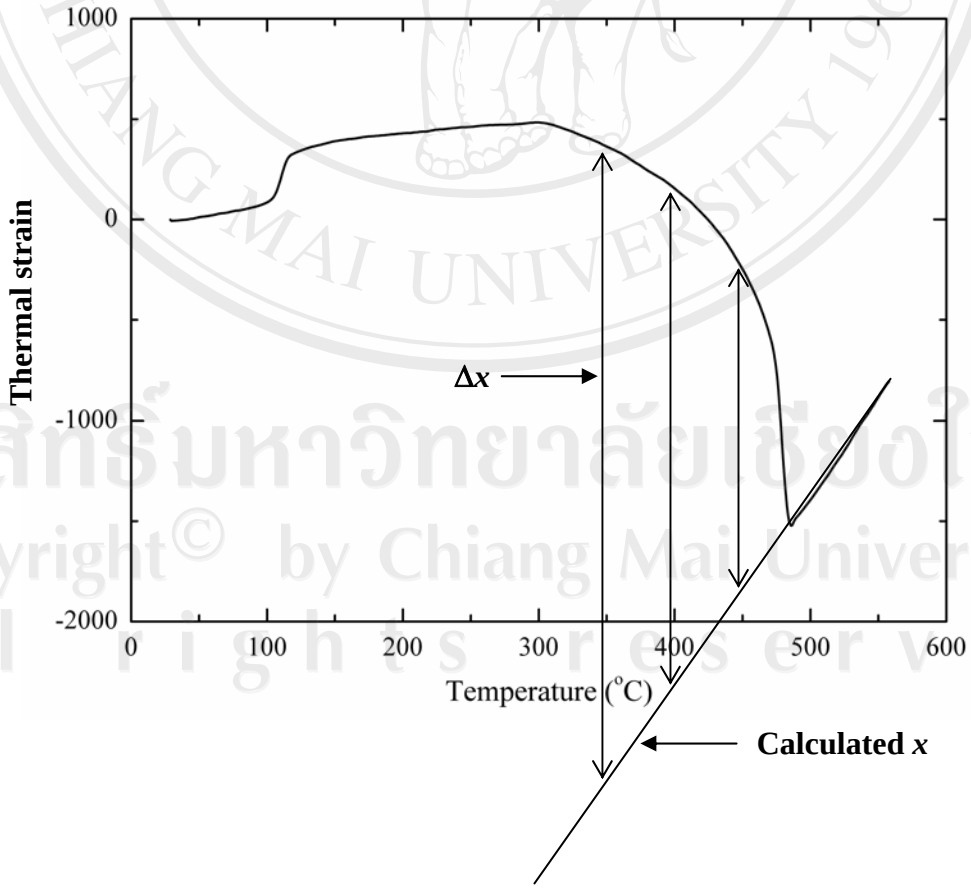
# APPENDIX

## POLARIZATION BEHAVIOR OF PT CERAMICS

In general with the increase in temperature and due to the increase in losses in the PT samples it hinders the real spontaneous polarization and its ($P_S$) temperature dependence measurements at higher temperature by using the hysteresis and pyroelectric techniques. Furthermore, some alternate approaches have to be made in order to extract some useful data on PT for the polarization versus temperature behavior. The highest-temperature data, far above $T_C$, can be approximated by a straight line. By analyzing the deviation of the strain from the high-temperature linear behavior via Eq. (3.8) to obtain $P_S$, then $P_S$ can be calculated



