

LIST OF FIGURE

Figure No.	CHAPTER	Page No.
---------------	---------	-------------

CHAPTER 1: ZnO based Varistor Ceramics- An Introduction

- 1.1. Parallel connection of varistor to a circuit [Gupta et. al (1979)] 1
- 1.2. Schematic depiction of the Microstructure [Levinson (1975)], and Block model of ZnO varistor Bueno (2008)], Electrodes are attached and current flows as indicated. 4
- 1.3. Photomicrographs of polished and etched varistor sample [Levinson (1975)] 5
- 1.4. Simplified equivalent circuit for varistors and Current density versus applied field for a typical varistor. 11
- 1.5. Equivalent circuits in which Z_{source} symbolizes the voltage-independent source impedance [www.epcos.com] 13
- 1.6. Principle of overvoltage protection by varistors [www.epcos.com] 14
- 1.7. Principle circuit diagram of SC station with MOV[CIGRÉ Publication 33/14-05] 18
- 1.8. SC station (left) and surge arrester bank (right) [CIGRÉ Publication 33/14-05] 19
- 1.9. Principle circuit diagram of HVDC station with arresters [CIGRÉ Publication 33/14-05] 20
- 1.10. Examples of „B“- (left) and „A“-arresters (right) in a HVDC station [CIGRÉ Publication 33/14-05] 20

CHAPTER 2: Literature Review

- 2.1. Stick and ball representation of ZnO crystal structures: (a) cubic rocksalt, (b) cubic zinc blende and (c) hexagonal wurtzite structure. The shaded gray and black spheres denote zinc and oxygen atoms respectively [N. R. Yogamalar-2013] 25

- 2.2. (a) Defect formation energies as a function of the FE at the oxygen 28
poor and oxygen rich limits and (b) Defect thermodynamic
transition levels [N. R. Yogamalar-2013]
- 2.3. The current density versus voltage per grain, V_g , of pure ZnO and 33
ZnO doped with V_2O_5 of 0.25, 0.5, 1 and 2 mol%, respectively.
Specimens were sintered at 900°C for 4 h (J K Tsai, 1996).
- 2.4. Nonlinear $I-V$ characteristics of ZnO-0.25 mol% V_2O_5 ceramics 33
sintered at 900°C for various lengths of time. Current density
dependence of the nonlinearity coefficient α is a result for the
specimen sintered for 4 h (J K Tsai, 1996).
- 2.5. SEM micrographs of ceramics sintered at 900°C containing various 35
amounts of V_2O_5 : (a) 1mol%, (b) 2mol%, (c) 3mol%, (d) 4mol%, and
(e) 5mol% (M. Mirzayi et al, 2013).
- 2.6. SEM micrographs of ceramics sintered at 700°C containing various 35
amounts of V2O5: (a) 1mol%, (b) 2mol%, (c) 3mol%, (d) 4mol%,
and (e) 5mol% (M. Mirzayi et al, 2013).
- 2.7. Non-linear E-J curve of the prepared ceramics sintered at 36
temperatures 900°C (M. Mirzayi et al, 2013).
- 2.8. Variation of activation energy (E_a) in term of V_2O_5 content and 36
sintering temperature (M. Mirzayi et al, 2013)
- 2.9. SEM micrographs of V_2O_5 -doped ZnO varistors (H H Hng, 2000) 38
- 2.10. $E-J$ curves showing (a) effects of additives and (b) effects of V_2O_5 39
content in Mn -doped ZnO- V_2O_5 materials. (H H Hng, 2000)
- 2.11. SEM images of different specimens: (a) ZV, (b) ZVM, (c) ZVP, and 42
(d) ZVMPB
- 2.12. E-J curves of different specimens tested at room temperature 43
- 2.13. (a) A typical equivalent circuit, a sketch of the AC impedance 44
spectrum and (b) AC impedance spectra of the specimens tested at
room temperature [Jun Wu et al (2012)].

