CHAPTER-6
DIELECTRIC, FERROELECTRIC AND PIEZOELECTRIC CHARACTERISTICS OF LANTHANUM MODIFIED LEAD TITANATE CERAMICS.
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6.1 Introduction

Lead titanate (PT) ceramics modified by rare earth elements and alkaline earth elements have emerged as highly promising materials for several piezo-electric applications due to existence of large electro-mechanical anisotropy in the coupling factors along and transverse direction of polarization [1]. These modified materials are extremely good for high frequency applications [2]. Pyroelectric lead titanate ceramics have been found useful for use in thermal imaging and human detection [3].

Several dopants have been employed as individual additives, combination doping by two or more ions. Very encouraging results boosted the research activity in the modified PT ceramics. Most successful modifications have been achieved by simultaneous addition of 24mol % calcium 2mol % cobalt 2mol % tungsten and 1-2mol % MnO₂ [1]. Addition of 8 mol % of La₂O₃ or 24 mol % CaO strongly diminishes Curie temperature and dielectric constant of PT ceramics. Such decrease is more pronounced in case of CaO addition [4]. Samarium modified PT ceramics are reported to exhibit best piezoelectric features [5-6]. BiFeO₃ and Ba(Cu₀.₅W₀.₅)O₃ added to samarium-modified PT ceramics are reported to be very effective in lowering the sintering temperature without adversely affecting dielectric and piezoelectric anisotropy properties [7]. Lowering of sintering temperature also reduces loss of lead during sintering. In calcium modified PT ceramics grain size and porosity is found
to affect the behaviour of permittivity and planar / thickness frequency constant [8]. Addition of strontium in calcium modified PT ceramics increases permittivity and piezoelectric anisotropy [9]. Lower transition temperature and high tetragonality of these ceramics make them easy to pole at low fields and moderate temperatures.

Yamamoto [10] investigated the entire tetragonal range of La modified PT ceramics for ferroelectric and piezoelectric properties. Yamamoto observed that addition of 1mol% of MnO₂ in composition having 10mol% of La₂O₃ increases electro-mechanical thickness coupling factor by 20% to exhibit a high value of 0.6. It has been reported that addition of MnO₂ significantly enhances mechanical properties of PT, which in its pure form is difficult to make, as it tends to shatter. Since Fe₂O₃ and MnO₂ are reported to influence PT in a nearly similar manner, it was decided to use Fe₂O₃ for densification and improved mechanical strength [11-14]. Modification by tungsten and molybdenum are expected to promote grain growth kinetics and so molybdenum with iron was chosen to study the overall influence on the dielectric and ferroelectric properties. Further, the author did not come across any investigation using molybdenum ions as dopant in PT ceramics. Moreover, it is likely that substitution into Ti4⁺ sites by Mo⁶⁺ will enhance resistivity by compensation of charge due to off-valency substitution for Pb²⁺ sites. Consequently modified PT ceramics will be able to withstand severe poling conditions and saturated piezoelectric properties can be obtained [2,15]

Microstructural characteristics and phase transition behaviour of lanthanum modified lead titanate ceramics has been discussed by Rossetti et al [16]. The breakdown of conventional ferroelectric phase transition behaviour in lanthanum modified lead titanate ceramics has been correlated with the appearance of domain structures exhibiting texture on a nanometer scale. Saptial amplitude modulation in lanthanum doped lead titanate solid solution systems is also reported [16-18]. According to the authors the modulated structure in La doped lead titanate solid solution systems is induced by the lanthanum dopant. The phase transition
behaviour and structural characteristics of lanthanum substituted lead titanate ferroelectrics were investigated by high temperature X-ray diffraction and differential scanning calorimetry by Rossetti et al [19]. The relaxation of the lattice to the defects as observed in the X-ray measurements were correlated with the onset of diffuse phase transition behaviour revealed by the calorimetry experiments. According them the lattice relaxation mechanism is connected with the appearance of mesoscopic modulations of the ferroelectric domain structure and with anomalies in the dielectric behaviour near the transition.

