CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

5.1 Conclusions

The dynamic hysteresis behaviors in some ferroelectric materials were observed in this study and their power-law scaling relations in form of hysteresis area $< A >$ as a function of frequency f and field amplitude E_{0}, $< A > \propto f^{m}E_{0}^{n}$ (where m and n are exponents dependent on the dimensionality and symmetry of the system) were demonstrated. All investigations in this study were to support the hypothesis that materials with similar domain states should have very comparable dynamic hysteresis and scaling behaviors.

1. To observe the dynamic hysteresis and scaling behaviors dependent on domain structures, materials with various crystal structures providing various domain states were selected for examination. The materials in this study include $BaTiO_3$ single crystal and bulk ceramic, $0.7Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.3PbTiO_3$ [0.7PMN-0.3PT] single crystal and $Pb(Zr_{1/2}Ti_{1/2})O_3$-$Pb(Zn_{1/3}Nb_{2/3})O_3$ [PZT-PZN] ceramic systems.
2. The exponent m and n for power-law scaling relation in form of $< A > \propto f^{m}E_{0}^{n}$ for ferroelectric materials obtained in this study can be summarized as follows.

Table 5.1 Summary of scaling exponents for ferroelectric materials in this study

		Sub-coercive field		Saturated field	
Systems	Temperature (ºC)	*m*	*n*	*m*	*n*
BaTiO$_3$ single crystal (1-300 Hz)	-60	-0.34±0.08	3.53±0.16	-0.16±0.03	1.01±0.10
	25	$(0.71)E_0$-1.45	5.77±1.58	-0.27±0.05	0.65±0.20
	180	-0.95±0.02	2.25±0.02	-0.95±0.02	2.25±0.02
BaTiO$_3$ bulk ceramic (10-100 Hz)	-120	-0.17±0.09	3.06±0.08	-	-
	-100	-0.16±0.08	3.04±0.18	-	-
	-90	-0.17±0.07	3.28±0.16	-	-
	-60	-0.28±0.15	3.04±0.10	-0.16±0.05	1.38±0.09
	-40	-0.19±0.08	3.09±0.07	-0.21±0.07	1.05±0.13
	-20	-0.26±0.13	3.09±0.11	-0.36±0.13	1.06±0.26
	25	-0.30±0.16	3.49±0.15	-0.28±0.10	0.86±0.15
	60	-0.20±0.15	3.48±0.18	-0.25±0.08	0.76±0.15
	90	-0.28±0.14	3.41±0.13	-0.31±0.10	0.72±0.19
	130	-0.38±0.08	2.11±0.02	-0.38±0.08	2.11±0.02
	150	-0.54±0.07	2.25±0.03	-0.54±0.07	2.25±0.03
	170	-0.78±0.03	2.17±0.01	-0.78±0.03	2.17±0.01
BaTiO$_3$ bulk ceramic (20-100 Hz)	25	-0.32	3.68	-0.25	0.82

Table 5.1 (continued) Summary of scaling exponents for ferroelectric materials in this study

Systems	Temperature (ºC)	Sub-coercive field *m*	Sub-coercive field *n*	Saturated field *m*	Saturated field *n*
$BaTiO_3$ bulk ceramic (1-100 Hz)	25	-0.55	3.40	-0.39	1.06
P_r-scaling relations of $BaTiO_3$ bulk ceramic (1-100 Hz)		-0.43	1.73	-0.18	0.47
E_C-scaling relations of $BaTiO_3$ bulk ceramic (1-100 Hz)		-0.27	1.35	-0.33	0.46
0.7PMN-0.3PT Single crystal	25				
Sinusoidal waveform		-0.27	3.72	-0.21	2.64
Triangle waveform		-0.20	3.26	-0.13	2.41
PZT-PZN bulk ceramic (Minor loop)	25				
0.9PZT-0.1PZN		-0.42	3.65	-	-
0.8PZT-0.2PZN		-0.36	3.32	-	-
0.7PZT-0.3PZN		-0.35	3.47	-	-
0.6PZT-0.4PZN		-0.36	4.03	-	-
0.5PZT-0.5PZN		-0.34	3.68	-	-

3. It is clearly seen from this study that the materials with similar domain states have very comparable dynamic hysteresis and scaling behaviors.

