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Structural, magnetic and electrical properties of La_{1-x}Mg_xFeO₃ perovskites

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ABSTRACT

In this study, we synthesized La_{1-x}Mg_xFeO₃ (x = 0.1, 0.2, and 0.3) powdered ceramics using sol – gel and sintering methods and their structure, magnetic and electrical properties have been investigated. All samples showed the Pbnm single phase, and structural analyses revealed a lattice distortion due to the addition of Mg that increases with increasing Mg content. Transmission electron microscopy revealed a decrease in particle size with increasing Mg content. The M – H hysteresis loops of the samples revealed that the samples with Mg substitution at the La site exhibits weak ferromagnetic behaviour, and the hysteresis loops increases with an increase in Mg content. The magnetisation increases as the Mg content is increased, which is might be related to the lower crystallite and particle sizes, as well as higher Fe⁴⁺/Fe³⁺ ratio, as shown by X-ray diffraction and X-ray photoelectron spectroscopy, respectively. Analysis of the electrical properties showed grain–grain boundary the grain effect and one relaxation mechanism were observed at higher Mg contents (x = 0.3). The temperature dependence of direct current conductivity obeys the Arrhenius law. The activation energy for the conduction mechanism decrease in the Mg content. These results contribute the important knowledge in promising the candidate electrode material in electrochemical application.

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1. Introduction

Ferrite-based materials have paid attention in materials science field due to their interesting properties, such as high resistivity, chemical stability, photoelectric, etc which is offering numerous applications, i.e magnetic resonance imaging, transformer cores, microwave-absorbing devices, etc [1,2]. Several studies have been mentioned for the ferrite-based compounds [1–3]. Gd³⁺ substituted on MnCrFeO₄ revealed the increasing of coercivity and lower dielectric constant with increasing Gd³⁺ ions accompanied by the existence of non-collinear spin interaction [1]. Zn–Cr substituted cobalt ferrite ($Co_{0.75}Zn_{0.25}Cr_{0.2}Fe_{1.8}O_4$) nanoparticles exhibited large converse magneto-electric effect at room temperature with maximum ME coefficient is approximately 7.92 kV/cm [2]. Dy^{3+} -substituted Co – Cu – Zn nanoferrites increased the saturation magnetisation and coercivity as well as dielectric constant [3].

Among these ferrite-based materials, rare-earth orthoferrites $(RFeO_3)$ and their derivatives have been extensively studied owing to their unique structural, magnetic and electrical properties and thermal stability [4–8]. Generally, they have the orthorhombic perovskite

structure with Pbnm or Pnma symmetry and antiferromagnetic (AFM) phase at room temperature (RT) [4,5]. The magnetic transition temperature (in this case, Néel temperature) and magnetisation are strongly related to the R ion [4].

Several studies have reported the substitution of elements on the La site of LaFeO₃ [4,6–8]. Yttrium (Y)-substituted LaFeO₃ ceramics showed an enhanced direct current (DC) conductivity, semiconductor to metal phase transition, a decrease in the magnetic transition temperature and an increase in remnant magnetisation [4]. Strontium (Sr)-substituted LaFeO₃ showed an enhanced conductivity and dielectric constant accompanied by the reduction in activation energy for electrical relaxation and conduction mechanism [6]. Lead (Pb)-substituted LaFeO₃ showed a typical colossal dielectric constant and the presence of hopping polaron in the electrical transport mechanism [7]. Replacing La³⁺ with Mg^{2+} in magnesium (Mg)-substituted LaFeO₃ was found to inhibit the particle growth and enhancing the magnetisation [8].

Since the improvement of structural changes, magnetic behaviour (magnetic transition temperature, magnetisation and magnetic phase) and electrical properties (electronic–ionic conduction and dielectric relaxation processes) of $RFeO_3$ is strongly related to the R ion, the

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Fig. 1. (a) XRD patterns of La_{1-x}Mg_xFeO₃ powdered ceramics and (b) refinement the sample with x = 0.1. The black dots, magenta line and olive line describe the experimental data, calculated and difference, respectively.

modification on the R site has attracted research interest in perovskite materials [4,6–8]. Specifically, the effects of rare-earth cation substitution on the La site have been widely studied [6–11]. However, structural changes, magnetic behaviour and electrical properties for an Mg-substituted La site (La_{1-x}Mg_xFeO₃) have not been reported. In this study, we investigated the physical properties of La_{1-x}Mg_xFeO₃ (x = 0.1, 0.2 and 0.3) powdered ceramics. The samples were prepared using sol–gel and sintering methods. The magnetic, surface and electrical properties of the ceramics for all substitutions were determined and studied. The details of the structural information, magnetic properties and electrical transport mechanism are discussed.