The modification in these multi doped ceramics reduces stress caused during cooling through Curie temperature by way of reduction in crystal tetragonality. These modifications are expected to yield hard dense microstructured polarizable ceramics possessing high hydrostatic coefficient which would subsequently be employed for hydrostatic applications. Mixed lanthanum modification can be tailored to exhibit improved ferroelectric and electro-mechanical properties. The ceramics prepared by Yamamoto etal [10] were prepared by hot pressing technique and contained only single modifier as lanthanum. Their investigation does not include detailed studies. Therefore, attempt was made to carry out a systematic study of lanthanum modified PT ceramics also in order to investigate dielectric, ferroelectric and piezoelectric properties. Another goal was to fabricate these ceramics by conventional solid state reaction in air atmosphere at lower sintering temperature and time, while improving or at least maintaining the comparable dielectric, ferroelectric and piezoelectric properties obtained by hot pressing technique. Most reported lanthanum modified PT ceramics employ hot pressing technique or atmosphere sintering at very high temperatures (1280-1350 °C) [20-21] for long periods (8 to 20 hrs) [22-23].

6.2 Experimental

Sintered pallets were lapped to make surfaces flat and parallel with thickness of about 1mm. Samples were fired at 500 °C after applying fire-
on silver paste for electrode formation. Dielectric constant and tangent loss as function of frequency and temperature were measured by using Impedance Analyzer (HP 4192 A). Dielectric constant and a.c. conductivity were calculated from the measured capacitance and tangent loss using equations (6.1) and (6.2) respectively:

\[ \varepsilon' = \frac{C.t}{\varepsilon_0.A} \]  
\[ \sigma_{ac} = \omega \varepsilon' \varepsilon_0 \tan \delta \]

where \( C \) is the capacitance of the sample, \( t \) the thickness, \( A \) the area, \( \varepsilon_0 \) the permittivity of free space, \( \omega \) the frequency and \( \tan \delta \) the dissipation factor.

The variation of polarization with respect to field was recorded at 50Hz with modified Sawyer Tower circuit. The samples were poled by applying electric field of 30kV/cm at 150°C in silicone oil for 30 minutes and then cooled to room temperature under application of the field. Electromechanical properties were calculated by measuring the frequency of resonance and anti-resonance as per the IRE standards [24] described in chapter-2. Belincourt meter was used for piezoelectric measurements.

### 6.3 Dielectric characteristics

#### 6.3.1 Effect of poling

The dielectric constant of the poled samples is found to be lower than that of the unpoled samples. A representative plot of the composition \( \text{Pb}_{98} \text{La}_{0.2} \text{Ti}_{0.66} \text{Mo}_{0.02} \text{Fe}_{0.02} \text{O}_{3} \) (20% La) is given in figure 6.1. It is observed that the dielectric constant decreases in all the compositions considered here with poling. The results can be explained by recognizing the fact that for lower La content, O-site vacancies are produced by \( \text{Fe}^{2+} \) and Ti\(^{4+}\) site vacancies produced by \( \text{Fe}^{3+} \) dominate. While as at higher La content A-site vacancies increase over O-site vacancies, there is an increased amount of 90° domain reorientation by poling field which is able to retain the new status. These remnant 90° domains are thus responsible for decrease in dielectric constant upon poling [25]. The dielectric constant is
expected to reduce as the amount of 90° domain switching increases after poling treatment [26]. The relative dielectric constant of tetragonal polycrystalline Pb₄La₃TiO₁₀ along c-axis is lower than that along a-axis [27]. Thus, the dielectric constant is expected to decrease due to domain orientation which occurs during poling treatment.

6.3.2 Room temperature dielectric dispersion

The dielectric dispersion was observed in all the samples, only the magnitude of dispersion between 100Hz to 100KHz was different but was always within 10-15%. Fig.6.2(a,b) shows representative curves for the dielectric constant and tangent loss versus frequency for samples with 2 and 15 mole % La composition. The tangent loss shows decrease with increasing frequency and is well represented by hopping conduction. A plot of Logω(ω) against Logω (Fig. 6.3a) is expressed as [28]

\[ \sigma(\omega) = A\omega^s \]

(6.3)

where \( \omega (2\pi f) \) is the measuring frequency and exponent \( s < 1 \)

It can be shown from Kramers Kronig relation that dielectric constant for such frequency dependent conductivity can be expressed as [29]:

\[ \varepsilon(\omega) - \varepsilon_\infty = A\omega^{s-1} \]

(6.4)

where \( \varepsilon \) is measured dielectric constant and \( \varepsilon_\infty \) is dielectric constant at high frequency

The variation of dielectric constant with frequency is consistent with equation (6.4) (fig.6.3b) with \( s = 0.91 \) for 2 mol% La composition and \( s=0.93 \) for 15 mol% La composition. The room temperature resistivity of samples is very high \( (10^{10} - 10^{12} \Omega \text{cm}) \) and hence the dispersion due to space charge is unlikely. The most probable origin of small dielectric dispersion at room temperature lies in hopping of charge carriers with random distribution of hopping distances and potential wells [30].
6.3.3 Phase transition

