



Experimental investigation of structural, surface, optical and electrical properties of gallium sesquioxide doped tausonite compounds



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ABSTRACT

We report that 1% and 3% wt concentration of gallium sesquioxide (Ga₂O₃) doped tausonite (SrTiO₃) compounds have been developed by mechanochemical synthesis followed by calcination process and their microstructural, spectral and opto-electrical characterization are discussed for the first time. The lattice parameter values of the Ga₂O₃ doped SrTiO₃ samples were examined using the X-ray Diffraction (XRD) and Williamson-Hall (W-H) plot. The cubic structure of SrTiO₃ is confirmed by the XRD and Raman studies. The Field Effect-Scanning Electron Microscopy (FE-SEM) images of the Ga₂O₃ doped SrTiO₃ samples were composed of spherical particles with agglomeration throughout the surface. The chemical elements and chemical states of the prepared compound have been tested in the Fourier Transform Infrared (FT-IR), Energy Dispersive X-ray (EDX) and X-ray Photoelectron Spectroscopy (XPS) studies. The optical spectra displayed that the absorption wavelength shifted near the red shift with the increase of the Ga₂O₃ doped SrTiO₃. The dielectric and electrical conductivity responses of the 1% and 3 wt % Ga₂O₃ doped SrTiO₃ materials were investigated in the dielectric and electrical studies.

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1. Introduction

The incorporation of transition metals or non-metals or mixed transition ions doping in tausonite (SrTiO₃) material and its consequences can alter the size, shape, optical absorption, and optical band gap of the particles and the photocatalytic, magnetic, thermal and electrical properties. This is due to the dopants creating the distortion of the lattice or surface modification in tausonite. SrTiO₃ has some unique properties, such as the formation of paraelectric or ferroelectric material depending on room temperature or low temperature, good structural and thermal stability, broad optical band gap and optical absorption in the ultraviolet portion and large dielectric constant [1–31]. These unique properties which satisfy the material of SrTiO₃ material and may be suitable for a wide range of applications like optical and electronic devices, photocatalysts, gas sensors, spintronics, and high frequency tunable devices [1–31].

Over the last few years, the doping effects of transition metals (Fe, Cr, Mn, Sn, Co) [1–11], non-metals (N, C) [12,13], rare earth metals (La, Nd, Y, Nb, Gd, Er, Pr, Sm, Ce) [17–27] and mixed

two elements (La/Fe, La/Co, La/Dy, La/Y, Bi/Cu, Cu/Nb, Bi/Li) [24–31] have been applied to SrTiO₃ materials by different chemical methods, such as solid state reaction, ball milling, sol-gel, combustion, solvothermal, hydrothermal etc. The literatures referred to above investigated the impact of dopants on the crystal structure, particle size and shape, lattice parameters, optical, catalytic and electrical responses of SrTiO₃ for optoelectronic devices, photocatalysts etc. Based on the above literatures, the preparation of the doped SrTiO₃ material requires certain conditions like autoclave, high pressure, above 1000 °C temperature, microwave, vacuum, ultrasonicator and inert gas (He or N₂ or H₂/N₂) and sometimes a secondary phase etc. In this work, we used Ga₂O₃ as a doping material for SrTiO₃ material. Ga₂O₃ material has multifunctional properties like wide optical band gap and good insulator for dielectric coating and optoelectronic device applications. We have prepared Ga₂O₃ doped SrTiO₃ materials using a solid state synthesis method, sintering at 1000 °C without using any solvent, autoclave, vacuum, inert gas etc. The novelty of this present work is that the effects of Ga₂O₃ doping on crystal structure and strain, crystallite and particle size and shape, energy gap and electrical activity (relative permittivity, dielectric loss and electrical conductivity) of the tausonite compounds have been studied and reported for the time.

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2. Experimental

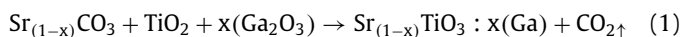
2.1. Materials

Strontium (SrCO₃) (Merck), titanium dioxide (TiO₂) (Merck) and gallium sesquioxide (Ga₂O₃) (Merck) were obtained commercially and used as received without further purification.

2.2. Preparation of Ga₂O₃-doped SrTiO₃ powders

Ga₂O₃-doped tausonite materials were produced by mixing carbonate salt of strontium (SrCO₃), titanium dioxide (TiO₂) and gallium sesquioxide (Ga₂O₃) as a dopant via the mechanochemical synthesis followed by a calcination process. 3.20 g of SrCO₃, 1.68 g of TiO₂ 0.04 and 0.12 g of Ga₂O₃ (1 and 3 wt%) selected compounds were measured and the following chemicals were admixed together to be in a hot plate pre heated at 200 °C for 1 hr. Further, the obtained mixed chemicals' powder was well ground for 1 hr in an agate mortar, followed by calcination at 400 °C for 6 hrs in a muffle oven. The reason for the choosing the above calcined temperature was to completely eliminate the carbonate from the mixed powder. Furthermore, the above burnt powder was transferred to the mortar and well ground for 3600 seconds. After that, the fine ground powder was kept in an alumina crucible and preserved in the furnace sintered at 1000 °C for 6 hrs. After ample cooling, the Ga₂O₃ doped tausonite (SrTiO₃) powders were taken out from the electronic furnace.

The probable formation mechanism of the Ga₂O₃ doped SrTiO₃ compounds are expressed below: [24].



Where x = 1% and 3% gallium sesquioxide dopant concentration.

2.3. Characterization

The crystal phase of the prepared ceramic compounds was characterized with the assistance of the X'pert PRO XRD instrument (CuK_α=1.54056Å). The chemical bond between the elements was examined by the Nicolet spectrometer- model 6700 FTIR spectra. The crystal phase was identified by the Renishaw in the VIA model Raman spectrometer instrument using the laser light as an excitation source with an optical wavelength of 785 nm. The surface morphology and chemical elemental analysis were examined by the HITACHI S-3400N. The optical behavior was tested on the Shimadzu- UV-VIS-NIR spectrometer instrument. Chemical states were detected through the PHI 5000 versa probe III-XPS instrument. The calcined ceramic compounds were pelletized; polished and a single electrical conductor made of copper was fixed using silver paste coated on two faces of the pellet, which reacts as a conductive (electrode) material. Then, the dielectric properties were studied on the HIOKI 3532-50 LCR Hi TESTER instrument for different temperatures (305 K to 573 K) and recorded at different frequencies ranging between 10² and 10⁶ Hertz.

