

---

## List of Figures

---

Figure No.	Title	Page#
Fig. 1.1	Odorant receptors and organization of the olfactory system	4
Fig. 1.2	A comparison of the biological and artificial olfactory systems	7
Fig. 1.3	Photo image of compact hand-held device developed by NASA for space application	7
Fig. 1.4	Basic configuration of Taguchi (Figaro products) gas sensor	15
Fig 1.5	Classification scheme of the multivariate pattern analysis techniques applied to e-nose data	20
Fig. 2.1	Crystalline structure of SnO <sub>2</sub> unit cell	38
Fig. 2.2	Band diagram for SnO <sub>2</sub> (left) and the projection of the density of states (right)	40
Fig. 2.3	Schematic band diagram of SnO <sub>2</sub> , donor level $E_{D1} = 0.03$ eV, $E_{D2} = 0.15$ eV	40
Fig. 2.4	Potential energy and atomic distance at the adsorption of a dissociative chemisorption oxygen on tin oxide	43
Fig. 2.5	Adsorption process of oxygen on a SnO <sub>2</sub> surface. Two Sn-O bondings are developed from one chemical bonding in the oxygen molecule on the surface	43
Fig. 2.6	Surface charge layers on the surface of n-type semiconductor with a wide band gap (a) Distribution of charges (b) Band scheme near conduction band edge (c) Concentration $n(z)$ of electrons in the conduction band	46
Fig. 2.7	Energy diagram of various oxygen species in the gas phase adsorbed at the surface and bound within the lattice of a binary metal oxide.	48
Fig. 2.8	Model of inter-grain potential barrier in the absence of gases (left) and in the presence of gases (right)	49
Fig. 2.9	Schematics indicating the mechanisms leading to SnO <sub>2</sub> sensor response to oxidizing and reducing gases	50
Fig. 2.10	Effect of doping on SnO <sub>2</sub> as Chemical (Left) and Electronic (Right) Sensitization	51
Fig. 2.11	Flow chart for thick film sensor array fabrication	54
Fig. 2.12	Patterns for fabricating sensor array (a) Heater (b) Interdigitated electrode (c) Sensor patterning mask	56

Fig. 2.13	Schematic diagram of mesh of screen	56
Fig. 2.14	(a) Manual screen preparation tool (b) Prepared screens	58
Fig. 2.15	Schematic diagram of snap off process	60
Fig. 2.16	Essential part of a screen printer	61
Fig. 2.17	Photograph of screen printing machine	62
Fig. 2.18	Variation of viscosity of a typical thick-film at different stages during the printing cycle	62
Fig. 2.19	Conventional box oven used for drying process	63
Fig. 2.20	Schematic of cross section of thick film furnace	64
Fig. 2.21	Photograph of thick film furnace	65
Fig. 2.22	Photo image of fabricated sensor array (a) Heater, (b) Interdigitated electrodes (c) Fabricated sensors array	66
Fig. 2.23	The response and recovery analysis for a thick film sensor	68
Fig. 2.24	(a) Locally developed test chamber used for sensor array characterization (b) Sensor array connections	70
Fig. 2.25 (a)	Response graphs of sensor array upon exposure of LPG	71
Fig. 2.25 (b)	Response graphs of sensor array upon exposure of N <sub>2</sub> O	71
Fig. 2.25 (c)	Response graphs of sensor array upon exposure of Acetone	72
Fig. 2.25 (d)	Response graphs of sensor array upon exposure of 2-Propanol	72
Fig. 2.26	Response bars for sensor array upon exposure of LPG, N <sub>2</sub> O, Acetone and 2-Propanol at 600 ppm	73
Fig. 2.27 (a)	Sensitivity variation with time for LPG	74
Fig. 2.27 (b)	Sensitivity variation with time for N <sub>2</sub> O	74
Fig. 2.27 (c)	Sensitivity variation with time for Acetone	75
Fig. 2.27 (d)	Sensitivity variation with time for 2-propanol	75
Fig. 2.28 (a)	Response and recovery plots for single cycle for LPG	76
Fig. 2.28 (b)	Response and recovery plots for single cycle for N <sub>2</sub> O	76
Fig. 2.28 (c)	Response and recovery plots for single cycle for Acetone	77
Fig. 2.28 (d)	Response and recovery plots for single cycle for 2-propanol	77
Fig. 2.29	Variation in response and recovery time of sensor with change in concentration of test gas	79
Fig. 2.30	Validation of the experimental results with tin oxide thick film sensor model	80
Fig. 3.1	Schematic of Sensor Array-1 fabricated by Mishra and Agarwal (1998)	84

