of single-phase compounds. For the dielectric measurements, the encapsulated pellets are immersed in a temperature controlled oil bath and the capacitance \((C_p)\), the modulus of complex impedance \((|Z|)\) and phase angle \((\theta)\) of the samples were measured over the frequency range 100 Hz to 3 MHz and over the temperature from 300 K to 373 K as described for \(\text{n-AlPO}_4\) in section 5.2.

6.3. Results and Discussion

6.3(i) Dielectric constant

The dielectric constant \(\varepsilon'\) of the given samples are calculated from the measured values of capacitance using the formula

\[
\varepsilon' = \frac{C_p \cdot d}{\varepsilon_0 \cdot A}
\]  

(6.1)

where \(d\) is the thickness, \(A\) is the cross sectional area and \(\varepsilon_0\) is the permittivity of free space.
The variation of dielectric constant ($\varepsilon'$) with frequency of the applied field for temperatures from 300 K to 373 K of samples C1, C2 & C3 are shown in Fig. 6.1 to Fig. 6.3. The dielectric constants, at all temperatures, are high at lower frequencies, which decrease as frequency increases and attains a constant low value at higher frequencies. For 323 K, $\varepsilon'$ is 795 at 100 Hz for sample C1, which decreases to 28 at 100 KHz. The corresponding variation at 373 K is from 130 to 21. The nature is similar for samples C2 and C3 also, but the values of $\varepsilon'$ increases at low frequencies when the grain size is decreased. For sample C2 at 323 K, $\varepsilon'$ is 875 at 100 Hz, which decreases to 24 at 100 KHz. For C3, the corresponding variation is from 1105 to 33. The values of $\varepsilon'$ at still higher frequencies remain almost the same at an average of 28 for all samples. In order to obtain the high frequency variations of the dielectric properties of the samples in detail, they are separately studied. Fig. 6.4 presents a typical example in which the variations of $\varepsilon'$ for sample C3 in the high frequency range (from 100 KHz to 3 MHz) are plotted. In this case, at 300 K, $\varepsilon'$ changes from 27.5 to 24.5 when frequency changes from 100 KHz to 3 MHz. At 373 K, the corresponding variation is from 30.5 to 28.5. The variation of dielectric constant with grain size of nano- Cu$_2$P$_2$O$_7$ is shown in Fig.6.5.
Fig. 6.2 Variation of dielectric constant ($\varepsilon'$) with frequency of n-Cu$_2$P$_2$O$_5$, sample C2

Fig. 6.3 Variation of dielectric constant ($\varepsilon'$) with frequency of n- Cu$_2$P$_2$O$_5$, sample C3
Fig. 6.4 Variation of dielectric constant with frequency of n- \( \text{Cu}_2\text{P}_2\text{O}_7 \) sample C3 in the high frequency region.

Fig. 6.5 Variation of dielectric constant (\( \varepsilon' \)) with frequency of \( \text{Cu}_2\text{P}_2\text{O}_7 \) samples with different grain sizes at 323 K.
The dielectric constant ($\varepsilon'$) at 323 K and at 100 Hz decreases from 1105 to 795 when the particle size increases from 27 nm to 34 nm.

The variations of dielectric constants with temperature for nano- Cu$_2$P$_2$O$_7$ of different grain sizes are plotted in Fig.6.6 to Fig.6.8. As in the case of nano - AlPO$_4$, the low value of dielectric constant at 300 K increases and attains a peak value at 323 K and then decreases gradually as temperature increases. This variation is high at lower frequencies as shown in the figures. The dielectric constant of n- Cu$_2$P$_2$O$_7$ sample C1 at 100 Hz increases from 120 to 795 and then decreases to 110 as temperature increases from 300 K to 373 K (Fig. 6.6). For sample C2, the corresponding variation is from 170 to 875 and then to 109 and for sample C3, it is from 210 to 1105 and then to 143 as shown in Fig. 6.7 and Fig. 6.8.

The variations of $\varepsilon'$ with temperature for sample C3 in the high frequency range (from 100 KHz to 3 MHz) are shown in Fig.6.9. The value of $\varepsilon'$ changes from 30.5 at 100 KHz and 373 K to 24.5 at 3 MHz and 300 K.