3. Results and discussions

3.1. Powder X-ray diffraction (XRD) analysis

We have already reported the preparation of pure SrTiO₃ material via the solid state reaction method and its powder XRD pattern [23]. In this present work, we have prepared 1% and 3 wt% concentrations of gallium sesquioxide doped SrTiO₃ and their XRD pattern is displayed in Fig. 1 (a&b). The powder XRD patterns of the doped samples were recorded at the diffraction angle (2θ) in the range of 20° to 80° on the x-axis and the intensity on the y-axis for the determination of their crystalline phase.

The XRD patterns of the Ga₂O₃-doped SrTiO₃ samples indicated the reflected diffraction peaks of (100), (110), (111), (200), (210), (211), (220) and (310) planes, respectively. The detected sharp reflected diffraction planes and peak positions were compared to the reported reflected peak positions of the SrTiO₃ compound in the XRD pattern. After examining the obtained reflected peak position in the XRD pattern with the reported reflected peak position, the prepared 1% and 3% Ga₂O₃ doped SrTiO₃ samples confirmed the formation of cubic perovskite crystal structure of the SrTiO₃ compound (JCPDS.No.01-084-0443) [23]. However, there was no modification in the crystalline phase of the XRD pattern of the synthesized samples by the addition of the Ga₂O₃ doping to the host lattice. This was due to the difference between the ionic radii of the dopant (Ga = 0.062 nm) and the parent ions (Sr = 0.132 nm) [35] which confirmed the incorporation of Ga₂O₃ into the strontium titanate lattice. Further, no additional impurity compounds, such as Ga₂O₃ or SrCO₃ were found in the XRD pattern of the synthesized gallium doped SrTiO₃ samples, suggesting the confirmed formation of a mono phase with high phase purity. The purpose of adding a lower concentration of Ga₂O₃ doping was to retain the high purity single phase of the prepared SrTiO₃ material. Suppose, we increase the dopant concentration in the host material, it can create a secondary phase in the XRD pattern. In addition, the sharp diffraction peaks showed that the prepared Ga₂O₃-doped SrTiO₃ samples were of a very crystalline nature. The XRD pattern of the 3% Ga₂O₃-doped SrTiO₃ sample indicated that the high intensity reflection plane (110) was shifted to a higher angle with a slightly narrow broadening peak compared to that of the 1% Ga₂O₃-doped sample, as shown in Fig. 1b, which may increase the crystallite size due to the lattice deformation (strain). In addition, we observed increasing crystallinity with the increasing of the Ga₂O₃ dopant concentration in the SrTiO₃ material. The mean size of crystallites (D) was calculated from the XRD pattern through Scherer's equation [24]:

$$D = k\lambda/\beta \cos \theta \quad (2)$$

Where, λ is the wavelength of the CuK_α radiation (0.15405 nm), θ is the diffraction angle and k is a geometric factor (k = 0.89 for spherical particles). Full Width Half Maximum (FWHM) values are detected from the high intensity peak of (110) in the XRD pattern of the Ga₂O₃ doped samples.

The FWHM values are detected to be 0.2521 and 0.2389 from the sharp intensity peaks (110) at diffraction angles located at 32.44° and 32.64°, respectively for the 1% and 3% Ga₂O₃ doped SrTiO₃ samples. After that the above FWHM and reflected angle position values are substituted in Scherer's equation and it was determined that the crystallite sizes were 36.5 and 38.5 nm respectively, for 1% and 3% Ga₂O₃-doped SrTiO₃ samples. Based on the above findings, the crystalline size of the SrTiO₃ compound increased with an increase in the concentration of Ga₂O₃ dopant in the XRD pattern. Some lattice parameter values of the Ga₂O₃ doped samples have been computed from XRD data and are given in Table 1.

From Table 1, we could notice decreasing d-spacing, lattice constant and volume of the unit cell with increasing the Ga₂O₃ doped concentration in the SrTiO₃ sample. The calculated lattice parameter values of the Ga₂O₃ doped SrTiO₃ samples, are comparable with the previously reported lattice parameter values of the doped SrTiO₃ material [1,3,5,31].

3.2. Williamson-Hall (W-H) plot analysis

The average crystallite size (D) and crystalline strain (ε) values of 1% and 3% Ga₂O₃ doped STO was determined through the Williamson-Hall (W-H) plot by using this formula: [24]