- 2.14. Frequency dependence of $-\rho''$ of different specimens, (b) 45
 Frequency dependence of the relative dielectric constant of the specimens tested at room temperature.
- 2.15. J-E curves of the samples sintered at different temperatures (a) ZV 46 and (b) ZVM [Jun Wu et al (2012)]
- 2.16. Ac impedance spectra of a) ZV& b) ZVM sintered at different 46 temperatures [Jun Wu et al (2012)]
- 2.17. Frequency dependence of ρ' and $-\rho''$ of a ZV and b ZVM [Jun Wu et al (2012)] 47

CHAPTER 4: Synthesis and Characterization Methods

- | | | |
|-------|--|----|
| 4.1. | Conventional ball mill | 52 |
| 4.2. | A 25 Ton hydraulic press and an oven | 53 |
| 4.3. | Muffle furnace with programmable controller | 54 |
| 4.4. | Photographs of sintered ZnO-V ₂ O ₅ sample | 54 |
| 4.5. | Processing and characterization of ZnO varistor | 55 |
| 4.6. | Principle and arrangement of X-ray Powder Diffraction (XRD) | 57 |
| 4.7. | Figure of X-Ray Diffractometer | 58 |
| 4.8. | SEM device and the interaction of an incident electron beam | 59 |
| 4.9. | shows a schematic of a simple scanning electron microscope | 61 |
| 4.10. | Equivalent circuit for a sample having grain, grain boundary and electrode polarisation processes | 64 |
| 4.11. | Equivalent circuit for a polycrystalline ceramic sample and corresponding frequency response in the complex plane plots for four electrical formalisms | 65 |
| 4.12. | An Alpha A High Performance Frequency Analyzer Novocontrol Technologies | 68 |
| 4.13. | I-V source/measure unit Keithley 2410, U.S | 70 |

CHAPTER 5: Electrical and structural characterization of Nb₂O₅ doped ZnO-V₂O₅ varistor ceramics sintered at different temperature.

- 5.1. X-ray diffraction patterns of samples sintered at 850 °C with 76
following compositions: (a) 850N000 (0.00 mol% Nb); (b)
850N005 (0.05 mol% Nb); (c) 850N010 (0.10 mol% Nb); (d)
850N025 (0.25 mol% Nb) and (e) 850N050 (0.50 mol% Nb)
- 5.2. X-ray diffraction patterns of samples sintered at 900 °C with 77
following compositions: (a) 900N000 (0.00 mol% Nb); (b)
900N005 (0.05 mol% Nb); (c) 900N010 (0.10 mol% Nb); (d)
900N025 (0.25 mol% Nb) and (e) 900N050 (0.50 mol% Nb)
- 5.3. X-ray diffraction patterns of samples sintered at 950 °C with 78
following compositions: (a) 950N000 (0.00 mol% Nb); (b)
950N005 (0.05 mol% Nb); (c) 950N010 (0.10 mol% Nb); (d)
950N025 (0.25 mol% Nb) and (e) 950N050 (0.50 mol% Nb)
- 5.4. SEM micrographs of the sample sintered at 850 °C with following 83
compositions: (a) 850N000 (0.00 mol% Nb); (b) 850N005 (0.05
mol% Nb); (c) 850N010 (0.10 mol% Nb); (d) 850N025 (0.25 mol%
Nb); and (e) 850N050 (0.50 mol% Nb).
- 5.5. SEM micrographs of the samples sintered at 900 °C with following 84
compositions: (a) 900N000 (0.00 mol% Nb); (b) 900N005 (0.05
mol% Nb); (c) 900N010 (0.10 mol% Nb); (d) 900N025 (0.25 mol%
Nb); and (e) 900N050 (0.50 mol% Nb).
- 5.6. SEM micrographs of the samples sintered at 950 °C with following 85
compositions: (a) 950N000 (0.00 mol% Nb); (b) 950N005 (0.05
mol% Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol%
Nb); and (e) 950N050 (0.50 mol% Nb)
- 5.7. EDS spectra of binary ZnO-V₂O₅ (900N000) (a) SEM micrograph (b) 89
at the ZnO grain (c) at the ZnO grain boundary showing V
segregation in it and (d) sum spectrum or full frame
- 5.8. EDS elemental maps for binary ZnO-V₂O₅ System (900N000) (a) 90
SEM micrograph (b) Zn map (c) O map and (d) V map.