The dielectric constant measured at 1kHz at room temperature shows an increase with increase in lanthanum content (fig.6.4) which is consistent with the results reports by Henings and Hardtlm [22]. It is apparent that the dielectric constant is affected more by grain size and density and less by tetragonality. However, it is difficult to differentiate the affect of density and grain size. The dielectric constant showed a peak at transition temperature for all the samples and the magnitude of peak width is found to depend on the frequency of measurement (Figs.6.5,6.6,6.7). The frequency dependence was more pronounced in samples with higher lanthanum content. Dielectric loss did not show any peak in any samples at any frequency or temperature (Figs.6.8,6.9). If we concentrate on dielectric constant as at 1KHz for different compositions (Fig.6.10), it becomes clear that the peak value of dielectric constant decreases and the peak width increases with increase in lanthanum content. Increase in peak width with increase in lanthanum content has been reported by different workers [31-32]. Diffused transition also has been reported in La₂O₃ modified lead titanate thin films by Schwartz etal [33]. The degree of diffuseness of the transition is studied by using expression [34]:

\[
\frac{1}{\epsilon'} - \frac{1}{\epsilon_{\text{max}}}(T-T_c)^\gamma \quad \text{..................} \quad (6.5)
\]

where \(\epsilon'\) is the dielectric constant at temperature \(T\) and \(\epsilon_{\text{max}}\) is the maximum dielectric constant at transition temperature \(T_c\), and \(\gamma\) is the degree of diffuseness. The value of \(\gamma = 1\) represents ideal Curie Weiss behaviour while \(\gamma\) between 1 and 2 indicates diffused transition [35]. The value \(\gamma\) is found to be 1.34, 1.39, 1.45 and 1.68 for 2 mol\%, 5 mol\%, 15 mol\% and 20 mol\% lanthanum substituted compositions respectively. The value \(\gamma > 1\) suggests diffused transition [36]. This suggests a microscopic heterogeneity in the samples with local curie points. Due to varying amount of lanthanum addition the crystal structure of the various compositions does not have the same lattice parameters, resulting in change in curie temperature. A linear decrease in Curie temperature with the decrease in c/a ratio is reported by Yamamoto [10] for lanthanum.
modified lead titanate. It has also been reported that as the internal stress decreases with the decreasing c/a ratio, the curie temperature is lowered [35]. It is observed in the samples considered here that the curie temperature decreases at the rate of 14°C/mol% of lanthanum addition (Fig 6.11). Decrease in T_c at the rate of 17°C/mol% of La_1.5O has also been reported [12,22]. Linear decrease in T_c at the rate of 18°C/mol% has been reported in lead titanate thin films doped with La by Lijima et al [38] and Schwartz et al [33].

6.4 Spontaneous polarization and coercive field

For low La ceramics the value of spontaneous polarization is significantly less, implying that there is stiff opposition to reorientation and rotation of domains and the specimens are as good as virgin within the limits of applied field. As has been seen from the hysteresis curves (Fig.6.12) lanthanum extends significant influence on the shape and size of the loops as well as the numerical value of polarization. At low lanthanum content, values are rather very small indicative of the hindrance to the rotation of domains. Similarly, low residual polarization has been observed with several dopants by Udea [39] and attributed to increase in coercive field. This behaviour may be attributed to dominance of acceptor effects, small grain size and greater crystal tetragonality. The value of spontaneous polarization is seen to sharply increase for composition more than 5 mol% La and attains maximum value for composition having 15% of La which has a value of 14.07 μC/cm². Similar to this observation has been reported in calcium doped ceramics [40]. Theoretically, \( P_s \) values should have decreased because of decreasing relative displacement of unit cell contents. The increase in \( P_s \) for composition having greater than 5 mol% La, exhibit a trend as if \( P_s \) is trying to suddenly catch up with its expected behaviour, as though it has kept \( P_s \) suppressed till 5mol % of La (Fig 6.13). Here the role played by critical multi ion doping has critical and controlling role.
The coercive field of the La modified PT shows a decrease with increasing La concentration (Fig 6.13), since the domain reorientation and rotation is facilitated due to decreasing crystal tetragonality and increasing grain size. The coercive field i.e. the field at which the domains begin to switch their polarity, is influenced by the presence of iron in addition to grain size and crystal tetragonality.