$$\beta \cos \theta = k\lambda/D + \varepsilon(4 \sin \theta) \quad (3)$$

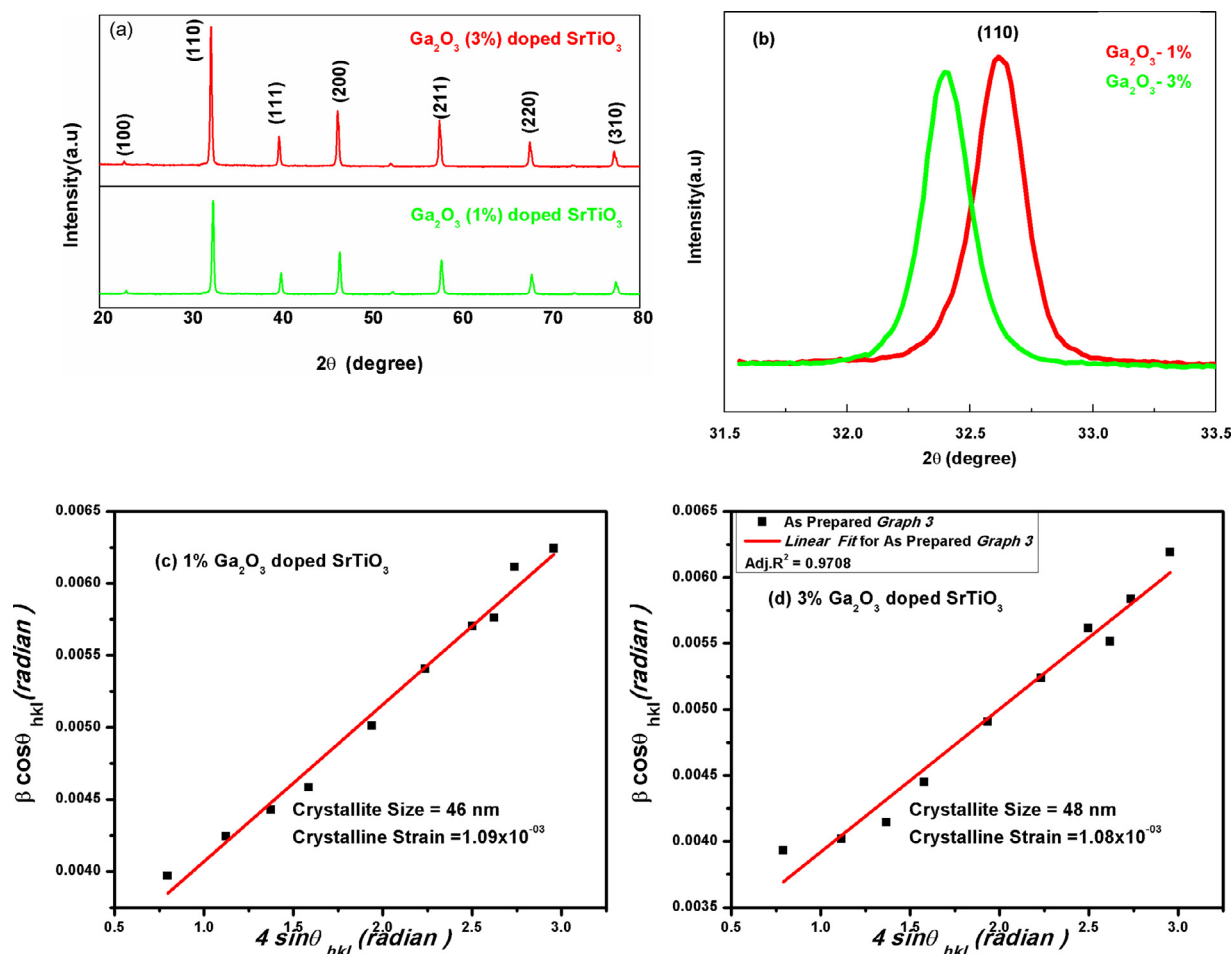


Fig. 1. (a) XRD pattern of Ga_2O_3 (1% & 3%) doped SrTiO_3 samples. (b) High Intensity diffraction peak (110) of Ga_2O_3 (1% & 3%) doped SrTiO_3 samples. W-H plot of (c) 1% and (d) 3% Ga_2O_3 -doped SrTiO_3 samples.

Table 1

Some lattice parameter values of the Ga_2O_3 doped samples were computed from the XRD data.

Ga_2O_3 doped SrTiO_3 samples	d-spacing values are calculated by using formula $d = n\lambda/2\sin\theta$ (Å)	Lattice constant (a) values are calculated by using formula $a = d/\sqrt{(h^2+k^2+l^2)}$ (Å)	Volume of the unit cell (a) ³ (Å) ³
1% Ga_2O_3 doped SrTiO_3	2.73	3.86	57.51
3% Ga_2O_3 doped SrTiO_3	2.70	3.82	55.74

Table 2

Crystallite size and strain, slope, intercept, Adj R^2 of the Ga_2O_3 doped SrTiO_3 samples using W-H plot with the assistance of linear fit curves.

Ga_2O_3 doped SrTiO_3 samples	Crystallite size estimated by using W-H plot	Crystalline strain	Intercept	Slope	Adj R^2 using linear fit
1% Ga_2O_3	46 nm	1.09×10^{-3}	0.0029	0.0010	0.9866
3% Ga_2O_3	48 nm	1.08×10^{-3}	0.00284	0.00108	0.9708

The average crystallite size and crystalline strain values of the 1% and 3% Ga_2O_3 doped SrTiO_3 were determined through the Williamson-Hall (W-H) plot using the XRD data and their determined values are mentioned in plots (Fig. 1.c). The crystallite size and strain, slope, intercept, and Adj R^2 of the Ga_2O_3 -doped SrTiO_3 samples using the W-H plots with the assistance of linear fit curves are given in Table 2. From Table 2 we could observe the increasing crystallite size and intercept, and decreasing slope

and Adj R^2 values on increasing the Ga_2O_3 concentration in the SrTiO_3 .

We noticed the increasing average crystallite size and decreasing crystalline strain with the increase in the dopant concentration in the SrTiO_3 (Table 2). The estimated average crystallite size values are comparable with the calculated crystallite size using Scherer's formula. The crystalline strain is directly related to the crystal imperfections like dislocation or oxygen vacancy [32]. In ad-

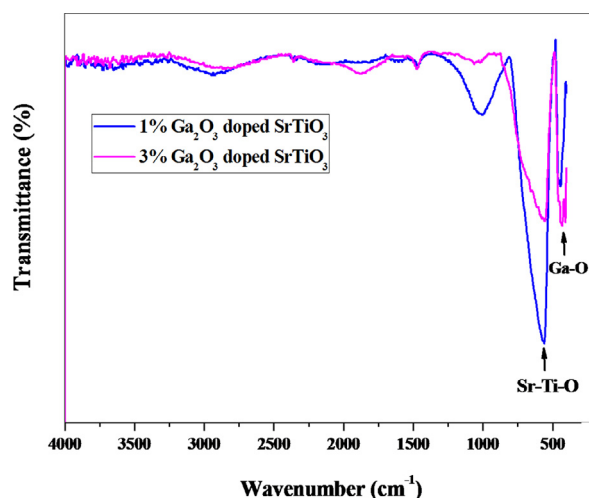


Fig. 2. FT-IR spectra of Ga_2O_3 (1% & 3%) doped SrTiO_3 samples.

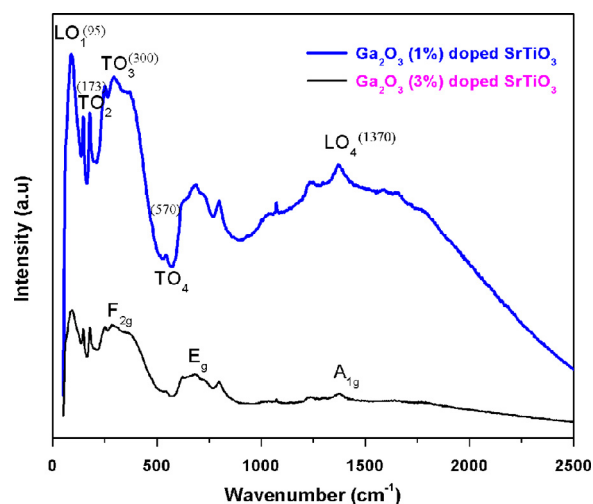


Fig. 3. Raman spectra of Ga_2O_3 (1% & 3%) doped SrTiO_3 samples.

dition, the dislocation density is inversely proportional to the volume of the unit cell. Thus, from Table 1, we found that the dislocation density is slightly higher for the 3% Ga_2O_3 doped SrTiO_3 compared to that of the 1% Ga_2O_3 doped sample using the volume of the unit cell, which indicates that a slightly higher value of strain for the 3% Ga_2O_3 doped sample is indirectly correlated with the obtained strain values of the Ga_2O_3 doped samples, as seen from the W-H plot. Dislocation plays a vital role in the resistance switching phenomenon [32].