Thermal strain data and calculated polarization of PT ceramic sintered at 900/1200 $^{o}$C

| **Temperature ($^{o}$C)** | **Thermal strain ($x$)** | **Calculated $x^{*}$** | **$\Delta x$** | **$P_S^2$** | **$P_S$ (C/m$^2$)** | **$P_S$ ($\mu$C/cm$^2$)** |
|---|---|---|---|---|---|---|
| -100 | 54.94 | -8534.40 | 8589.34 | 0.70 | 0.84 | 83.57 |
| -90 | 70.32 | -8416.89 | 8487.21 | 0.69 | 0.83 | 83.07 |
| -80 | 94.46 | -8299.37 | 8393.83 | 0.68 | 0.83 | 82.61 |
| -70 | 113.96 | -8181.85 | 8295.81 | 0.67 | 0.82 | 82.13 |
| -60 | 129.65 | -8064.34 | 8193.99 | 0.67 | 0.82 | 81.62 |
| -50 | 158.26 | -7946.82 | 8105.08 | 0.66 | 0.81 | 81.18 |
| -40 | 177.59 | -7829.31 | 8006.90 | 0.65 | 0.81 | 80.68 |
| -30 | 230.99 | -7711.79 | 7942.78 | 0.65 | 0.80 | 80.36 |
| -20 | 246.62 | -7594.27 | 7840.89 | 0.64 | 0.80 | 79.84 |
| -10 | 271.37 | -7476.76 | 7748.13 | 0.63 | 0.79 | 79.37 |

| Temperature ($^oC$) | Thermal strain ($x$) | Calculated $x^*$ | $\Delta x$ | $P_S^2$ | $P_S$ ($C/m^2$) | $P_S$ ($\mu C/cm^2$) |
|---|---|---|---|---|---|---|
| 0 | 290.05 | -7359.24 | 7649.29 | 0.62 | 0.79 | 78.86 |
| 10 | 313.82 | -7241.72 | 7555.54 | 0.61 | 0.78 | 78.38 |
| 20 | 333.01 | -7124.21 | 7457.22 | 0.61 | 0.78 | 77.86 |
| 30 | 354.25 | -7006.69 | 7360.94 | 0.60 | 0.77 | 77.36 |
| 40 | 377.53 | -6889.18 | 7266.71 | 0.59 | 0.77 | 76.86 |
| 50 | 395.33 | -6771.66 | 7166.99 | 0.58 | 0.76 | 76.33 |
| 60 | 416.06 | -6654.14 | 7070.20 | 0.57 | 0.76 | 75.82 |
| 70 | 431.71 | -6536.63 | 6968.34 | 0.57 | 0.75 | 75.27 |
| 80 | 447.97 | -6419.11 | 6867.08 | 0.56 | 0.75 | 74.72 |
| 90 | 462.87 | -6301.59 | 6764.46 | 0.55 | 0.74 | 74.16 |
| 100 | 470.91 | -6184.08 | 6654.99 | 0.54 | 0.74 | 73.56 |
| 110 | 483.31 | -6066.56 | 6549.87 | 0.53 | 0.73 | 72.97 |

| Temperature ($^oC$) | Thermal strain ($x$) | Calculated $x^*$ | $\Delta x$ | $P_S^2$ | $P_S$ (C/m$^2$) | $P_S$ ($\mu$C/cm$^2$) |
|---|---|---|---|---|---|---|
| 120 | 489.75 | -5949.05 | 6438.80 | 0.52 | 0.72 | 72.35 |
| 130 | 496.73 | -5831.53 | 6328.26 | 0.51 | 0.72 | 71.73 |
| 140 | 501.14 | -5714.01 | 6215.15 | 0.51 | 0.71 | 71.08 |
| 150 | 506.38 | -5596.50 | 6102.88 | 0.50 | 0.70 | 70.44 |
| 160 | 510.18 | -5478.98 | 5989.16 | 0.49 | 0.70 | 69.78 |
| 170 | 510.70 | -5361.46 | 5872.16 | 0.48 | 0.69 | 69.09 |
| 180 | 509.59 | -5243.95 | 5753.54 | 0.47 | 0.68 | 68.39 |
| 190 | 508.71 | -5126.43 | 5635.14 | 0.46 | 0.68 | 67.69 |
| 200 | 506.73 | -5008.92 | 5515.65 | 0.45 | 0.67 | 66.96 |
| 210 | 501.39 | -4891.40 | 5392.79 | 0.44 | 0.66 | 66.21 |
| 220 | 482.93 | -4773.88 | 5256.81 | 0.43 | 0.65 | 65.37 |
| 230 | 468.15 | -4656.37 | 5124.52 | 0.42 | 0.65 | 64.55 |