The stresses at grain boundaries of these La modified ceramics are influenced also by respective anisotropy and lattice imperfections. As the crystal anisotropy is reduced by increasing lanthanum content, the stress at grain boundaries is consequently reduced. Since the crystal anisotropy is large for 2 & 5% lanthanum compositions so the stress at grain boundaries prevent an effective polarization, while as contrary is true for decreasing tetragonality specimens (10,15,20% La compositions). By similar arguments decrease in coercive field can be explained as being due to reduced lattice strain and reduced grain boundary stresses. Yamamoto et al. [10] have reported decrease in \( P_t \), and \( E_c \) values with decreasing c/a ratio which approaches to zero when c/a tends to 1.00.

6.5 Piezoelectric coefficients

6.5.1 Electromechanical coupling coefficients

The electromechanical coupling coefficients, including both planar \( (k_p) \) and thickness \( (k_t) \) coupling coefficients, were found to show dependence on lanthanum substitution. However, \( k_p \) is observed to show slight variation, while as \( k_t \) is greatly influenced by variation of the lanthanum substitution. Fig 6.14 shows the effect of lanthanum substitution on \( k_p \) and \( k_t \) of lanthanum modified lead titanate ceramics. It has been observed that thickness coupling factor sharply increases from 0.167 for 2 mol% La substituted to 0.613 for 15 mol % substituted La composition and beyond this \( k_t \) sharply decreases. The planar coupling coefficients \( (k_p) \) does not show much dependence on lanthanum substitution. Yamamoto et al. [10] has reported similar electromechanical behaviour for lanthanum modified PT ceramics prepared by hot pressing technique. Maximum
values of 0.46 and 0.29 for $k_i$ and $k_p$, respectively are also reported. In our ceramics the higher value of $k_i$ is attributed to the presence of additional modifiers of iron and molybdenum. Yamamoto et al [10] also reported that addition of 1 mol% of MnO$_2$ to 10 mol% lanthanum modified PT ceramics increases $k_i$ value sharply from 0.4 to 0.6. This increase in $k_i$ is attributed to increase in resistivity by the small addition of MnO$_2$ which results in better poling treatment. The maximum value of $k_i$ obtained in our 15 mol% lanthanum composition is attributed to the presence of 2% Fe$_2$O$_3$ in our samples which is believed to have affected in the same manner as that of the MnO$_2$. The values 0.42 and 0.14 for $k_i$ and $k_p$ respectively reported by Duran et al [41] are in good agreement with our findings. It has been observed in samarium modified PT ceramics that the planar coupling coefficient decreases and thickness coupling coefficient increases by stronger poling field [15,42]. This has been attributed to large crystal anisotropy. Takeuchi et al [15] have suggested that the origin of the electromechanical anisotropy is related to crystallographic characteristics. According to them electromechanical anisotropy reflects crystal lattice anisotropy. However, this does not seem to be true in the ceramics considered during the present investigations, since it was found that upto 15 mol% substitution of lanthanum $k_i$ increases, while $k_p$ increases slightly, although the crystallographic anisotropy is actually decreasing as has already been reported in chapter 5. So, the cause does not seem to be due to crystallographic characteristics alone. In the literature [43] it is reported that $k_i$ and $k_p$ increases with increase in grain size for lanthanum modified ceramics. The lanthanum modified ceramics with 1 µm grain size are reported to have $k_i$ and $k_p$ of 0.4 and 0.113 respectively, while as for ceramics with coarser grains of 1-3 µm in size, the $k_i$ and $k_p$ is 0.45 and 0.117 respectively. The lanthanum modified ceramics considered here have coarser grains and hence $k_p$ is in perfect agreement with the reported values. However, $k_i$ is slightly less than the expected value which may be due to difference in B-site substitution.