3.3. Fourier transform infrared (FT-IR) spectra analysis

We plotted the wavenumber on the x-axis vs transmittance on the y-axis to identify the interaction between the chemical elements of the synthesized Ga_2O_3 -doped strontium titanate, as represented in Fig. 2. We recorded a wavenumber range of $4000\text{--}400\text{ cm}^{-1}$ for the detecting chemical bonds. The intense absorption bands appeared in the wavenumber range of $400\text{--}700\text{ cm}^{-1}$, and are assigned to the normal characteristic stretching modes of the metal oxides (M-O) of strontium-oxygen (Sr-O), titanium-oxygen (Ti-O), gallium-oxygen (Ga-O) and titanium-oxygen-titanium (Ti-O-Ti) [33]. These types of normal characteristic modes were reported in the electromagnetic radiation of infrared (IR) bands wavenumbers less than 1000 cm^{-1} . This was due to the deformation modes of titanium-oxygen (Ti-O) bonds in the TiO_6 octahedran stretching mode distortion or the distortion of Ti-O-Ti bridges. There was no additional band perceived in the FT-IR spectra, which indicated that the prepared samples corroborate the formation of strontium titanate material.

3.4. Raman spectra analysis

The vibrational-rotational spectra are generally plotted between the wavenumber on the x-axis and intensity on the y-axis to detect the chemical bond elements. This plot is commonly called the Raman spectroscopic study. The Raman spectra of the Ga_2O_3 doped SrTiO_3 samples are laid out in Fig. 3. In both the Ga_2O_3 doped SrTiO_3 samples, two broad scattering peaks appear around as $(230\text{--}410)$ and $(610\text{--}760)\text{ cm}^{-1}$ in the Raman spectra, which represent the second order Raman scattering modes respectively. In general, SrTiO_3 exhibits a cubic structure, so that Raman scattering was allowed only for second order. This was due to the presence of a broad active lattice vibration (phonon) mode [34].

The first order Raman scattering was not allowed because the lattice vibration mode becomes null at the middle of the allowed

energy region (Brillouin zone). The Raman spectra of the active intense peak was noticed around 110 and 610 cm^{-1} and ascribed to the longitudinal optical phonon and transverse modes [35], respectively. The transverse optical modes TO_2 and TO_4 were assigned to the bending mode vibrations of oxygen. In addition, the transverse optical mode TO_3 represents the rotation of oxygen ions [36]. The longitudinal phonon (LO_4) mode peak at 1370 cm^{-1} reveals the wider, due to the induced deformation arising from an irregular distribution of Ga_2O_3 in the SrTiO_3 surface lattice [37]. The peak intensity keeps on the Raman LO mode increasing for 3% Ga_2O_3 doped SrTiO_3 a small active phonon mode seems around as 1076 cm^{-1} . This was due to the degrees of lattice vibration was disturbed by the incorporation of Ga_2O_3 dopant in cubic structured SrTiO_3 material.

3.5. Field effect-scanning electron microscopy (FE-SEM) analysis

We have given the undoped SrTiO_3 sample micrographs for comparison with the Ga_2O_3 doped SrTiO_3 samples micrographs (FE-SEM) for finding the variation of the microstructural behavior (Fig. 4 (a-c)). This was due to the surface modification that occurred (ie. particulate systems likely to change their total surface tension) when increased Ga_2O_3 dopant concentration was incorporated into the host lattice of SrTiO_3 . In addition, we could notice the distinct morphology like cubical particles, spherical particles with non-uniform size and irregular sheets/spherical particles (as inset with a blue arrow in Fig. 4) for the undoped, 1% and 3% Ga_2O_3 doped SrTiO_3 samples. In addition, particles are clearly visible, suggesting that the prepared Ga_2O_3 doped SrTiO_3 samples are quite crystalline in nature.

3.6. UV-visible absorption spectra analysis

The UV-Visible absorption spectra and T_{auc} plot of the Ga_2O_3 doped SrTiO_3 samples are depicted in Fig. 5 (a&b). In general, if a sharp optical absorption edge is found in the optical absorption spectra, the optical band gap energy could be calculated directly using the energy gap formula $E_g = 1240/\lambda_{abs}$. This energy gap is called the direct band gap.

However, the absorption peak of Ga_2O_3 doped SrTiO_3 samples is not detect sharp band edge; so it exhibits an indirect band gap nature of SrTiO_3 compound. We will find out the optical energy gap energy values from the indirect energy band gap na-