Fig. 3.2	Steady state responses of Sensor Array-1 upon exposure to (a) LPG, (b) H <sub>2</sub> (c) CH <sub>4</sub> (d) CO	85
Fig. 3.3	Schematic of the sensor array (Sensor Array-2) fabricated by the author	86
Fig. 3.4	Steady state responses of Sensor Array-2 upon exposure to LPG, N <sub>2</sub> O, Acetone and 2-Propanol	87
Fig. 3.5	3-D Scatter plot of the raw data obtained from response of the Sensor Array-1	89
Fig. 3.6	Scatter plot of the raw data obtained from response of the Sensor Array-2	89
Fig. 3.7	The extracted data using the LDA and PCA model with the Gaussians fitted by the Maximum-Likelihood for the first dimension for Dataset-1	95
Fig. 3.8	The extracted data using the LDA and PCA model with the Gaussians fitted by the Maximum-Likelihood for the first two dimensions of Dataset-1	96
Fig. 3.9	The extracted data using the LDA and PCA model with the Gaussians fitted by the Maximum-Likelihood for the first two dimensions of Dataset-2	97
Fig. 3.10	Typical Multilayer Feed Forward Neural Network	98
Fig. 3.11	Neuron 'j' being fed by a set of signals from a previous layer of neurons	100
Fig. 3.12	Classification accuracy vs. number of neurons in the single hidden layers for BPNN trained with raw data (Dataset-1)	107
Fig. 3.13(a)	Classification accuracy vs. number of hidden layers for BPNN trained with PCA transformed data (Dataset-1)	108
Fig. 3.13(b)	Classification accuracy vs. number of neurons in the single hidden layer for BPNN trained with PCA preprocessed data (Dataset-1)	108
Fig. 3.14(a)	Classification accuracy vs. number of hidden layers for BPNN trained with LDA transformed data (Dataset-1)	109
Fig. 3.14(b)	Classification accuracy vs. number of neurons in the single hidden layer for BPNN trained with LDA transformed data (Dataset-1)	109
Fig. 4.1	The method followed for the gases/odors classification using ASM	116
Fig. 4.2	The thick film gas sensor array device used for generating dynamic responses	117

Fig. 4.3	Response–recovery plot of the sensor array for different concentrations of (a) LPG and (b) CCl <sub>4</sub>	118
Fig. 4.3	Response–recovery plot of the sensor array for different concentrations of (c) CO and (d) C <sub>3</sub> H <sub>7</sub> OH	119
Fig. 4.4	2-D scatter plot of raw data extracted from dynamic responses for 25 ppm concentration band	121
Fig. 4.5	3-D scatter plot of raw data extracted from dynamic responses for 25 ppm concentration band	122
Fig. 4.6	Average slope calculation method used for dynamic responses	122
Fig. 4.7	Average slope values of response of each sensor for different gases/odors plotted on 2-D scatter graph for 25-ppm conc. band	123
Fig. 4.8	2-D scatter plot of ASM transformed data for 25-ppm conc. band	123
Fig. 4.9	3-D scatter plot of ASM transformed data for 25-ppm conc. Band	124
Fig. 4.10	Typical multilayer feed forward neural network used as classifier	125
Fig. 4.11	Variation in classification accuracy of raw data with (a) Momentum (b) Learning rate (c) Number of neurons in the hidden layer	127
Fig. 4.12	Variation in classification accuracy with ASM data with (a) Momentum (b) Learning Rate (c) Number of neurons in the hidden layer	127
Fig. 4.13	Variation in classification accuracy with PCA preprocessed ASM data with (a) Momentum (b) Learning Rate (c) Number of Neurons in the hidden layer	127
Fig. 4.14	Neural network architecture-1 (NNA-1) adopted for quantification	129
Fig. 4.15	Neural network architecture-2 (NNA-2) adopted for quantification	129
Fig. 4.16	The method followed for the gases/odors classification cum quantification for response and recovery data individually	132
Fig. 5.1	Schematic of methods used for gases/odors mixture analysis.	138
Fig. 5.2	Schematic of fabricated sensor array with common electrode (a) Sensor electrodes (a) Heater pattern (b) Sensor printing mask	140
Fig. 5.3	Combinations of selected Acetone and 2-propanol concentrations in their mixture used in the gas sensing	140
Fig. 5.4	Response of sensor array for (a) acetone and (b) 2-propanol	141

Fig. 5.5	(a)-(b) Response of sensor array for acetone and 2-propanol mixture in different proportions	142
Fig. 5.5	(c)-(d) Response of sensor array for Acetone and 2-propanol mixture in different proportions ( <i>Continued on next page...</i> )	143
Fig. 5.5	(e)-(f) Response of sensor array for Acetone and 2-propanol mixture in different proportions	144
Fig. 5.6	2-D scatter plot of raw data considering two of the four sensors data at a time.	146
Fig. 5.7	The 2-D scatter plot of first two principal components obtained after applying the PCA to the raw dataset.	147
Fig. 5.8	BPNN architecture for classification of individual and binary mixture of VOCs	149
Fig. 5.9	Predicted against true concentration of (a) acetone alone, (b) 2-propanol alone (c) acetone in mixture, (d) 2-propanol in mixture	157