- 5.9. EDS spectra of 0.05 mol% Nb doped ZnO-V₂O₅ sample (900N005) 91
 (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V segregation in it and (d) at the selected region.
- 5.10. EDS elemental maps for 0.05 mol% Nb doped ZnO-V₂O₅ System 92 (900N005): (a) SEM micrograph (b) Zn map (c) O map and (d) V map and (e) Nb map.
- 5.11. EDS spectra of 0.10 mol% Nb doped ZnO-V₂O₅ sample (900N010) 93
 (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V segregation in it and (d) at the triplet point.
- 5.12. EDS elemental maps for 0.10 mol% Nb doped ZnO-V₂O₅ sample 94 (900N010) (a) SEM micrograph (b) Zn map (c) O map (d) V map and (e) Nb map.
- 5.13. EDS spectra 0.50 mol% Nb doped ZnO-sample (900N050) (a) SEM 95 micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V segregation in it and (d) at the bubble/dot on ZnO grain.
- 5.14. EDS elemental maps for 0.50 mol% Nb doped ZnO-V₂O₅ System 96 (900N050) (a) SEM micrograph (b) Zn map (c) O map (d) V map and (e) Nb map.
- 5.15. Shows the plot of percentage theoretical density vs. mol% Nb₂O₅ 97 for the samples sintered at (a) 850 °C; (b) 900 °C and (c) 950 °C.
- 5.16. E-J curve showing the effects of Nb₂O₅ content in ZnO-V₂O₅ 100 materials sintered at 850 °C: (a) 850N000 (0.00 mol% Nb); (b) 850N005 (0.05 mol% Nb); (c) 850N010 (0.10 mol% Nb); (d) 850N025 (0.25 mol% Nb) and (e) 850N050 (0.50 mol% Nb).
- 5.17. E-J curve showing the effects of Nb₂O₅ content in ZnO-V₂O₅ material 101 sintered at 900°C: (a) 900N000 (0.00 mol% Nb); (b) 900N005 (0.05 mol% Nb); (c) 900N010 (0.10 mol% Nb); (d) 900N025 (0.25 mol% Nb) and (e) 900N050 (0.50 mol% Nb).
- 5.18. E-J curve showing the effects of Nb₂O₅ content in ZnO-V₂O₅ 102 materials sintered at 950 °C: (a) 950N000 (0.00 mol% Nb); (b)

- 950N005 (0.05 mol% Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol% Nb) and (e) 950N050 (0.50 mol% Nb).
- 5.19. Plot of (i) $\dot{\epsilon}$ and (ii) $\tan \delta$ vs frequency of varying Nb_2O_5 doping in ZnO-V₂O₅ materials sintered at 850 °C.
- 5.20. Plot of (i) $\dot{\epsilon}$ and (ii) $\tan \delta$ vs frequency of varying Nb_2O_5 content in ZnO-V₂O₅ materials sintered at 900 °C.
- 5.21. Plot of (i) $\dot{\epsilon}$ and (ii) $\tan \delta$ vs frequency of varying Nb_2O_5 content in ZnO-V₂O₅ materials sintered at 950 °C.
- 5.22. Impedance plots for the composition sintered at 850°C and measurement done at 50 °C: (a) 850N000 (0.00 mol% Nb); (b) 850N005 (0.05 mol% Nb); (c) 850N010 (0.10 mol% Nb); (d) 850N025 (0.25 mol% Nb); (e) 850N050 (0.50 mol% Nb) and (f) Equivalent circuit.
- 5.23. Impedance plots for the composition sintered at 850°C and measurement done at 150 °C: (a) 850N000 (0.00 mol% Nb); (b) 850N005 (0.05 mol% Nb); (c) 850N010 (0.10 mol% Nb); (d) 850N025 (0.25 mol% Nb); (e) 850N050 (0.50 mol% Nb) and (f) Equivalent circuit.
- 5.24. Impedance plots for the composition sintered at 850°C and measurement done at 250 °C: (a) 850N000 (0.00 mol% Nb); (b) 850N005 (0.05 mol% Nb); (c) 850N010 (0.10 mol% Nb); (d) 850N025 (0.25 mol% Nb); (e) 850N050 (0.50 mol% Nb) and (f) Equivalent circuit.
- 5.25. Impedance plots for the composition sintered at 900 °C and measurement done at 50 °C: (a) 900N000 (0.00 mol% Nb); (b) 900N005 (0.05 mol% Nb); (c) 900N010 (0.10 mol% Nb); (d) 900N025 (0.25 mol% Nb); (e) 900N050 (0.50 mol% Nb) and (f) Equivalent circuit
- 5.26. Impedance plots for the composition sintered at 900 °C and measurement done at 150 °C: (a) 900N000 (0.00 mol% Nb); (b)