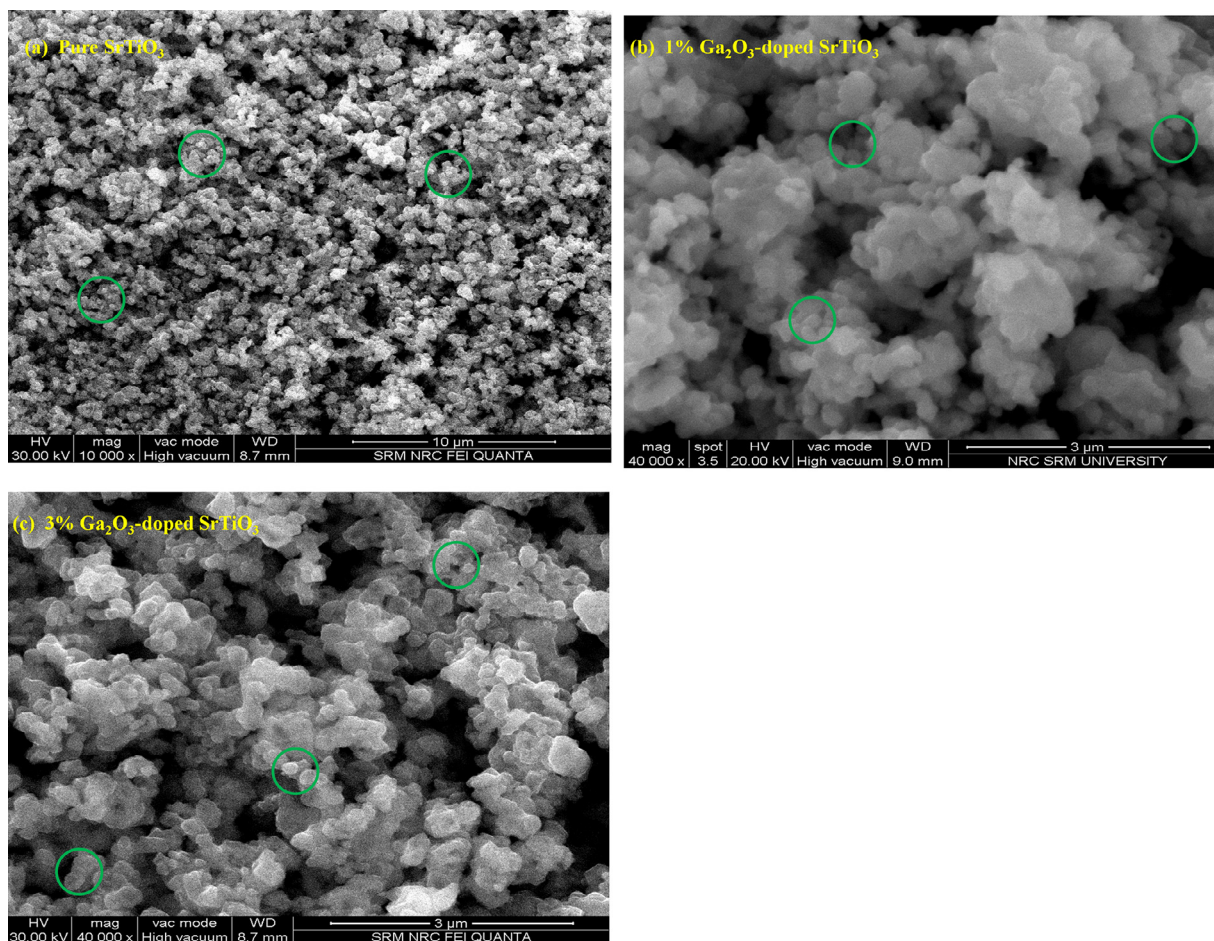


Fig. 4. FE-SEM images of (a) undoped SrTiO₃, (b) 1% and (c) 3% Ga₂O₃-doped SrTiO₃ samples.

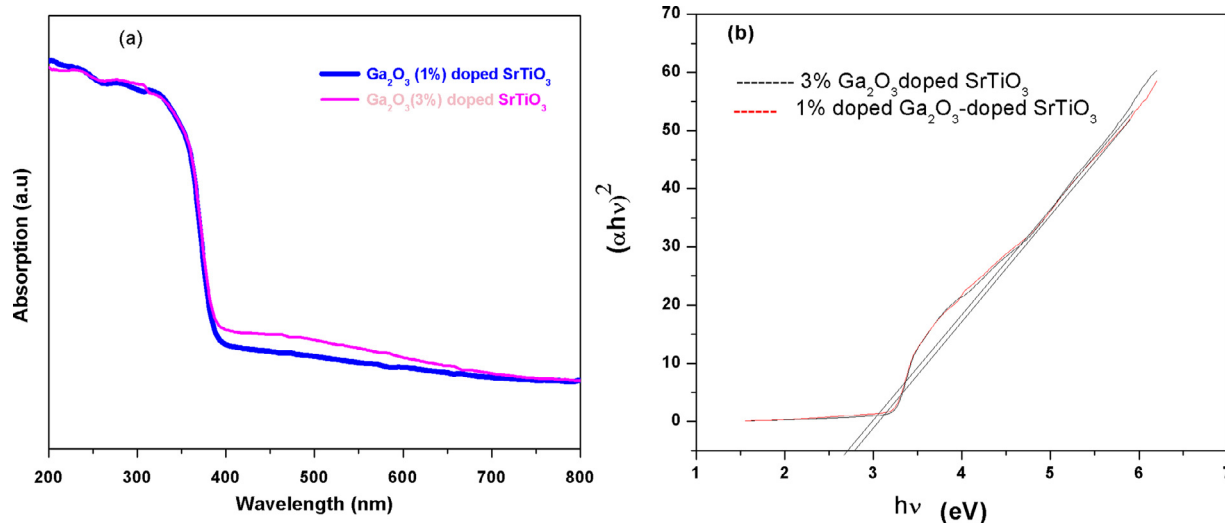


Fig. 5. (a) UV-absorption spectra and (b) Tauc plot of 1% and 3% Ga₂O₃-doped SrTiO₃ samples.

ture of SrTiO₃ via the Tauc plots. The energy gap values were determined around 3.11 eV and 3.07 eV for 1% and 3% Ga₂O₃ doped STO samples from the Tauc plot using optical absorption data. The energy gap decreasing of SrTiO₃ material with the increasing of Mn impurity concentration was reported by Wu et al. [7], which are correlate the phenomena with obtained energy gap values of Ga₂O₃ doped SrTiO₃ samples. This was due to the red

shift was happened in the optical absorption spectra. In addition, optical band gap values are decreased with the addition of Ga₂O₃ doped into the host lattice SrTiO₃. This decreasing optical band gap could have occurred, when the light source interacts with the Ga₂O₃ dopant incorporated into the host lattice to create a multi-inner energy state in the valence band and conduction band.