2. Experimental details

 $La_{1-x}Mg_xFeO_3$ (x = 0.1, 0.2 and 0.3) powdered ceramics were prepared via standard sol–gel sintering using high-purity raw materials, including lanthanum (III) oxide (La₂O₃, 99.99%), magnesium nitrate hexahydrate (Mg(NO₃)₂.6H₂O, 99.9%), iron (III) nitrate nonahydrate (Fe(NO₃)₃.9H₂O, 99.9%) and citric acid monohydrate (C₆H₈O₇.H₂O, 99.98%), as the solvent. The stoichiometric raw materials were stirred and heated at 80 °C until the gel phase was formed. The obtained gel

phase was dried at 100 °C for 24 h to eliminate the organic phase and water. Then, the powders obtained from the drying process were calcined at 700 °C, after which they were ground and pressed into pellets. Pellets with different compositions were sintered for 3 h.

The structural information of all samples was studied by X-ray diffraction (XRD) measurements using a PANalytical X'Pert PRO diffractometer with Cu K α radiation ($\lambda = 1.5405$ Å), 2θ of 10°–90° and a step size of 0.02°/s. The XRD results were refined using Fullprof 2k software. The particle size was analysed by transmission electron microscopy (TEM, JEOL 2100F). The magnetic M – H hysteresis loops were measured using a vibrating-sample magnetometer (VSM, 250). The oxidation states of all samples were analysed by X-ray photoelectron spectroscopy (XPS, PHI-5400) with an Al Ka (1486.6 eV) X-ray source, and the binding energy was corrected using the C1s peak at 285.0 eV. Electrical analysis was conducted using IS instrument (RLC meter, FLUKE-PM 6303) in the temperature range of 50 °C-150 °C and frequencies ranging from 100 Hz to 1 MHz using a single parallel resistance – capacitance circuit configuration.

3. Results and discussion

3.1. XRD analysis

Fig. 1(a) shows the XRD patterns for $La_{1,x}Mg_xFeO_3$ powderedceramics. The observed diffraction peaks match with the ICDD database No. 96-152-6451. Rietveld refinement for the XRD pattern of x =0.1 sample of are displayed in Fig. 1(b). The refinement analysis revealed that the calculated peak intensities are well matched with orthorhombic LaFeO₃ perovskite structure with Pbnm (62) symmetry indicating all the doped samples are of single phase with the Pbnm symmetry. It is known that the undoped LaFeO₃ sample crystallizes in the Pbnm space group [5,11], therefore Mg substitution on the La site does not changes the crystal structures.

The structural parameters from the refinement results are tabulated in Table 1. Due to the decrease of the average ionic radii, the lattice constants, cell volume, and bond length tend to decrease, which is commonly occurring to the other perovskite orthoferrites [4,9]. The average crystallite size is calculated from X-ray peaks broadening of the (121) diffraction peaks using Scherrer method and found to decrease with increasing Mg content. The tilt angle decreases and tolerance factor increases the deviation from 1 confirming that the lattice becomes more distorted from cubic symmetry due to the increasing Mg content.

3.2. TEM images

Fig. 2 shows the TEM images of $La_{1-x}Mg_xFeO_3$ powdered ceramics, which show the presence of uniform and homogeneous particles greater than 200 nm in size. The particle size decreased with an increase in Mg content. The average particle size was approximately 68.7, 38.2 and 28.6 nm for x = 0.1, 0.2 and 0.3, respectively. The crystallite size estimated using the Scherrer method decreased as the particle size decreased, suggesting that all samples have a single-domain structure [12].

3.3. Magnetic properties

Fig. 3 shows the isothermal magnetisation (M - H) curves obtained from VSM measurements for $La_{1-x}Mg_xFeO_3$ powdered ceramics measured at 10 K and RT. The hysteresis loops of ferromagnetic (FM) behaviour are found to increase with an increase in Mg content. The magnified M – H curves also show an increase in magnetisation as the temperature is lowered. Previous reports show that pure LaFeO₃ exhibits AFM behaviour due to the super-exchange interaction between Fe³⁺ with O²⁻ ligands in lattice [10,11]. However, the magnetisation curves for Mg substitution on the La site of LaFeO₃ showed a saturation-like hysteresis loop, suggesting the existence of weak FM behaviour.