900N005 (0.05 mol% Nb); (c) 900N010 (0.10 mol% Nb); (d) 900N025 (0.25 mol% Nb); (e) 900N050 (0.50 mol% Nb) and (f) Equivalent circuit

- 5.27. Impedance plots for the composition sintered at 900 °C and 116 measurement done at 250 °C: (a) 900N000 (0.00 mol% Nb); (b) 900N005 (0.05 mol% Nb); (c) 900N010 (0.10 mol% Nb); (d) 900N025 (0.25 mol% Nb); (e) 900N050 (0.50 mol% Nb) and (f) Equivalent circuit
- 5.28. Impedance plots for the composition sintered at 950 °C and 117 measurement done at 50 °C: (a) 950N000 (0.00 mol% Nb); (b) 950N005 (0.05 mol% Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol% Nb); (e) 950N050 (0.50 mol% Nb) and (f) Equivalent circuit.
- 5.29. Impedance plots for the composition sintered at 950 °C and 118 measurement done at 150 °C: (a) 950N000 (0.00 mol% Nb); (b) 950N005 (0.05 mol% Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol% Nb); (e) 950N050 (0.50 mol% Nb) and (f) Equivalent circuit.
- 5.30. Impedance plots for the composition sintered at 950 °C and 119 measurement done at 250 °C: (a) 950N000 (0.00 mol% Nb); (b) 950N005 (0.05 mol% Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol% Nb); (e) 950N050 (0.50 mol% Nb) and (f) Equivalent circuit.
- 5.31. Arrhenius plots for resistance R_1 and R_2 of composition sintered at 127 850 °C: (a) 850N000 (0.00 mol% Nb); (b) 850N005 (0.05 mol% Nb); (c) 850N010 (0.10 mol% Nb); (d) 850N025 (0.25 mol% Nb) and (e) 850N050 (0.50 mol% Nb).
- 5.32. Arrhenius plots for resistance R_1 and R_2 of composition sintered at 128 900 °C: (a) 950N000 (0.00 mol% Nb); (b) 950N005 (0.05 mol%

Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol% Nb) and (e) 950N050 (0.50 mol% Nb).

- 5.33. Arrhenius plots for resistance R_1 and R_2 of composition sintered at 129 900 °C: (a) 950N000 (0.00 mol% Nb); (b) 950N005 (0.05 mol% Nb); (c) 950N010 (0.10 mol% Nb); (d) 950N025 (0.25 mol% Nb) and (e) 950N050 (0.50 mol% Nb).

CHAPTER 6: Electrical and structural characterization of MnO doped ZnO - V₂O₅ - Nb₂O₅ varistor ceramics sintered at different temperatures.

- 6.1. X-ray diffraction patterns of samples sintered at 850°C with 144 following compositions: (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO) and (e) 850NM300 (3.00 mol% MnO)
- 6.2. X-ray diffraction patterns of samples sintered at 900°C with 145 following compositions: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO) and (e) 900NM300 (3.00 mol% MnO)
- 6.3. X-ray diffraction patterns of samples sintered at 950°C with 146 following compositions: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO) and (e) 950NM300 (3.00 mol% MnO)
- 6.4. SEM micrographs of the sample sintered at 850 °C with following 149 compositions: (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO); and (e) 850NM300 (3.00 mol% MnO)
- 6.5. SEM micrographs of the sample sintered at 900 °C with following 150 compositions: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150