![Fig. 6.6 Variation of dielectric constant ($\varepsilon'$) with temperature of n- Cu$_2$P$_2$O$_7$, sample C1](image-url)
Fig. 6.7 Variation of dielectric constant ($\varepsilon'$) with temperature of n- Cu$_2$P$_2$O$_7$, sample C2

Fig. 6.8 Variation of dielectric constant ($\varepsilon'$) with temperature of n- Cu$_2$P$_2$O$_7$, sample C3
According to theory, the dielectric behaviour of nanostructured materials is primarily due to different types of polarizations present in the material.\textsuperscript{12} Nanocrystalline materials contain enormous number of interfaces, and the large number of defects present in these interfaces can cause a change of positive or negative space charge distribution. When an electric field is applied these space charges move and are trapped by these defects resulting in the formation of dipole moments. This is called space charge polarization. Interfaces in nanostructured materials posses many oxygen or nitrogen ion vacancies, which are equivalent to positive charges giving dipole moments. Exposed to an electric field these dipoles will rotate, giving a resultant dipole moment in the direction of the applied field. This is rotation direction polarization.\textsuperscript{12} Thus the high value of $\varepsilon'$ in the present study at low frequencies is mainly due to space charge polarization and rotation direction polarization.\textsuperscript{12,14} As temperature increases more and more dipoles will be oriented in the direction of the applied field,\textsuperscript{15} resulting an increase in the value of dipole moment. This is how $\varepsilon'$ increases with increase in temperature for fixed
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frequencies. The dielectric constant ($\varepsilon'$) initially decreases rapidly with increase in frequency but remains fairly constant at higher frequencies for all samples. This is due to the fact that beyond a certain frequency of the applied field, the electron exchange does not follow the alternating field, and hence the polarization decreases resulting a decrease in $\varepsilon'$.

6.3(ii) Dielectric loss

The variations of dielectric loss factor ($\tan \delta$) of nano-$\text{Cu}_2\text{P}_2\text{O}_7$ samples of different grain sizes with frequency are shown in Fig. 6.10 to Fig. 6.12. It can be seen that $\tan \delta$ decreases with increase of frequency and at higher frequencies the loss angle has almost the same value at all temperatures. For n-$\text{Cu}_2\text{P}_2\text{O}_7$ sample C1, the value of the dielectric loss at 323 K is 8 at 100 Hz, which decreases to 0.1 at 3 MHz. The corresponding variations for samples C2 and C3 are from 9 to 0.1 and from 10.5 to 0.15 respectively. The same behaviour is observed with reduced values for all other temperatures except at room temperature, where the loss factors do not change with frequency.

![Figure 6.10 Variation of dielectric loss (tan \(\delta\)) with frequency of n-$\text{Cu}_2\text{P}_2\text{O}_7$, sample C1](image-url)
Fig. 6.11 Variation of dielectric loss \((\tan \delta)\) with frequency of \(n\text{-Cu}_2\text{P}_2\text{O}_7\) sample C2

Fig. 6.12 Variation of dielectric loss \((\tan \delta)\) with frequency of \(n\text{-Cu}_2\text{P}_2\text{O}_7\) sample C3
Fig. 6.13 Variation of dielectric loss (tan δ) with frequency of n-Cu$_2$P$_2$O$_7$, sample C3 in the high frequency region

Fig. 6.14 Variation of dielectric loss (tan δ) with frequency of n-Cu$_2$P$_2$O$_7$ samples with different grain sizes at 323 K
The high frequency variations of $\tan \delta$ for all samples are separately studied. Fig 6.13 shows the variation of $\tan \delta$ for sample C3 in the high frequency range (from 100 KHz to 3 MHz). In this case, at 373 K, $\tan \delta$ changes from 0.8 at 100 KHz to 0.1 at 3 MHz. Similar variations are observed for other temperatures also as shown in the figure. The variation of $\tan \delta$ with grain size of nano- Cu$_2$P$_2$O$_7$ is shown in Fig.6.14. It can be seen that the dielectric loss ($\tan \delta$) at 323 K and at 100 Hz decreases from 11 to 0.8 when the particle size increases from 27 nm to 34 nm.

The variations of $\tan \delta$ with temperature for fixed frequencies are shown in Fig.6.15 to Fig.6.17. For all samples, $\tan \delta$ initially increases with frequency, attains a high value and then decreases as shown in the figures. For sample C1, dielectric loss at 100 Hz and 300 K increases from 0.4 to 8 at 323 K and then decreases to 0.1 as temperature increases to 373 K. The corresponding variation for sample C2 (Fig.6.16) is from 0.4 to 6 and then to 0.7. For sample C3 (Fig.6.17), it is from 0.7 to 11 and then to 1.4. Similar variations are observed for all other higher frequencies as shown in the figures.