Fig. 2. TEM images of $La_{1-x}Mg_xFeO_3$ powdered ceramics.



Fig. 3. Comparison of magnetic hysteresis loop at 10 K and room temperature (RT) for $La_{1-x}Mg_xFeO_3$ powdered ceramics.

Table 1

Structural refinement parameters and tolerance factors for ${\rm La}_{1-x} Mg_x {\rm FeO}_3$ powdered-ceramics.

	x = 0.1	x = 0.2	x = 0.3
Lattice parameters (Å)			
a	5.5545	5.5484	5.5432
b	5.5609	5.5641	5.5675
c	7.8459	7.8451	7.8423
Cell volume (Å ³)	242.34	242.19	242.03
Crystallite size (nm) Bond angles (°)	42.8	36.5	31.7
La/Mg - O1 - La/ Mg	99.889	99.911	99.904
La/Mg – O2 – La/ Mg	106.84	106.83	106.82
Fe-O1-Fe	157.08	157.11	157.14
Fe-O2-Fe	154.04	154.06	154.08
Bond length (Å)			
La/Mg - O1 (m)	2.6906	2.6902	2.6892
La/Mg - O1 (l)	2.7586	2.7582	2.7575
La/Mg - O2 (s)	2.5759	2.3824	2.3802
<La/Mg $-$ O $>$	2.6750	2.6103	2.6090
Fe - O1 (s)	1.9236	1.9226	1.9218
Fe – O2 (m)	2.0127	2.0126	2.0118
Fe - O1 (l)	2.0861	2.0861	2.0826
<fe- o=""></fe->	2.0075	2.0071	2.0054
Tilt angle (°)	14.925	14.917	14.914
Tolerance factor	0.9422	0.9196	0.9189

Table 2

Saturated magnetisation (M_s) and remnant magnetisation (M_r) La_{1-x}Mg_xFeO₃ powdered-ceramics measured under a magnetic field (H).

x	M _s (emu/gr)	M _s (emu/gr)		M _r (emu/gr)	
	10 K	RT	10 K	RT	
0.1	1.82	0.37	0.68	0.06	
0.2	2.95	0.86	1.37	0.11	
0.3	4.58	2.43	1.64	0.57	

The saturation magnetisation (M_s) and remnant magnetisation (M_r) increase with an increase in Mg content at 10 K and RT, showing a regular increase in the FM nature (see Table 2). At RT, M_s surprisingly reached 2.43 emu/gr at x = 0.3. This increase in M_s might be attributed to both canting of sub-lattice spins (weak FM) and surface spin uncompensated. Furthermore, oxygen vacancies, as a form of structural defects, can increase the magnetic moment, thereby increasing M_s as Mg content increases. Hence, the most possible origins of FM behaviour in La_{1-x}Mg_xFeO₃ are related to the large surface area, in other words, reduced particle size with increasing Mg content, and the state of Fe ions at the surface region, such as uncompensated Fe spins and Fe³⁺/Fe⁴⁺ interaction. Therefore, the surface composition and valence state of each element, especially Fe, in the samples needs to be identified by surface sensitive such as XPS measurements.

We note that our observation on the increasing saturation magnetisation with increasing Mg concentration is in stark contrast with the substitutional effects on other ferrite-based compounds. Doping effects on other ferrite-based compounds, such as in Li_{0.5}Zr_xCo_xFe_{2.5-2x}O₄ [13], Li_{0.5}Co_{1.5-x}Fe_{2.5-x}O₄ [14] and Co_{0.5}Ni_{0.5}Al_xFe_{2-x}O₄ [15] have been investigated previously. The studies revealed that the replacement of Zr, Co and Al on the Fe sites tends to weaken the Fe–Fe super-exchange interaction which leads to the reduction of magnetic moment and saturation magnetisation as the doping concentration increases. On the other hand, the coercivity increases which was attributed to the increase in the magnetic anisotropy constant with doping concentration.



Fig. 4. XPS spectra for La_{1-x}Mg_xFeO₃ powdered ceramics.