(1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO); and (e) 900NM300 (3.00 mol% MnO)

- 6.6. SEM micrographs of the sample sintered at 950 °C with following 151 compositions: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO); and (e) 950NM300 (3.00 mol% MnO)
- 6.7. EDS spectra of 2.00mol% MnO Doped ZnO-V₂O₅-Nb₂O₅ System 154 (900NM200) sintered at 900 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Nb and Mn segregation in it and (d) at the selected region.
- 6.8. Figure 6.8: EDS elemental maps for 2.00 mol% MnO Doped ZnO- 155 V₂O₅-Nb₂O₅ System (900NM200) sintered at 900 °C: (a) SEM micrograph (b) Zn map (c) O map (d) V map (e) Nb map and (f) Mn map
- 6.9. EDS spectra of 2.50mol% MnO Doped ZnO-V₂O₅-Nb₂O₅ System 156 (900NM250) sintered at 900 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Nb and Mn segregation in it and (d) at the selected region.
- 6.10. EDS elemental maps for 2.50 mol% MnO Doped ZnO-V₂O₅-Nb₂O₅ 157 System (900NM250) sintered at 900 °C: (a) SEM micrograph (b) Zn map (c) O map (d) V map (e) Nb map and (f) Mn map.
- 6.11. EDS spectra of 2.50mol% MnO Doped ZnO-V₂O₅-Nb₂O₅ System 158 (950NM250) sintered at 950 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Nb and Mn segregation in it and (d) at the selected region.
- 6.12. EDS elemental maps for 2.50 mol% MnO Doped ZnO-V₂O₅-Nb₂O₅ 159 System (950NM250) sintered at 950 °C: (a) SEM micrograph (b) Zn map (c) O map (d) V map (e) Nb map and (f) Mn map.

- 6.13. EDS spectra of 3.00 mol MnO Doped ZnO-V₂O₅-Nb₂O₅ System 160 (950NM300) sintered at 950 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Nb and Mn segregation in it and (d) at the selected region.
- 6.14. EDS elemental maps for 3.00 mol% MnO Doped ZnO-V₂O₅-Nb₂O₅ 161 System (950NM300) sintered at 950 °C: (a) SEM micrograph (b) Zn map (c) O map (d) V map (e) Mn map and (f) Nb map.
- 6.15. shows the plot of percentage theoretical density vs. mol% MnO for 162 the samples sintered at (a) 850 °C, (b) 900 °C & (c) 950 °C
- 6.16. E-J curve showing the effects of MnO content in ZnO-V₂O₅-Nb₂O₅ 165 samples sintered at 850°C: (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO) and (e) 850NM300 (3.00 mol% MnO)
- 6.17. E-J curve showing the effects of MnO content in ZnO-V₂O₅-Nb₂O₅ 166 samples sintered at 900°C: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO) and (e) 900NM300 (3.00 mol% MnO).
- 6.18. E-J curve showing the effects of MnO content in ZnO-V₂O₅-Nb₂O₅ 168 samples sintered at 950°C: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO) and (e) 950NM300 (3.00 mol% MnO).
- 6.19. Dielectric spectroscopy (i) ϵ' and (ii) Tan δ, showing the effects of 171 MnO content in ZnO-V₂O₅-Nb₂O₅ materials: (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO) and (e) 850NM300 (3.00 mol% MnO).