The variation of $\tan \delta$ with temperature for sample C3 in the high frequency range (from 100 KHz to 3 MHz) is shown in Fig.6.18. The value of $\tan \delta$ at 100 KHz changes from 0.007 at 373 K to 0.003 at 300 K. Similar variations are observed for other frequencies also.

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![Graph](image.png)

**Fig. 6.15 Variation of dielectric loss ($\tan \delta$) with temperature of n-Cu$_2$P$_2$O$_7$, sample C1**
**Figure 6.16** Variation of dielectric loss ($\tan \delta$) with temperature of $n$-$Cu_2P_2O_7$, sample C2

**Figure 6.17** Variation of dielectric loss ($\tan \delta$) with temperature of $n$-$Cu_2P_2O_7$, sample C3
The dielectric loss of a material is given as

\[ \tan \delta = \frac{4 \pi \sigma / \varepsilon \omega}{\varepsilon} \]  \hspace{1cm} (6.2)

where \( \sigma \) is the conductivity and \( \omega \) is the frequency.

There is a strong correlation between the conduction mechanism and the dielectric behaviour. The conduction mechanism is due to hopping of electrons; as such when the hopping frequency is nearly equal to the frequency of the externally applied electric field, a maximum of loss tangent may be observed.\(^{16}\) In nanophase materials the inhomogeneities present in the interface layers produce an absorption current\(^{17}\) resulting in a dielectric loss. This absorption current decreases with increase in frequency of the applied field, resulting the dielectric loss to be reduced as shown in figures. The hopping or jumping probability per unit time increases with increase in temperature.\(^{16}\) Correspondingly the loss tangent also increases. The variation of \( \tan \delta \) for different grain sizes (shown in Fig 6.14) is due to size effect.\(^{11}\) The volume percentage of interface boundaries and therefore the amount of defects that causes the various types of polarizations increase as the particle size is reduced.
This explains the upward shift in the values of dielectric constant and dielectric loss tangent as the particle size is reduced.

6.3(iii) A.C. conductivity

The variations of a.c. electrical conductivity (\(\sigma_{ac}\)) as a function of frequency and temperature for the three samples are shown in Fig.6.19 - Fig.6.21. At low frequencies \(\sigma_{ac}\) has a small value, which increases as frequency increases, reaches a high value and then decreases with further increase in frequency up to about 1 MHz. Thereafter a similar variation with reduced values is observed in the high frequency region (> 1 MHz) as shown in each figure. The nature is similar with increased values of \(\sigma_{ac}\) as temperature is raised. The highest value of \(\sigma_{ac}\) for the nano- \(\text{Cu}_2\text{P}_2\text{O}_7\) sample C1 at 300 K is \(1.1 \times 10^{-4}\ \text{ohm}^{-1}\text{cm}^{-1}\) while the corresponding value at 373 K is \(4.57 \times 10^{-4}\ \text{ohm}^{-1}\text{cm}^{-1}\). Similar variations for samples C2 and C3 are from \(1.0 \times 10^{-4}\ \text{ohm}^{-1}\text{cm}^{-1}\) to \(5.5 \times 10^{-4}\ \text{ohm}^{-1}\text{cm}^{-1}\) and from \(7.9 \times 10^{-5}\ \text{ohm}^{-1}\text{cm}^{-1}\) to \(6.6 \times 10^{-4}\ \text{ohm}^{-1}\text{cm}^{-1}\) respectively.

![Fig. 6.19 Variation of a.c. conductivity (\(\sigma_{ac}\)) with frequency of n- \(\text{Cu}_2\text{P}_2\text{O}_7\) sample C1](image-url)
Fig. 6.20 Variation of a.c. conductivity ($\sigma_{ac}$) with frequency of $n$-$\text{Cu}_2\text{P}_2\text{O}_7$ sample C2

Fig. 6.21 Variation of a.c. conductivity ($\sigma_{ac}$) with frequency of $n$-$\text{Cu}_2\text{P}_2\text{O}_7$ sample C3
Fig. 6.22 Variation of a.c. conductivity ($\sigma_{ac}$) with frequency of n- Cu$_2$P$_2$O$_7$ sample C3 in the high frequency region.