3.4. XPS analysis

Fig. 4 shows the entire survey and elemental XPS spectra for $La_{1-x}Mg_{x}FeO_{3}$ powdered ceramics (x = 0.1, 0.2 and 0.3). The undoped LaFeO₃ have been reported in our previous study [11]. The entire survey spectrum shows that no impurity element was present in all samples. The details of the oxidation states for all samples are shown in Fig. 5(a)-(d). La 3d, Fe 2p, Mg 1s and O 1s were observed, which agree well with previous reports [11,16-19]. Inspection of La 3d and Fe 2p states implies that the La ions are in the 3+ valence state, and the Fe ions are in the +3and + 4 mixed state [11,16]. Lattice oxygen (OL) and surface adsorbed oxygen (O_H) were observed, which is in agreement with our previous report [11]. The well-fitted of Mg 1s shows the single peak of Mg 1s state, indicating that Mg exists in the Mg²⁺ state. The binding energies associated with the Fe states are listed in Table 3. The binding energy increased with an increase in Mg content, which is also in agreement with the opposite tendency to the Fe-O bond length from the XRD analysis.

The surface atomic composition and the corresponding atomic ratios for La_{1-x}Mg_xFeO₃ powdered ceramics are listed in Table 4. The concentration of Mg agrees with the determined stoichiometric and is comparable to that of La and Fe, implying that the Mg ions are homogeneously distributed in the system. The high ratio of the adsorbed oxygen to total oxygen (O_H/O) increased with an increase in Mg content, which is in agreement with the XRD results. Mg ions decrease crystallite and particle sizes, demanding more adsorption sites for oxygen. The Fe⁴⁺/Fe³⁺ ionic ratio increased with an increase in Mg content, indicating that the systems exhibit the charge neutrality condition [16].

The lower crystallite size and higher Fe^{4+}/Fe^{3+} ratio with increasing Mg content are attributed to the increase in the Fe/La ratio [11,18]. As the crystallite size decreased, the FM shell expanded relative to the AFM core, strengthening the FM behaviour [17,18]. Also, as the Mg content increases, the increase in the lattice distortion and two AFM coupled Fe sub-lattice angles were observed from the XRD analyses. Moreover, Mg content increased the Fe^{4+}/Fe^{3+} ratio, i.e. increasing the Fe^{4+} in the lattice, thereby enhancing the FM Fe^{3+} –O–Fe⁴⁺ double exchange interaction and suppressing the AFM Fe^{3+} –O–Fe³⁺ super-exchange interaction. In addition, the increase in the uncompensated spins at the surface caused by smaller crystallite and particle sizes could be another factor responsible for the improvement of FM behaviour (increasing the hysteresis loop) and enhanced magnetisation in the La_{1-x}Mg_xFeO₃ system.



Fig. 5. (a) La 3d, (b) Fe 2p, (c) O 1s and (d) Mg1s spectra for $La_{1-x}Mg_xFeO_3$ powdered ceramics. The black dots, red dashed line and blue dash line describe the experimental data, background and fitting, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3 Binding energy associated with Fe states for $La_{1-x}Mg_xFeO_3$ powdered ceramics.

x	Binding energy (eV)			
	Fe ³⁺	Fe ³⁺		
	2p _{3/2}	2p _{1/2}		
0.1	710.04	724.06	711.49	
0.2	710.06	724.08	711.60	
0.3	710.08	724.19	711.69	

3.5. Electrical properties

Fig. 6 shows the Nyquist plots of $La_{1-x}Mg_xFeO_3$ (x = 0.1, 0.2 and 0.3). The diameter of the semicircle decreases with an increase in temperature, in other words, a decrease in impedance *Z*. This also shows that *Z* decreases with an increase in Mg content in the La site.

The temperature dependence of impedance shows grain and grain boundary contributions. The Nyquist plots have two semicircular at low (grain boundary contribution) and high (grain contribution) frequency regions [20]. Increasing Mg content decreased the low-frequency semicircular arc, indicating that an increase in Mg content results in the lowly dominant grain boundary relaxation and the highly dominant grain relaxation. Grain and grain boundary effects appeared at low Mg

Table 4 Surface atomic composition (%) and corresponding the atomic ratios for $La_{1-x}Mg_xFeO_3$ powdered ceramics.

	-			1	a oa oi				
x	La	Fe	0	С	Mg	Fe/La	Mg/La	O _H /O	$\mathrm{Fe}^{4+}/\mathrm{Fe}^{3+}$
0.1	7.87	5.31	36.05	48.88	1.88	0.675	0.239	0.341	0.565
0.2	7.07	5.73	37.02	48.35	1.83	0.810	0.259	0.323	0.698
0.3	6.32	5.53	35.59	49.94	2.63	0.875	0.416	0.301	0.796



Fig. 6. Nyquist plots for $La_{1-x}Mg_x$ FeO₃ ceramics. The color dots represent the experimental data. The green lines represent the fitting results of each temperature for all samples. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 5

Variation of grain and grain boundary electrical parameters for $La_{1-x}Mg_xFeO_3$ powdered ceramics at different temperatures (R_g and R_{gb} : grain and grain boundary resistances, respectively; CPE_g and CPE_{gb} : constant phase elements of grain and grain boundary, respectively).