- 6.20. Dielectric spectroscopy (i) ϵ' and (ii) Tan δ , showing the effects of 172 MnO content in ZnO-V₂O₅-Nb₂O₅ materials: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO) and (e) 900NM300 (3.00 mol% MnO)
- 6.21. Dielectric spectroscopy (i) ϵ' and (ii) Tan δ , showing the effects of 173 MnO content in ZnO-V₂O₅-Nb₂O₅ materials: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO) and (e) 950NM300 (3.00 mol% MnO)
- 6.22. Experimental plots, fitted plots and equivalent circuit for fitting of 176 impedance spectra of the samples as a function of MnO amount measured at 50°C : (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO); (e) 850NM300 (3.00 mol% MnO) and (f) equivalent circuit.
- 6.23. Experimental plots, fitted plots and equivalent circuit for fitting of 177 impedance spectra of the samples as a function of MnO amount measured at 150°C : (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO); (e) 850NM300 (3.00 mol% MnO) and (f) equivalent circuit.
- 6.24. Experimental plots, fitted plots and equivalent circuit for fitting of 178 impedance spectra of the samples as a function of MnO amount measured at 250°C : (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO); (e) 850NM300 (3.00 mol% MnO) and (f) equivalent circuit.
- 6.25. Experimental plots, fitted plots and equivalent circuit for fitting of 182 impedance spectra of the samples as a function of MnO amount

- measured at 50°C: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO); (e) 900NM300 (3.00 mol% MnO) & (f) equivalent circuit.
- 6.26. Experimental plots, fitted plots and equivalent circuit for fitting of 183 impedance spectra of the samples as a function of MnO amount measured at 150°C: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO); (e) 900NM300 (3.00 mol% MnO) & (f) equivalent circuit.
- 6.27. Experimental plots, fitted plots and equivalent circuit for fitting of 184 impedance spectra of the samples as a function of MnO amount measured at 250°C: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO); (e) 900NM300 (3.00 mol% MnO) & (f) equivalent circuit.
- 6.28. Experimental plots, fitted plots and equivalent circuit for fitting of 186 impedance spectra of the samples as a function of MnO amount measured at 50 °C: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO); (e) 950NM300 (3.00 mol% MnO) and (f) equivalent circuit.
- 6.29. Experimental plots, fitted plots and equivalent circuit for fitting of 187 impedance spectra of the samples as a function of MnO amount measured at 150 °C: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO); (e) 950NM300 (3.00 mol% MnO) and (f) equivalent circuit.
- 6.30. Experimental plots, fitted plots and equivalent circuit for fitting of 188 impedance spectra of the samples as a function of MnO amount

measured at 250 °C: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO); (e) 950NM300 (3.00 mol% MnO) and (f) equivalent circuit.

- 6.31. Arrhenius plots for resistance R_1 and R_2 associated with low and 192 high frequency grain boundary respectively of the samples as a function of MnO amount: (a) 850NM000 (0.00 mol% MnO); (b) 850NM150 (1.50 mol% MnO); (c) 850NM200 (2.00 mol% MnO); (d) 850NM250 (2.50 mol% MnO) and (e) 850NM300 (3.00 mol% MnO).
- 6.32. Arrhenius plots for resistance R_1 and R_2 associated with low and 193 high frequency grain boundary respectively of the samples as a function of MnO amount: (a) 900NM000 (0.00 mol% MnO); (b) 900NM150 (1.50 mol% MnO); (c) 900NM200 (2.00 mol% MnO); (d) 900NM250 (2.50 mol% MnO) and (e) 900NM300 (3.00 mol% MnO).
- 6.33. Arrhenius plots for resistance R_1 and R_2 associated with low and 194 high frequency grain boundary respectively of the samples as a function of MnO amount: (a) 950NM000 (0.00 mol% MnO); (b) 950NM150 (1.50 mol% MnO); (c) 950NM200 (2.00 mol% MnO); (d) 950NM250 (2.50 mol% MnO) and (e) 950NM300 (3.00 mol% MnO)

CHAPTER 7: Electrical and Structural Characterization of ZrO_2 doped ZnO – V_2O_5 – Cr_2O_3 Varistor Ceramics Sintered at Different Temperatures.