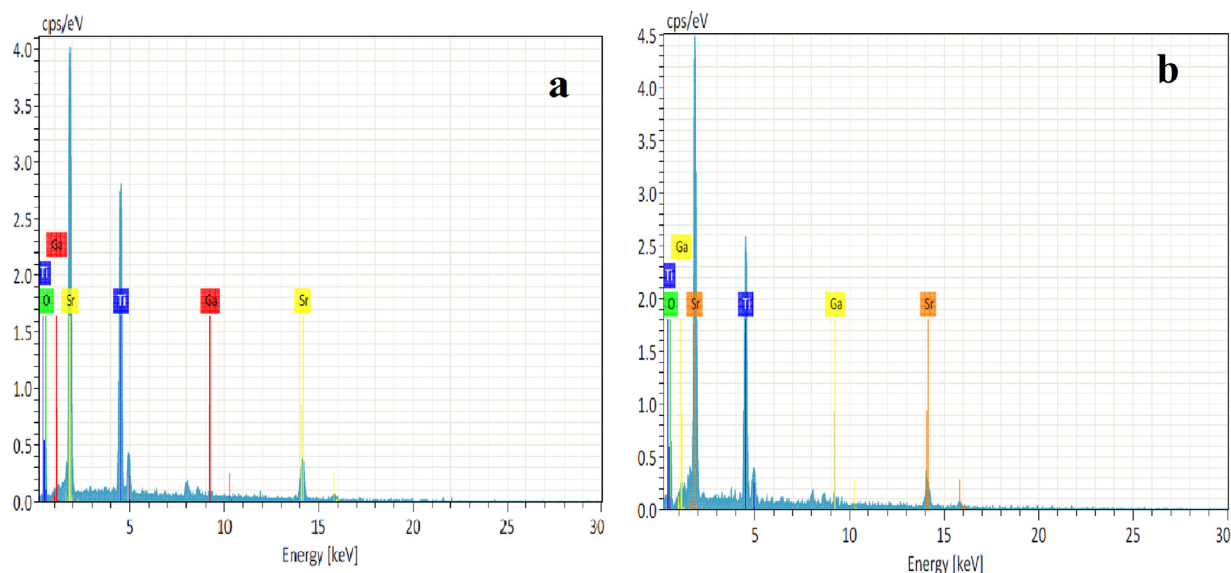


Fig. 6. EDX spectra of (a) 1% and (b) Ga_2O_3 (3%) doped SrTiO_3 samples.

3.7. Energy dispersive X-ray (EDX) spectra analysis

We traced only strontium (Sr), titanium (Ti) and oxygen (O) with gallium (Ga) elements in the EDX images of the Ga_2O_3 doped SrTiO_3 prepared samples as displayed in Fig. 6. These results indicate the evidence of the incorporation of Ga in strontium material. For the 1% Ga doped sample, the Sr element peak was located at energy level of 1.98 and 14 keV. In addition, the Ti element's position peak is at energy (0.5 and 4.5 KeV). Moreover, the O element is located at energy 0.51 KeV. The Ga element is position peak at 0.48 and 6.2 KeV, respectively. For the 3% Ga doped sample, we noticed the Sr peak position at energy (1.98 and 14.1KeV), Ti peak at energy (0.2 and 4.5 KeV), O element peaks at energy (0.5 KeV) and Ga element at 1.1 and 9.2KeV, respectively. Based on the EDX results, the peak position energy level is slightly changed due to the gallium oxide dopant concentration in the host lattice.

3.8. X-ray photoelectron spectroscopy (XPS) analysis

The chemical oxidation state of metals and non-metal elements and their corresponding binding energy of the 3% Ga_2O_3 doped SrTiO_3 sample are presented in XPS, as represented in Fig. 7. In the Ga_2O_3 doped SrTiO_3 sample (Fig. 7a), metals like Sr, Ti, Ga and the non-metal (O) element were traced in the XPS. The deconvolution spectra of the Sr 3d ion are illustrated in Fig. 7b. A strong spin-orbit interaction between the Sr ($3d_{3/2}$) and Sr ($3d_{1/2}$) has been found. The binding energies of Sr ($3d_{3/2}$) and Sr ($3d_{1/2}$) positions are 133 and 134.6 eV [1]. When the Ga impurity is introduced into the SrTiO_3 material, the drift in the binding energy of Sr 3d state is forwarded to the lower edge in the XPS studies. In addition, it showed that Ti^{3+} signals were detected (Fig. 7c), giving $\text{Ti}^{3+}/\text{Ti}^{4+}$ proportion of the 7.0 eV for Ga doped SrTiO_3 sample. The binding energies of Ti ($2p_{3/2}$) and Ti ($2p_{1/2}$) states are located at 458.1 and 463.8 eV [1]. In addition, the strong spin-orbit effect is displayed for the Ti (2p) state and is evident of the symmetric interaction between the Ti ($2p_{3/2}$) and Ti ($2p_{1/2}$) states and also between the Sr ($3d_{3/2}$) and Sr ($3d_{1/2}$) states. The position of the chemical oxidation state of the non-metal (oxygen) in the 3% Ga doped SrTiO_3 sample is shown in Fig. 7d. Fig. 7d, records the binding energy around 528.2 and 530.2 eV. In the Ga3d5 spectrum the peak was observed in 19.2 eV and it has been attributed to the trivalent Ga ion. Finally, based on the above XPS studies, it is confirmed that the Ga

dopant has been incorporated into the SrTiO_3 lattice. Furthermore, the XPS spectra have shown that the oxygen vacancy is present in the gallium oxide doped SrTiO_3 material.

3.9. Dielectric analysis

Fig. 8 (a&b) displays the frequency dependent dielectric constant of the Ga_2O_3 doped SrTiO_3 samples at different temperatures (305, 323, 373, 423, 437, 523 and 573 K). In general, the polarization will be highly responsive in the lower frequency portion and inactive in the higher frequency region in nanomaterials samples [38]. In Fig. 8, we could notice that the high dielectric constants were observed in the lower frequency portion; this was because of the presence of interfacial polarization [39].

The electrons present in the samples were not able to remain within the field, when the frequency of the applied electric field increased and as a result, their directional delays beyond the field applied were altered. This was due to the interfacial polarization disappeared in the high frequency portion, which reduced the relative permittivity (dielectric constant). We could see that the 3% Ga_2O_3 doped SrTiO_3 observed high relative permittivity (40000) at lower frequency portion compared to that of the 1% Ga_2O_3 doped sample (dielectric constant value ~ 10000) at 573K. In addition, the dielectric constant values of both the Ga_2O_3 doped SrTiO_3 samples increased with increasing temperatures [31]. This was due to the increasing contribution of space charge polarization [31].

Fig. 9 (a&b) displayed the frequency dependent dielectric loss of the Ga_2O_3 doped SrTiO_3 samples at various temperatures. When there is an increase in the applied frequency, the dielectric loss gently decreases as exhibited in Fig. 9. We could detect that in the 3% Ga_2O_3 doped SrTiO_3 sample, the dielectric loss value is slightly lesser compared to that of the 1% Ga_2O_3 doped sample. The lower dielectric constant values obtained for the 3% doped SrTiO_3 sample suggested its excellent dielectric properties.

In addition, the variation of the dielectric constant values of Ga_2O_3 doped samples depends on the temperatures. From the Fig. 9, we could notice that the dielectric loss increases with increasing of temperatures for the 1% and 3% Ga_2O_3 doped SrTiO_3 samples. This was due to the thermally activated behavior of the dielectric relaxation of the system [40].