х	T (° <i>C</i>)	R_g (10 ⁴ Ohm)	CPEg (nF)	R_{gb} (10 ⁴ Ohm)	CPE _{gb} (nF)
0.1	50	20.39	0.02315	26.61	192.4
	75	8.391	0.02937	19.44	401.4
	100	8.221	321.0	4.007	0.04291
	125	3.580	146.3	3.281	0.05585
	150	2.325	0.01166	0.9692	188.1
0.2	50	28.51	0.01587	24.11	508.3
	75	14.95	0.01920	10.31	781.4
	100	9.234	7.884 x 10 ⁻³	4.131	281.6
	125	5.717	0.01814	1.018	2.345
	150	2.991	3.722	0.2611	9.547 x 10 ⁻⁴
0.3	50	67.12	0.05924	-	-
	75	33.12	0.1311	-	-
	100	21.72	0.05102	-	-
	125	17.11	0.01796	-	-
	150	6.288	0.01652	_	-

contents, whereas at high Mg contents, the grain effect dominates following the reduction in the grain boundary effect. Thus, the low- and high-frequency regions correspond to different relaxation mechanisms [20,21].

The series connection of parallel (R-CPE) circuits could be used to represent the grain and grain boundary contribution for each temperature. The samples with x = 0.1 and 0.2 were fitted using the two parallel (R-CPE) circuits, whereas the sample with x = 0.3 was fitted with single parallel (R-CPE) circuits. The electrical parameters, i.e. grain resistance (R_g), grain constant phase element (CPE_g), grain boundary resistance (R_{gb}) and grain boundary capacitance (CPE_{gb}) values from fitting results, are listed in Table 5.

 R_g and R_{gb} decreased with increasing temperature, indicating an

Table 6

Activation energy calculated using the Arrhenius equation of grain and grain boundary effect for La_{1-x}Mg_xFeO₃ ceramics (E_g and E_{gb}: activation energy of grain and grain boundary effect, respectively).

x	E _g (eV)	E _{gb} (eV)
0.1	0.2651	0.3929
0.2	0.2567	0.5286
0.3	0.2522	-

increase in the charge carrier mobility [22]. Furthermore, R_g was higher than R_{gb} at x = 0.1 and 0.2, indicating that the relatively conducting grain boundary surrounds the insulating grains [21]. For the sample with x = 0.3, R_g is the only factor affecting the electrical mechanism.

The activation energies for grain and grain boundary responses were calculated using the Arrhenius law [23-25]. Eg and Egb represent the role of electronic and ionic charge carriers in the electrical mechanisms, respectively [23,24]. The electronic carrier is associated with electron and/or hole and ionic charge carrier is related to oxygen vacancy in the lattice [23]. Eg and Egb for La1-xMgxFeO3 powdered ceramics are listed in Table 6. E_{gb} increased with an increase in Mg content for x = 0.1 and 0.2, indicating that the Mg concentration reduces oxygen ion migration and decreases oxygen vacancy concentration in the lattice which leads to decreasing the oxygen-ion conductivity at the grain boundary. This is consistent with the lattice distortion degree based on XRD analysis. As we mentioned in XRD analysis, Mg content increased the lattice distortion from cubic symmetry, in other words, the lattice tends to more stabilize to orthorhombic symmetry. Accompanied by the distortion effect on the nearby lattice, Mg ions may also influence the oxygen vacancy as well as changing the chemical properties of nearby oxygen ions. The lattice distortion near grain boundary alters the distance between oxygen ions in that region causing the harder of the charge carrier to transfer between oxygen ions in lattice [26-28]. Moreover, Eg decreased with an increase in Mg content for all samples, indicating that Mg ions reduce the barrier that blocks the movement of electronic charge



Fig. 7. Bode plots of Z'(f) for $La_{1-x}Mg_xFeO_3$ ceramics.



Fig. 8. Bode plots of Z''(f) for $La_{1-x}Mg_xFeO_3$ ceramics.

carriers at the insulating grain [23].