| Temperature ($^oC$) | Thermal strain ($x$) | Calculated $x^*$ | $\Delta x$ | $P_S^2$ | $P_S$ (C/m$^2$) | $P_S$ ($\mu$C/cm$^2$) |
|---|---|---|---|---|---|---|
| 240 | 457.79 | -4538.85 | 4996.64 | 0.41 | 0.64 | 63.74 |
| 250 | 445.49 | -4421.33 | 4866.82 | 0.40 | 0.63 | 62.90 |
| 260 | 435.77 | -4303.82 | 4739.59 | 0.39 | 0.62 | 62.08 |
| 270 | 422.25 | -4186.30 | 4608.55 | 0.37 | 0.61 | 61.21 |
| 280 | 404.12 | -4068.79 | 4472.91 | 0.36 | 0.60 | 60.30 |
| 290 | 388.53 | -3951.27 | 4339.80 | 0.35 | 0.59 | 59.40 |
| 300 | 368.92 | -3833.75 | 4202.67 | 0.34 | 0.58 | 58.45 |
| 310 | 345.94 | -3716.24 | 4062.18 | 0.33 | 0.57 | 57.47 |
| 320 | 321.50 | -3598.72 | 3920.22 | 0.32 | 0.56 | 56.46 |
| 330 | 296.59 | -3481.20 | 3777.79 | 0.31 | 0.55 | 55.42 |
| 340 | 263.81 | -3363.69 | 3627.50 | 0.29 | 0.54 | 54.31 |
| 350 | 231.57 | -3246.17 | 3477.74 | 0.28 | 0.53 | 53.17 |

| Temperature ($^oC$) | Thermal strain ($x$) | Calculated $x^*$ | $\Delta x$ | $P_S^2$ | $P_S$ ($C/m^2$) | $P_S$ ($\mu C/cm^2$) |
|---|---|---|---|---|---|---|
| 360 | 194.15 | -3128.66 | 3322.81 | 0.27 | 0.52 | 51.98 |
| 370 | 157.05 | -3011.14 | 3168.19 | 0.26 | 0.51 | 50.75 |
| 380 | 113.99 | -2893.62 | 3007.61 | 0.24 | 0.49 | 49.45 |
| 390 | 66.16 | -2776.11 | 2842.27 | 0.23 | 0.48 | 48.07 |
| 400 | 10.45 | -2658.59 | 2669.04 | 0.22 | 0.47 | 46.58 |
| 410 | -40.62 | -2541.07 | 2500.45 | 0.20 | 0.45 | 45.09 |
| 420 | -114.07 | -2423.56 | 2309.49 | 0.19 | 0.43 | 43.33 |
| 430 | -195.62 | -2306.04 | 2110.42 | 0.17 | 0.41 | 41.42 |
| 440 | -291.24 | -2188.53 | 1897.29 | 0.15 | 0.39 | 39.27 |
| 450 | -399.05 | -2071.01 | 1671.96 | 0.14 | 0.37 | 36.87 |
| 460 | -550.52 | -1953.49 | 1402.97 | 0.11 | 0.34 | 33.77 |
| 470 | -807.67 | -1835.98 | 1028.31 | 0.08 | 0.29 | 28.91 |

| Temperature ($^{o}$C) | Thermal strain ($x$) | Calculated $x^{*}$ | $\Delta x$ | $P_S^2$ | $P_S$ (C/m$^2$) | $P_S$ ($\mu$C/cm$^2$) |
|---|---|---|---|---|---|---|
| 480 | -1682.49 | -1718.46 | 35.97 | 0.00 | 0.05 | 5.41 |

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**Publications:**

1. **R. Wongmaneerung**, T. Sarakonsri, R. Yimnirun and S. Ananta, "Effects of Milling Method and Calcination Condition on Phase and Morphology Characteristics of $Mg_4Nb_2O_9$ Powders," *Materials Science and Engineering B*, **130** (2006) 246-253.
2. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Effect of Vibro-Milling Time on Phase Formation and Particle size of Lead Titanate Nanopowders," *Materials Letters*, **60** (2006) 1447-1452.
3. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Effect of Milling Time and Calcination Condition on Phase Formation and Particle size of Lead Titanate

Nanopowders Prepared by Vibro-milling," *Materials Letters*, **60** (2006) 2666-2671.