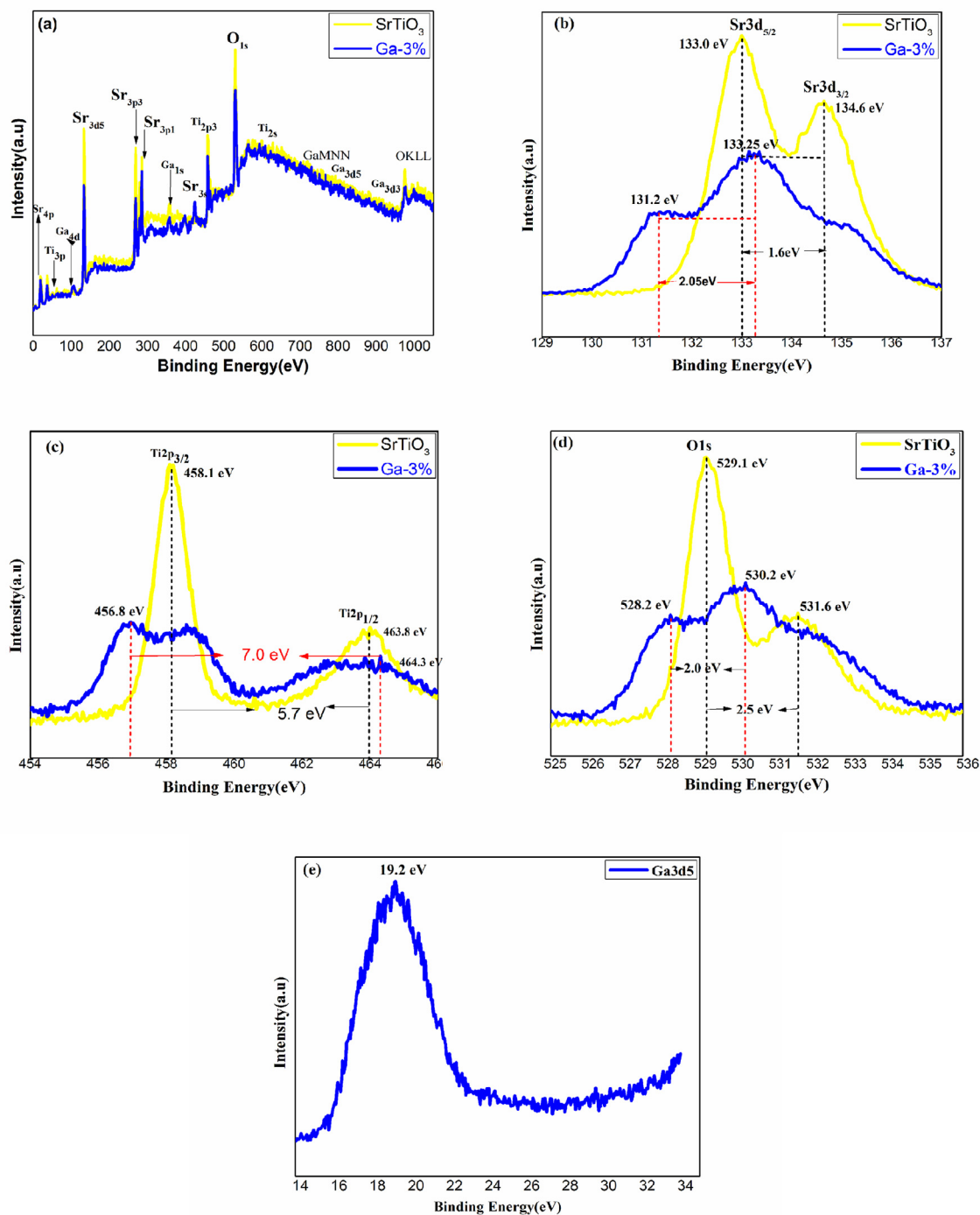


Fig. 7. XPS of 3% Ga₂O₃ doped SrTiO₃ sample.

3.10. Electrical conductivity analysis

Fig. 10 (a&b) demonstrates the frequency dependent electrical conductivity of the 1% and 3% Ga₂O₃ doped SrTiO₃ samples at various temperatures. From Fig. 10, the 3% Ga₂O₃ doped SrTiO₃ sample was observed to have slightly higher electrical conductivity compared to the 1% of Ga₂O₃ doped sample. Generally, electrical conductivity increases as the optical band of nanomaterials is reduced. Based on the above concept, a slightly higher electrical conductivity was observed for the 3% Ga₂O₃ doped SrTiO₃, which is in

good agreement with the obtained optical band gap (E_g) value of the 3% Ga₂O₃ doped (3.07 eV) compared to that of the 1% Ga₂O₃ doped SrTiO₃ material ($E_g = 3.11$ eV). In addition, From the Fig. 10, we could observed that the electrical conductivity increases with an increasing the temperatures. This was due to the movement of hopping of charge carriers between the ions present in the material [40,41]. The behavior of conductivity exhibits two distinct portions in the studied frequency range. In the low frequency region, the charge carriers have ample time to assemble at the interfaces of the electrode, and hence result in the electrode polarization ef-

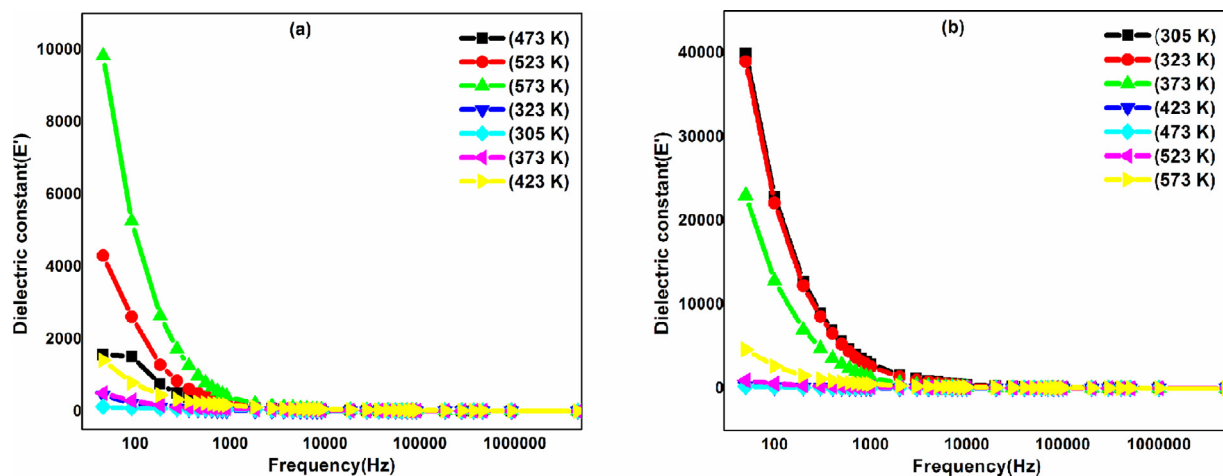


Fig. 8. Frequency dependent dielectric constant of (a) 1% and (b) 3% Ga_2O_3 -doped SrTiO_3 samples.