Fig. 6.23 Variation of a.c. conductivity ($\sigma_{ac}$) with frequency of Cu$_2$P$_2$O$_7$ samples with different grain sizes at 300 K.
As in the cases of $\varepsilon'$ and $\tan \delta$, the high frequency variations of $\sigma_{ac}$ are separately studied. Fig. 6.22 is a typical plot, in which the variations of $\sigma_{ac}$ for sample C3 in the high frequency range (from 100 KHz to 3 MHz) are plotted. In this case, the maximum value of $\sigma_{ac}$ at 2 MHz changes from $4.5 \times 10^{-5} \text{ohm}^{-1}\text{cm}^{-1}$ at 373 K to $0.5 \times 10^{-5} \text{ohm}^{-1}\text{cm}^{-1}$ at 300 K. The variation of a.c. electrical conductivity with grain size of nano- $\text{Cu}_2\text{P}_2\text{O}_7$ is shown in Fig.6.23. It can be seen that the highest value of $\sigma_{ac}$ at 323 K and at 2 MHz increases from $4.57 \times 10^{-4} \text{ohm}^{-1}\text{cm}^{-1}$ to $6.6 \times 10^{-4} \text{ohm}^{-1}\text{cm}^{-1}$ when the particle size decreases from 34 nm to 27 nm.

The variations of $\sigma_{ac}$ with temperature for constant frequencies of all the three nano samples of $\text{Cu}_2\text{P}_2\text{O}_7$ are shown in Fig. 6.24 - Fig.6.26. At room temperature (300 K), $\sigma_{ac}$ has a low value, which increases steadily and reaches the maximum value at 373 K for all samples as shown in the plots.

![Graph](image)

**Fig. 6.24 Variation of a.c. conductivity ($\sigma_{ac}$) with temperature of n-$\text{Cu}_2\text{P}_2\text{O}_7$ sample C1**
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Fig. 6.25 Variation of ac conductivity ($\sigma_{ac}$) with temperature of n-Cu$_2$P$_2$O$_7$, sample C2

Fig. 6.26 Variation of ac conductivity ($\sigma_{ac}$) with temperature of n-Cu$_2$P$_2$O$_7$, sample C3
For sample C1, at 100 Hz, $\sigma_{ac}$ increases from $4.7 \times 10^{-5}$ ohm$^{-1}$ cm$^{-1}$ at 300 K to $44 \times 10^{-5}$ ohm$^{-1}$ cm$^{-1}$ at 373 K. The corresponding variation for sample C2 is from $6.6 \times 10^{-5}$ ohm$^{-1}$ cm$^{-1}$ to $35 \times 10^{-5}$ ohm$^{-1}$ cm$^{-1}$. For sample C3, it is from $6.1 \times 10^{-5}$ ohm$^{-1}$ cm$^{-1}$ to $58 \times 10^{-5}$ ohm$^{-1}$ cm$^{-1}$. The highest values of $\sigma_{ac}$ are obtained at about 500 Hz for all samples. The nature remains similar with reduced variations as frequencies are changed, as shown in figures.

The Arrhenius plot of temperature dependence of a.c. conductivity of nano-Cu$_2$P$_2$O$_7$ sample C1 is shown in Fig.5.27. The plot shows a linear dependence of $\log \sigma_{ac}$ on $1000/T$. The activation energy ($E_g$) for conduction is determined from the slope of the plot and is found nearly the same at about 0.42 eV for all frequencies.

The a.c. conductivity $\sigma_{ac}$ is obtained from the data of dielectric constant ($\varepsilon'$) and loss tangent ($\tan\delta$) using the relation

$$\sigma_{ac} = \varepsilon' \varepsilon_0 \omega \tan \delta$$

(6.3)

where $\varepsilon_0$ is the permittivity of vacuum and $\omega$ ($= 2\pi f$) the angular frequency.$^{18}$ Thus $\sigma_{ac}$ depends strongly on the frequency of the applied field. The conductivity initially increases, reaches a maximum and then decreases with frequency for all temperatures.
Electrical conductivity in copper phosphate is believed to arise through hopping of electrons between ions in different vacancy states. The sample can carry a current due to an electron moving from a $\text{Cu}^+$ to a $\text{Cu}^{2+}$ site. The dispersion in conductivity confirms the existence of electron hopping around lattice imperfections.

$\sigma_{ac}$ is much more sensitive to temperature in the higher temperature regime than the lower temperature regime. The low temperature a.c. conduction can be explained using bipolar hopping mechanism where as the high temperature behavior is due to thermally activated single polaron hopping. In copper phosphate conductivity increases with the ratio $C = \text{Cu}^+ / \text{Cu}_{\text{total}}$. The effect is a consequence of ionic conduction of $\text{Cu}^+$ ions. In other words $\text{Cu}_2\text{P}_2\text{O}_7$ exhibits a "mixed conduction" phenomenon in which ionic conduction as well as electronic conduction occurs.