Different mechanisms have been suggested by different workers for the origin of electromechanical anisotropy. However, the exact origin has
not been clearly established. Electromechanical anisotropy \((k_i/k_p)\) reflects crystallographic anisotropy [44]. It has been observed (chapter 5) that the addition of lanthanum in ceramics systematically decreases crystallographic anisotropy and that the ratio \(k_i/k_p\) attains maximum value for 15 mol% lanthanum substituted composition. Thus, the crystallographic anisotropy alone cannot explain the electromechanical anisotropy. It has been suggested that the increase in 90° domain wall reorientation by poling reduces \(k_p\) and enhances anisotropy [1]. Also, strong clamping caused by 90° domain reorientation is attributed to vanishing of \(k_p\) [45]. Porosity in ceramics and wider grain boundaries reduce the intergranular stress caused by spontaneous strain during para-ferroelectric transition [46]. The pressure acting on the 90° domain walls is lower in less dense ceramics than those with compact microstructures. If such ceramics having appropriate microstructures are poled to achieve relatively higher 90° domain reorientation, the \(k_p\) should become zero, although specific mechanism which attributes to this behaviour is not understood [46]. The lanthanum modified ceramic compositions with higher lanthanum content prepared for the present investigations are denser and hence have dense microstructure. In such ceramics, by the observations made by Pardo et al [46], the intergranular stresses produced by 90° domain reorientation would create higher intergranular stresses resulting in increase in tendency of 90° domains to come back to their initial orientation i.e., domains which were reoriented by poling field, should increasingly tend to relax back to their initial orientation in case of dense ceramics. If the intergranular stress caused by 90° domains is removed, the tendency of these domains to relax back will diminish and if these 90° domains are permanently reoriented by poling field then their contribution to planar coupling coefficients will decrease and may also vanish if the reorientation achieved is very high [47]. Non observance of zero \(k_p\) values in 15 mol% La composition, considered here, for which \(k_i\) is 0.613 may be attributed to coarse grains size as suggested by Takahashi et al [2] or the influence of composition which has direct effect on electrostrictive coefficients and permittivity on one hand and the coercive field on the other hand. Takahashi et al [2] considers that \(k_e = 0\) can be realized only when a special
Piezoelectric charge, voltage coefficients

Piezoelectric coefficients show dependence on lanthanum substitution in lanthanum modified lead titanate ceramics. The piezoelectric longitudinal charge coefficient \( (d_{33}) \) is 40.1 pC/N for 2 mol% substituted lanthanum composition and increases sharply to 87.7 pC/N for 15 mol% composition, thereafter the value exhibits a decreasing trend (Fig. 6.15). It is conjectured that the decrease of \( d_{33} \) and \( k_t \) for compositions exceeding 15 mol% of lanthanum concentration may be due to microstructural changes as reported in the literature [16-17]. It could be that the relaxor like properties at the higher lanthanum \( (\text{La}^{3+}) \) concentrations (>15 mol%) may probably account for the decay of piezoelectricity above 15 mol % substitution level of lanthanum. The transverse piezoelectric charge coefficient \( (d_{31}) \) exhibits a limited variation with the lanthanum addition. The value of \( d_{31} \) in all the compositions is around -11 pC/N. The variation of \( d_{31} \) is quite similar to variation of planar coupling coefficient \( (k_p) \). As for piezoelectric charge coefficient \( (d_{33}) \), the piezoelectric voltage coefficient \( (g_{33}) \) is also the highest for 15 mol % lanthanum composition which has a value of 27.3 mV.m/N among all the compositions. The variation of piezoelectric voltage coefficient \( (g_{33}) \) as a function of lanthanum substitution is shown in figure 6.16. The value of \( g_{33} \) for low lanthanum substituted compositions is almost constant around 18 mV.m/N which may be due to small increase in \( d_{33} \) and \( e_{33} \). The value of \( g_{31} \) decreases almost constantly, which is due to rise in dielectric permittivity and almost constant \( d_{31} \). To the best of author's knowledge, there exists no report on investigations of the variation of piezoelectric charge and voltage coefficients as a function of lanthanum content.
Scattered reports for a particular composition or small range of additives do exist. The $d_{33}$ value for 8mol % lanthanum and 12mol % lanthanum substituted PT ceramics is ~50pC/N [41] and 68 pC/N [49] respectively which is in good agreement with our interpolated composition as seen in fig.6.15. The $d_{33}$ in samarium modified ceramics varies from 54 to 74 pC/N when the samarium addition is changed from 6 to 14 mol % [50]. The variation is similar to our findings in lanthanum modified ceramics except that our maximum $d_{33}$ is slightly higher. Piezoelectric charge coefficient ($d_{33}$) in calcium modified ceramics doped with 4 mol% strontium is in good agreement with the $d_{33}$ values found in our 15 mol % lanthanum substituted ceramic composition [9]. De Frutos et al [51,52] reported saturated piezoelectric $d_{33}$ values of 110pC/N for calcium modified ceramics and have attributed this to increase in $180^\circ$ domain reversal and stress caused by the poling fields in higher calcium containing PT ceramics. In our results on lanthanum modified ceramics, $180^\circ$ domain reorientation is found to increase with decreasing tetragonality resulting in increased $180^\circ$ domain polarization contribution. Therefore, the piezoelectric coefficients arising due to $180^\circ$ domain reversal seems to be reasonable to explain the results presented here.