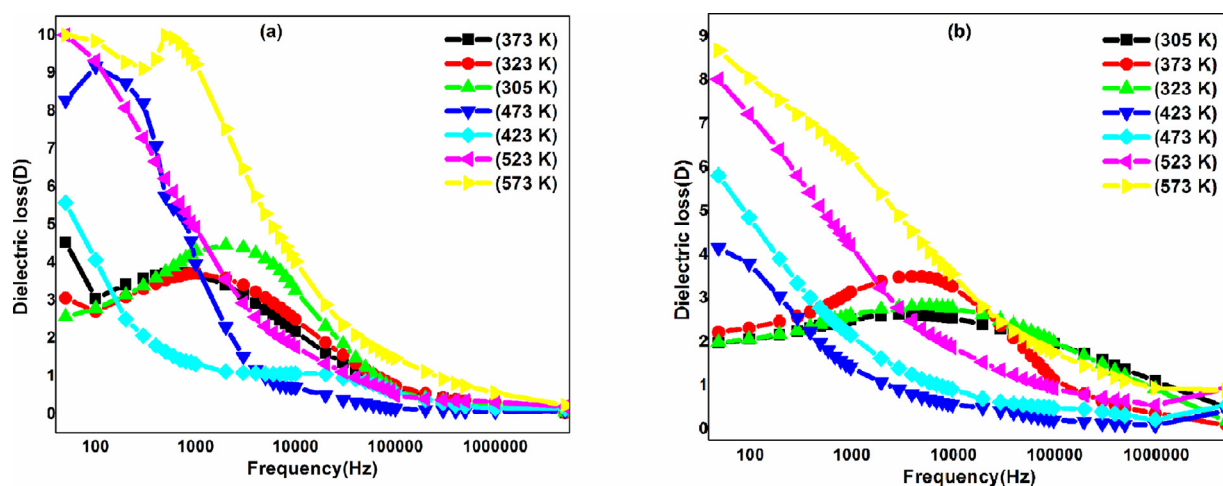


Fig. 9. Frequency dependent dielectric loss of (a) 1% and (b) 3% Ga_2O_3 -doped SrTiO_3 samples.

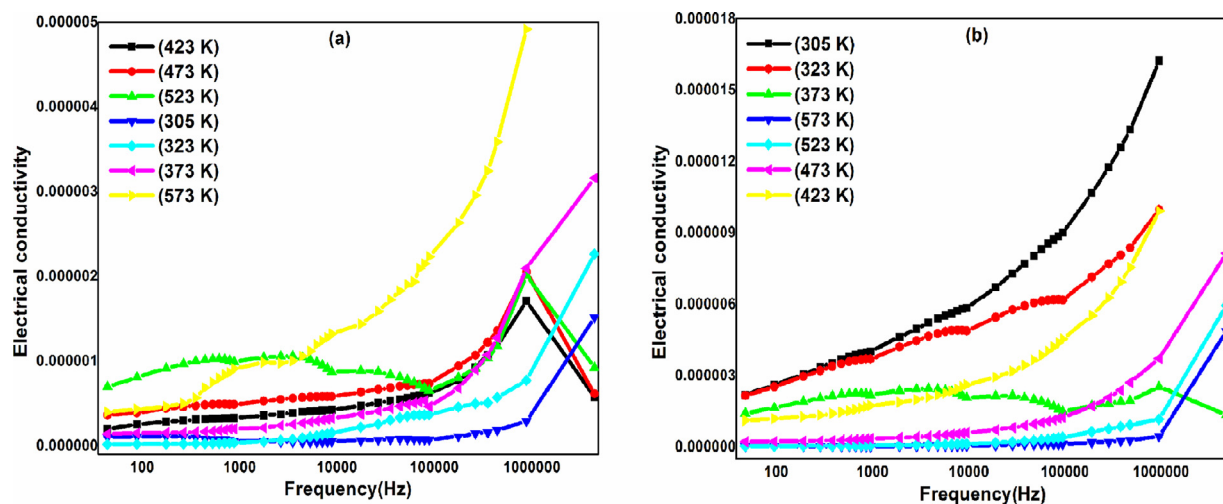


Fig. 10. Electrical conductivity of (a) 1% and (b) 3% Ga_2O_3 doped SrTiO_3 samples.

fect [42]. The conductivity is less at the low frequency scale due to the presence of the grain boundary effect, which corresponds to the absence of the mobility charge carriers [43]. Moreover, the change in the electrical conductivity values of the Ga_2O_3 doped samples in the higher frequency region depends on the temperatures.

4. Conclusions

In summary, we synthesized 1% and 3 wt% of Ga_2O_3 doped SrTiO_3 material via the mechanochemical synthesis followed by the calcination process. The XRD pattern of the synthesized Ga_2O_3 doped SrTiO_3 materials confirmed the presence of a single phase

and cubic perovskite crystal structure. The Sr-O and Ti-O bond and feasible incorporation of gallium oxide ions into the parent lattice were detected by the FT-IR analysis. The Raman modes showed that the cubic phase of SrTiO₃ was confirmed which was supported by the cubic structure obtained from the XRD data. Non-uniform spherical and irregular sheets/spherical particles were identified from the morphology studies. The 3% Ga₂O₃ doped SrTiO₃ material has a slightly reduced energy gap relative to the 1% Ga₂O₃ doped sample, and this was confirmed by optical spectra studies. The possible oxidation states of elements, the main drift in the binding energy of the elements, and surface defects (oxygen vacancy) in the synthesized Ga₂O₃-doped SrTiO₃ material have been discussed in the XPS studies. The frequency dependent range's relative permittivity and dielectric losses have been examined while the space charge polarization occurs. Hence the Ga₂O₃-doped SrTiO₃ ceramic compounds can find potential applications in the fabrication of optoelectronic devices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

G. Saravanan: Methodology, Writing - original draft. **K. Ramachandran:** Investigation, Writing - original draft, Writing - review & editing. **J. Gajendiran:** Investigation, Writing - original draft, Writing - review & editing. **S. Gnanam:** Writing - review & editing.

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