4. A. Rujiwatra, N. Thammajak, T. Sarakonsri, **R. Wongmaneerung** and S. Ananta, "Influence of Alkali Reagents on Phase Formation and Crystal Morphology of Hydrothermally Derived Lead titanate," *Journal of Crystal Growth*, **289** (2006) 224-230.
5. **R. Wongmaneerung**, T. Sarnkonsri, R. Yimnirun and S. Ananta "Effects of Magnesium Niobate Precursor and Calcination Condition on Phase Formation and Morphology of Lead Magnesium Niobate Powders," *Materials Science and Engineering B*, **132** (2006) 292-299.
6. **R. Wongmaneerung**, T. Sarakonsri, R. Yimnirun and S. Ananta, "Effects of Milling Method and Calcination Condition on Phase and Morphology Characteristics of $Mg_4Nb_2O_9$ Powders," *Materials Science and Engineering B*, **130** (2006) 246-253.
7. **R. Wongmaneerung**, R. Yimnirun, S. Ananta, R. Guo and A.S. Bhalla, "Polarization Behavior in the Two-Stage Sintered Lead Titanate Ceramics," *Ferroelectrics Letters*, **33** (2006) 137-146.
8. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Effects of Sintering Condition on Phase Formation, Microstructure and Dielectric Properties of Lead Titanate Ceramics," *Applied Physics A*: *Materials Science and Processing*, **86** (2007) 249-255.
9. R. Yimnirun, **R. Wongmaneerung**, S. Wongsaenmai, A. Ngamjarurojana, S. Ananta and Y. Laosiritaworn, "Temperature Scaling of Dynamic Hysteresis in

Soft Lead Zirconate Titanate Bulk Ceramics," *Applied Physics Letters*, **90** (2007) 112906-1-3.

10. R. Yimnirun, **R. Wongmaneerung**, S. Wongsaenmai, A. Ngamjarurojana, S. Ananta and Y. Laosiritaworn, "Dynamic Hysteresis and Scaling Behavior of Hard Lead Zirconate Titanate Bulk Ceramics," *Applied Physics Letters*, **90** (2007) 112908-1-3.
11. O. Khamman, **R. Wongmaneerung**, W. Chaisan, R. Yimnirun and S. Ananta, "Preparation of Perovskite Nanopowders by Vibro-Milling Technique," *Journal of Alloys and Compounds*, (2007) *in press*.
12. X. Tan, **R. Wongmaneerung**, R. McCallum, S. Ananta and R. Yimnirun, "Cation-, Dipole-, and Spin-Order in $Pb(Fe_{2/3}W_{1/3})O_3$-based Magnetoelectric Multiferroic Compounds," *Applied Physics Letters*, **90** (2007) 242905-1.
13. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Fabrication of Lead Titanate Ceramics by a Two-Stage Sintering Technique," *Journal of Electroceramics* (2007) *in press*.
14. R. Yimnirun, A. Ngamjarurojana, **R. Wongmaneerung**, S. Wongsaenmai, S. Ananta and Y. Laosiritaworn, "Temperature Scaling of Ferroelectric Hysteresis in Hard Lead Zirconate Titanate Bulk Ceramic," *Applied Physics A*, **89** (3) (2007) 737-741.
15. **R. Wongmaneerung**, R. Guo, A. Bhalla, R. Yimnirun and S. Ananta, "Thermal Expansion Properties of PMN–PT Ceramics," *Journal of Alloys and Compounds* (2007) *in press*.

16. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Processing and Properties of $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ Based Ceramics," *Journal of Electroceramics*, (2007) *in press*.
17. **R. Wongmaneerung**, W. Chaisan, O. Khamman, R. Yimnirun and S. Ananta, "Potential of Vibro-Milling Technique for Preparation of Electriceramic Nanopowders," *Ceramics International* (2007) *in press*.
18. O. Khamman, **R. Wongmaneerung**, W. Chaisan, R. Yimnirun and S. Ananta, "Preparation of Perovskite Nanopowders by Vobro-Milling Technique," *Journal of Alloy and Compounds* (2007) *in press*.

**International Conferences:**

1. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Synthesis and Characterizations of Lead Titanate Nano-Sized Powders Prepared via a Rapid Vibro-Milling", *International Conference on Smart/Intelligent Materials and Nanotechnology (SmartMat'04)*, Chiang Mai, Thailand. December, 2004.
2. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "The Fabrication of Lead Titanate Ceramics by a Two-Stage Sintering Technique", *International Conference on The Fourth Asian Meeting on Electroceramics (AMEC4)*, Hangzhou, China. June, 2005.
3. **R. Wongmaneerung**, P. Ketsuwan, R. Yimnirun and S. Ananta, "Preparation of Pyrochlore-Free Lead Magnesium Niobate Powders From $Mg_4Nb_2O_9$ Precursor," *KMITL International Conference on Science and Applied Science*, Bangkok, Thailand. March, 2006.

4. **R. Wongmaneerung**, R. Guo, A. Bhalla, R. Yimnirun and S. Ananta, "Effect of Sintering Temperature on Thermal Expansion and Dielectric Properties of $PbTiO_3$ Ceramics Prepared under Various Sintering Conditions," *15th International Symposium on the Application of Ferroelectrics (ISAF2006)*, North Carolina, USA. July, 2006.
5. **R. Wongmaneerung**, R. Guo, A. Bhalla, R. Yimnirun and S. Ananta, "Thermal Expansion Properties of Two-Step Processed Lead Titanate Ceramics," *Materials Science & Technology2006 Conference and Exhibition (MS&T'06)*, Ohio, USA. October, 2006.
6. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Processing and Properties of $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ Based Ceramics," *International Conference on The Fifth Asian Meeting on Electroceramics (AMEC5)*, Bangkok, Thailand. June, 2006.
7. **R. Wongmaneerung**, R. Guo, A. Bhalla, R. Yimnirun and S. Ananta, "Thermal Expansion and Polarization Behavior Studies of PMN-PT Ceramics," *International Conference on Materials for Advanced Technologies (ICMAT'07)*, Singapore. July, 2007.

**National Conferences:**

1. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Effect of Milling Time on Particle Size and Properties of Lead Titanate Ceramics", *The 29th Congress on Science and Technology of Thailand*, Bangkok, Thailand. October, 2003.
2. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Effect of Milling Time on Phase Formation and Particle Size of Lead Titanate Powders Synthesized by the Solid-State Reaction", *The Third Thailand Materials Science and Technology Conference*, Bangkok, Thailand. March, 2004.
3. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Effect of Milling Time on Phase Formation and Particle Size Distribution of Lead Titanate Powders", *The 30th Congress on Science and Technology of Thailand*, Bangkok, Thailand. October, 2004.
4. **R. Wongmaneerung**, Y. Laosiritaworn, R. Yimnirun and S. Ananta, "A Mixed Oxide Synthetic Route to $Mg_4Nb_2O_9$ Nanopowders in a Corundum-like Phase", *NanoMaterial Fabrication Technologies*, Chiang Mai, Thailand. July, 2005.
5. **R. Wongmaneerung**, R. Yimnirun, S. Ananta and Y. Laosiritaworn, "Monte Carlo Simulations of Nano-Powders from Mechanical Milling", *NanoMaterial Fabrication Technologies*, Chiang Mai, Thailand. July, 2005.
6. **R. Wongmaneerung**, R. Yimnirun and S. Ananta, "Dielectric Properties of Lead Titanate-Based Ceramic Nanocomposites," *The First Thailand National Nanotechnology Conference: Phamaceutical, Nanomaterials, Devices and Applications*, Chiang Mai, Thailand. August, 2007