4. The factors that were found influencing the scaling and dynamic behaviors include;

   1. The modeling conditions: the conditions applied in theoretical models do not fully cover the real behaviors in nature while the experimental models do, as seen from the difference between exponent *n* of $BaTiO_3$ single crystal and that of theoretical $(\Phi^2)^2$ and $(\Phi^2)^3$ model. A qualitative explanation for the difference may come from the polarization-interaction terms as considered in the $(\Phi^2)^2$ and $(\Phi^2)^3$ models, in which the polarization flip just has one contribution, i.e., polarization reversal [4-5].

   2. The switching mechanism: as seen from several materials in this study, the exponents *m* and *n* between sub-coercive and saturated field conditions of the same material were obviously different while exponents obtained from sub-coercive field ceramics were very similar to those obtained from thin films. This is attributed to the fact that the main polarization orientation mechanism in thin films and in sub-coercive field condition for single crystals and bulk ceramics is likely from the reversible 180° domain rotation (which also occurs at much faster rate than the irreversible process), as the irreversible non-180° domain switching is normally accompanied with mechanical strain, it occurs at higher *E*-field than 180° domain rotation does. Therefore, under low *E*-fields, one would expect the 180° domain rotation to occur first [23, 139-143]. This explains why the scaling behavior of the single crystals and bulk ceramics at low *E* fields is similar to that of thin films and why the

response to E_0 at sub-coercive field occurs at much faster response than that at higher field amplitude.

3. Defect concentration: as seen from comparison between exponents obtained from $BaTiO_3$ single crystal and bulk ceramic, exponents for $BaTiO_3$ single crystal were higher than those for bulk ceramic due to less defect concentration.

4. Observed range of f and E_0: we can see from $BaTiO_3$ bulk ceramic characterization at room temperature section, the scaling exponents obtained from f-range 1-100 Hz and f-range 20-100Hz were obviously different. For instance of different observed E_0-range we can see from 0.7PMN-0.3PT single crystal section. Exponent n obtained for saturated field condition in this study was quite far from that obtained in 0.7PMN-0.3PT thin film [21] because applied field in this study does not provide full saturation state.

5. Random field: as seen from the difference in scaling exponents between normal ferroelectric $BaTiO_3$ single crystal and relaxor ferroelectric material 0.7PMN-0.3PT single crystal, the exponents of scaling relations for 0.7PMN-0.3PT single crystal were lower than those for $BaTiO_3$ single crystal due to existence of random field.

6. Crystal structure: this can be seen obviously in PZT-PZN ceramic system section. The exponents were varied with composition.

7. Temperature: this one can also be seen clearly in temperature dependence of hysteresis properties and scaling relations in BT system section. Variations of exponents with temperature were revealed.

8. Waveform: this can be seen from the latest section of field-waveform dependence of dynamic hysteresis and scaling behaviors in 0.7PMN-0.3PT single crystal. The exponents slightly changed with field-waveform.

5.2 Suggestions

1. To enhance the accuracy and reliability of the experimental model, the power-law scaling relation, the other data analysis method should be used for comparison. The data analysis method used in this study is only the integrating technique which an error in data or noise is probably taken into mixing with true data, so the obtained data analysis may possibly mislead. The other interesting technique for data analysis is the differentiating technique. It can be used as complimentary with the integrating technique.
2. Dynamic hysteresis investigation should be extended to wider observation range in both of frequency and electric field parameters. This may lead to clearer understanding in dynamic hysteresis behavior and probably obtain universal scaling relation for ferroelectric materials.
3. The future study should be focused on microscopic view to clarify the relationship between scaling exponents and dimensionality and symmetry of the system for better insight of the dynamic hysteresis behavior.