The classical transport theory cannot be applied in the case of nanostructured materials, since striking new phenomena such as universal conductivity fluctuations were discovered. According to Elliot's barrier hopping model, the a.c. conductivity is given as

$$\sigma_{ac} = \frac{n \pi^2 N\varepsilon \varepsilon_0 R^6}{24}$$

where $n$ is the number of polarons involved in the hopping process $N\varepsilon$ is proportional to the square of the concentration of states $\varepsilon'$ is the dielectric constant and $R$ is the hopping distance. When the grain size of the sample is reduced, the hopping distance increases which increases $\sigma_{ac}$ as is evident from the equation. The increase of $\sigma_{ac}$ when the grain size of the sample is reduced from 34 nm to 27 nm in the present study is a direct confirmation of this theory.

6.3(iv) Impedance spectroscopy

Fig.6.28 and Fig.6.29 show the impedance spectra of nanocrystalline $\text{Cu}_2\text{P}_2\text{O}_7$ of different grain sizes at three different temperatures. There are traces for two semicircles, one at the low frequency region and the other at the high frequency region. The two semicircles at high and low frequencies are identified as due to the
Fig. 6.28 Impedance spectra of n-Cu$_2$P$_2$O$_7$ sample C1 at three different temperatures.

Fig. 6.29 Impedance spectra of n-Cu$_2$P$_2$O$_7$ sample C3 at three different temperatures.
Table 6.1: Grain boundary parameters of nano Cu₂P₂O₇ samples

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<th>Sample</th>
<th>Temperature</th>
<th>R_gb (kΩ)</th>
<th>ω_gb (rad/sec)</th>
<th>ϕ_gb (deg.)</th>
<th>C_gb (pF)</th>
<th>σ_gb (X10⁶Ω⁻¹cm⁻¹)</th>
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<td>C1</td>
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<td>11537</td>
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<td>8135</td>
<td>21</td>
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<td></td>
<td>353 K</td>
<td>238</td>
<td>5901</td>
<td>8</td>
<td>7.12</td>
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<tr>
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<td>22</td>
<td>10.32</td>
<td>7.45</td>
</tr>
</tbody>
</table>

The various grain boundary parameters are computed in a manner similar to that described in section 5.3(iv) using the model shown in Fig.5.23. The observed and calculated values are tabulated in table 6.1. It is found that the conductivities due to grain boundaries (σ_gb), increase with temperature for the same sample. The value of σ_gb increases further as the grain size decreases. For sample C1, σ_gb rises from 3.54x10⁶Ω⁻¹cm⁻¹ to 6.33x10⁶Ω⁻¹cm⁻¹ as temperature rises from 313 K to 353 K. For sample C3, the corresponding variation is from 4.12 x10⁶Ω⁻¹cm⁻¹ to 7.45 x10⁶Ω⁻¹cm⁻¹. The value of σ_gb at 313 K increases from 3.54x10⁶Ω⁻¹cm⁻¹ to 4.12 x10⁶Ω⁻¹cm⁻¹ when the grain size of the sample decreases from 34 nm to 27 nm. Thus
the impedance of nanocrystalline Cu$_2$P$_2$O$_7$ was found to arise from both grain and grain boundary components of which the major component is the latter. The presence of grains and grain boundaries in nanophase materials give valuable information about many of their electrical properties.$^{25,26}$

6.4. Conclusion

The dielectric properties and impedance spectroscopic studies of nanocrystalline Cu$_2$P$_2$O$_7$ having three different grain sizes were investigated over a wide range of frequencies 100 Hz - 3 MHz and over the temperature from 300 K (room temperature) to 373 K. The dielectric constants of all the samples are larger at low frequencies, which decrease with the applied frequency for all temperatures of measurement. The loss tangent ($\tan \delta$) decreases with frequency and at higher frequencies the loss angle has the same value for all samples. The a.c. electrical conductivity ($\sigma_{ac}$) increases with frequency for all samples. The low value at room temperature (300 K) rises to a peak at 323 K and then decreases for all samples. All the three quantities, $\epsilon'$, $\tan \delta$ and $\sigma_{ac}$ depend on grain size, frequency and temperature. The impedance spectra of nanocrystalline Cu$_2$P$_2$O$_7$ in the present investigation showed that the impedance arises from both grain and grain boundary components of which the major component is the latter.

References