- 7.1. X-ray diffraction patterns of samples sintered at 850 °C with 207 following compositions: (a) 850CZ000 (0.00 mol% ZrO_2); (b) 850CZ010 (0.10 mol% ZrO_2); (c) 850CZ050 (0.50 mol% ZrO_2); (d) 850CZ100 (1.00 mol% ZrO_2) and (e) 850CZ200 (2.00 mol% ZrO_2)
- 7.2. X-ray diffraction patterns of samples sintered at 900 °C with 208 following compositions: (a) 900CZ000 (0.00 mol% ZrO_2); (b)

900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂) and (e) 900CZ200 (2.00 mol% ZrO₂)

- 7.3. X-ray diffraction patterns of samples sintered at 950 °C with 209 following compositions: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂) and (e) 950CZ200 (2.00 mol% ZrO₂)
- 7.4. SEM micrographs of the sample sintered at 850 °C with following 212 compositions: (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d) 850CZ100 (1.00 mol% ZrO₂) and (e) 850CZ200 (2.00 mol% ZrO₂)
- 7.5. SEM micrographs of the sample sintered at 900 °C with following 213 compositions: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂) and (e) 900CZ200 (2.00 mol% ZrO₂)
- 7.6. SEM micrographs of the sample sintered at 950 °C with following 214 compositions: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂) and (e) 950CZ200 (2.00 mol% ZrO₂)
- 7.7. SEM micrographs of the fractured samples sintered at 900 °C with 215 following compositions: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂) and (e) 900CZ200 (2.00 mol% ZrO₂)
- 7.8. EDS spectra of 0.10 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ System 218 (900CZ010) sintered at 900 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V and Cr segregation in it and (d) at the selected region.
- 7.9. EDS elemental maps for 0.10 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ 219 System (900CZ010) sintered at 900 °C: (a) SEM micrograph (b) Zn map (c) O map (d) V map (e) Cr map and (f) Zr map

- 7.10. EDS spectra of 1.00 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ System 220
(900CZ100) sintered at 900 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Cr and Zr segregation in it and (d) at the selected region.
- 7.11. EDS elemental maps for 1.00 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ 221 System (900CZ100) sintered at 900 °C: (a) SEM micrograph (b) Zn map (c) O map (d) V map (e) Cr map and (f) Zr map.
- 7.12. EDS spectra of 2.00 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ System 222 (850CZ200) sintered at 850 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Cr and Zr segregation in it and (d) at the sum spectrum.
- 7.13. EDS spectra of 2.00 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ System 223 (900CZ200) sintered at 900 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Cr and Zr segregation in it and (d) at the sum spectrum.
- 7.14. : EDS spectra of 2.00 mol% ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ System 224 (950CZ200) sintered at 950 °C: (a) SEM micrograph (b) at the ZnO grain (c) at the ZnO grain boundary showing V, Cr and Zr segregation in it and (d) at the sum spectrum.
- 7.15. shows the plot of percentage theoretical density vs. mol% ZrO₂ for 225 the samples sintered at (a) 850 °C, (b) 900 °C & (c) 950 °C
- 7.16. E-J curve showing the effects of ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ 227 samples sintered at 850°C: (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d) 850CZ100 (1.00 mol% ZrO₂) and (e) 850CZ200 (2.00 mol% ZrO₂)
- 7.17. E-J curve showing the effects of ZrO₂ doped ZnO–V₂O₅–Cr₂O₃ 229 samples sintered at 900 °C: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂) and (e) 900CZ200 (2.00 mol% ZrO₂)

- 7.18. E-J curve showing the effects of ZrO₂ doped ZnO-V₂O₅-Cr₂O₃ 231 samples sintered at 950°C: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂) and (e) 950CZ200 (2.00 mol% ZrO₂)
- 7.19. Dielectric spectroscopy (i) ϵ' & (ii) Tan δ , showing the effects of ZrO₂ 234 doped ZnO-V₂O₅-Cr₂O₃ samples sintered at 850 °C: (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d) 850CZ100 (1.00 mol% ZrO₂) and (e) 850CZ200 (2.00 mol% ZrO₂)
- 7.20. Dielectric spectroscopy (i) ϵ' & (ii) Tan δ , showing the effects of 235 ZrO₂ doped ZnO-V₂O₅-Cr₂O₃ samples sintered at 850 °C: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂) and (e) 900CZ200 (2.00 mol% ZrO₂)
- 7.21. Dielectric spectroscopy (i) ϵ' & (ii) Tan δ , showing the effects of 236 ZrO₂ doped ZnO-V₂O₅-Cr₂O₃ samples sintered at 950 °C: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂) and (e) 950CZ200 (2.00 mol% ZrO₂)
- 7.22. Experimental plots, fitted plots and equivalent circuit for fitting of 239 impedance spectra of the samples as a function of ZrO₂ amount measured at 50 °C : (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d) 850CZ100 (1.00 mol% ZrO₂), (e) 850CZ200 (2.00 mol% ZrO₂) and (f) equivalent circuit.
- 7.23. Experimental plots, fitted plots and equivalent circuit for fitting of 240 impedance spectra of the samples as a function of ZrO₂ amount measured at 150 °C : (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d)