6.5.3 Hydrostatic coefficients

In lanthanum modified ceramics prepared for the present investigations, the hydrostatic charge coefficient ($d_h$) is found to increase with increase in lanthanum substitution. The value for 2 mol % substituted composition is 19.3pC/N and attains maximum of 64.3 pC/N in case of 15mol% substituted composition and falls to 52.1 pC/N in case of 20 mol% composition (fig.6.17). The maximum value is comparable to calcium modified ceramics as reported by Takahashi et al [2]. The hydrostatic voltage coefficient ($g_h$) exhibits a similar behavior as that of $d_h$ and attains peak for 15 mol% composition (fig.6.18). The value of $g_h$ is less than what is reported for calcium modified ceramics [2]. This is due to the higher dielectric constant of the ceramics considered in the present work.
6.6 Conclusion

Room temperature dielectric constant increases with increase in lanthanum addition while as peak dielectric constant decreases with increase in lanthanum content. Dielectric constant is reduced by poling which indicates that in low lanthanum content ceramics there is influence of oxygen vacancies whereas in case of high lanthanum content ceramics there is reorientation of 90° domains. Curie temperature is found to decrease at the rate of 14°C/mol% of lanthanum. $P_s$ and $P_r$ values are subdued in low lanthanum containing compositions which is attributed to small grain size and large lattice tetragonality of these ceramics. $P_s$ and $P_r$ exhibit peaks in case of 15% lanthanum composition. Coercive field decreases continuously with increasing lanthanum content due to decrease in tetragonality and increase in grain size.

The thickness coupling coefficient show significant compositional dependence and maximum thickness coupling coefficient has been observed for 15 mol% lanthanum composition. Planar coefficient does not show much dependence on the lanthanum substitution. Non observance of zero planar coupling coefficient is attributed to coarse grain size and compositional effect on electrostrictive coefficients. Origin of electromechanical anisotropy does not seem to be solely due to 90° domain reorientation or due to crystallographic considerations alone. Piezoelectric charge coefficient ($d_{33}$) exhibits dependence on lanthanum substitution and is maximum for 15 mol% lanthanum substitution. The hydrostatic charge and voltage coefficients are found to be maximum in case of 15 mol% compositions having values of 64pC/N and 20.2 mV.m/N respectively. Decay of piezoelectricity above 15 mol % La$^{3+}$ substitution level could be due to the onset of relaxor like properties at higher La$^{3+}$ concentrations.
References

Fig. 6.1 Effect of poling on dielectric constant at room temperature of PT ceramic with 20 mol% La.
Fig. 6.2 (a) Dielectric constant Vs frequency
(b) Dielectric loss Vs frequency at room temperature
Fig. 6.3(a) Conductivity Vs frequency at room temperature
Fig. 6.3(b) $\log(\varepsilon(\omega) - \varepsilon_\alpha)$ vs $\log(\text{Frequency})$
Fig. 6.4 Effect of lanthanum substitution on dielectric constant and grain size
Fig. 6.5 Dielectric constant Vs temperature of 5 mol% La composition.
Fig. 6.6 Dielectric constant Vs temperature of 15 mol% La composition.
Fig. 6.7 Dielectric constant Vs temperature of 20 mol% La composition.
Fig. 6.8 Dielectric loss Vs temperature of 5 mol% La composition.
Fig.6.9 Dielectric loss Vs temperature of 15 mol% La composition.
Fig. 6.10 Dielectric constant Vs temperature of different compositions measured at 1 kHz.
Fig. 6.11 Effect of lanthanum substitution on Curie temperature.
Fig. 6.12 (Continued on next page)
Fig. 6.12 Hysterisis loops of lanthanum modified lead titanate ceramics a) 2 mol % La; b) 5 mol % La; c) 10 mol % La; d) 15 mol % La; e) 20 mol% La.
Fig. 6.13 Variation of $P_s$, $P_r$, and $E_c$ with lanthanum substitution
Fig. 6.14 Thickness and planar coupling coefficient vs lanthanum concentration.
Fig. 6.15 Longitudinal and transverse charge coefficient vs lanthanum concentration.
Fig. 6.16 Longitudinal and transverse voltage coefficient vs lanthanum concentration.
Fig. 6.17 Hydrostatic charge coefficient Vs lanthanum concentration.
Fig. 6.18 Hydrostatic voltage coefficient Vs lanthanum concentration.