Fig. 7 shows the Bode plots of $Z^{\prime}(f)$ for $La_{1-x}Mg_xFeO_3~(x=0.1,~0.2$ and 0.3) at different temperatures. $Z^{'}$ decreased with an increase in

frequency. In the low-frequency region, Z' was higher at lower temperatures than at higher temperatures, indicating an increase in conductivity with a rise temperature. Z' was frequency-independence at the

Table 7

The activation energies obtained from the Bode plots of Z''(f) for La $_{1-x}Mg_xFeO_3$ ceramics.

x	E _{a1} (eV)	E _{a2} (eV)
0.1	0.3737	0.2977
0.2	0.7989	0.2905
0.3	_	0.2549

high-frequency region, which is attributed to the reduction of barrier at high temperatures as compensation for the release of space charges [24, 25].

Fig. 8 shows the Bode plots of Z''(f) for $La_{1-x}Mg_xFeO_3$ (x = 0.1, 0.2 and 0.3). Z'' increases until it reaches a maximum and then starts to decrease with frequency. The frequency peaks observed in this range of temperature broadened with increasing temperature, suggesting a thermal activation in the relaxation process [24,25]. Two peaks at different temperatures were observed for the samples with x = 0.1 and 0.2, indicating two relaxation mechanisms occurring in this temperature range, whereas only one peak was observed for the sample with x = 0.3, indicating the single relaxation process in this temperature range. Hereafter, the relaxation is referred to as relaxation I (f $< 10^4$ Hz) and relaxation II (f $> 10^4$ Hz). These relaxation peaks shifted towards high frequency as temperature increased. In addition, the relaxation peaks shifted towards low frequency as Mg content increased. The relaxation was analysed using thermal activation relations [7,21]. The observed activation energies for all samples are shown in Table 7. The activation energies obtained are comparable to the relaxation for several perovskite oxide systems [21,24,25].

The frequency and temperature dependence of the complex conductivity of $La_{1-x}Mg_xFeO_3$ ceramics (x = 0.1, 0.2 and 0.3) are shown in Fig. 9. The complex conductivity first decreased gradually with a decrease in frequency, which is known as the AC conductivity region. Then, the conductivity remained constant at lower frequencies, which is also known as the DC conductivity region. The complex conductivity spectra were fitted using Jonscher's power law [29]:

 $\sigma(\omega) = \sigma_{DC} + B\omega^n$

where σ_{DC} is the DC conductivity, $B\omega^n$ is the frequency-dependent AC conductivity (ω is the measured frequency, *B* is a prefactor, which is strongly related to the composition and temperature, and *n* is the frequency exponent.

Fig. 10 shows the temperature-dependent DC conductivity, σ_{DC} , of $La_{1-x}Mg_xFeO_3$ ceramics. The σ_{DC} value increased with an increase in temperature, indicating thermal activation in the conduction process.



Fig. 10. The Arhenius plots of DC conductivity, σ_{DG} vs inverse of temperature, 10³/T, for La_{1-x}Mg_xFeO₃ ceramics.



Fig. 9. Complex conductivity of $La_{1-x}Mg_xFeO_3$ ceramics.

The linear plots of ln σ_{DC} versus the inverse of temperature well satisfy the Arrhenius law [29,30]. The fitting plots show similar rules in this temperature range for all samples, indicating only that one mechanism works in the conduction process. The activation energy obtained from the slope of the Arrhenius plots slightly decreased with an increase in Mg content.

4. Conclusions

We have investigated the structural, magnetic and electrical properties of La1-xMgxFeO3 powdered ceramics. Structural analysis revealed that all doped samples have orthorhombic crystal structure with Pbnm symmetry similar to the undoped sample. The addition of Mg induces an increase in lattice distortion, resulting in a decrease in the lattice constant, lattice volume and bond length. TEM revealed a decrease in particle size with an increase in Mg content. The magnetisation increased with increasing Mg content. The temperature dependence of the electrical properties confirmed the grain and grain boundary effect at low Mg content (x < 0.2) and grain effect at high Mg content (x = 0.3) in the conduction mechanism. The activation energy for the grain response decreased with an increase in Mg content, whereas that of grain boundary responses increased. Electrical relaxation analysis revealed two relaxation mechanisms for samples with lower Mg content and one relaxation mechanism for those with higher Mg content. The temperature dependence of conductivity confirms the single conduction mechanism and a decrease in the activation energy with an increase in Mg content.

Declaration of competing interest

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

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