850CZ100 (1.00 mol% ZrO₂), (e) 850CZ200 (2.00 mol% ZrO₂) and (f) equivalent circuit.

- 7.24. Experimental plots, fitted plots and equivalent circuit for fitting of 241 impedance spectra of the samples as a function of ZrO₂ amount measured at 250 °C : (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d) 850CZ100 (1.00 mol% ZrO₂), (e) 850CZ200 (2.00 mol% ZrO₂) and (f) equivalent circuit.
- 7.25. Experimental plots, fitted plots and equivalent circuit for fitting of 244 impedance spectra of the samples as a function of ZrO₂ amount measured at 50 °C: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂), (e) 900CZ200 (2.00 mol% ZrO₂) & (f) equivalent circuit.
- 7.26. Experimental plots, fitted plots and equivalent circuit for fitting of 245 impedance spectra of the samples as a function of ZrO₂ amount measured at 150 °C: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂), (e) 900CZ200 (2.00 mol% ZrO₂) & (f) equivalent circuit.
- 7.27. Experimental plots, fitted plots and equivalent circuit for fitting of 246 impedance spectra of the samples as a function of ZrO₂ amount measured at 250°C: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂), (e) 900CZ200 (2.00 mol% ZrO₂) & (f) equivalent circuit.
- 7.28. Experimental plots, fitted plots and equivalent circuit for fitting of 248 impedance spectra of the samples as a function of ZrO₂ amount measured at 50 °C: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100

(1.00 mol% ZrO₂), (e) 950CZ200 (2.00 mol% ZrO₂) and (f) equivalent circuit.

- 7.29. Experimental plots, fitted plots and equivalent circuit for fitting of 249 impedance spectra of the samples as a function of ZrO₂ amount measured at 150 °C: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂), (e) 950CZ200 (2.00 mol% ZrO₂) and (f) equivalent circuit.
- 7.30. Experimental plots, fitted plots and equivalent circuit for fitting of 250 impedance spectra of the samples as a function of ZrO₂ amount measured at 250 °C: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂), (e) 950CZ200 (2.00 mol% ZrO₂) and (f) equivalent circuit.
- 7.31. Arrhenius plots for resistance R₁ and R₂ associated with low and 255 high frequency grain boundary respectively of the samples as a function of ZrO₂ amount: : (a) 850CZ000 (0.00 mol% ZrO₂); (b) 850CZ010 (0.10 mol% ZrO₂); (c) 850CZ050 (0.50 mol% ZrO₂); (d) 850CZ100 (1.00 mol% ZrO₂) and (e) 850CZ200 (2.00 mol% ZrO₂).
- 7.32. Arrhenius plots for resistance R₁ and R₂ associated with low and 256 high frequency grain boundary respectively of the samples as a function of ZrO₂ amount: (a) 900CZ000 (0.00 mol% ZrO₂); (b) 900CZ010 (0.10 mol% ZrO₂); (c) 900CZ050 (0.50 mol% ZrO₂); (d) 900CZ100 (1.00 mol% ZrO₂) and (e) 900CZ200 (2.00 mol% ZrO₂).
- 7.33. Arrhenius plots for resistance R₁ and R₂ associated with low and 257 high frequency grain boundary respectively of the samples as a function of ZrO₂ amount: (a) 950CZ000 (0.00 mol% ZrO₂); (b) 950CZ010 (0.10 mol% ZrO₂); (c) 950CZ050 (0.50 mol% ZrO₂); (d) 950CZ100 (1.00 mol% ZrO₂) and (e) 950CZ200 (2.00 mol% ZrO₂).