CHAPTER 5

Summary and Conclusion
5.1 Summary:

Life without any senses seems impossible. On the other hand; sensors of all kinds try to mimic the certain senses of living organisms, have developed in order to interact with the environment. Sensors are the most vital elements for building intelligent systems. Advanced sensor technology has been identified world over as one of the important technologies for the future. With the advent of information technology and easy availability of large processing power, advanced sensors will be utilised in several walks of human life. An analysis of the world market on production of sensors shows the following trend in sensing areas: temperature 33%; displacement and proximity 23%; flow and level 13%; pressure and force 8%; magnetic field 5%; optical 5%, chemical 3%, humidity 2%, and others 8%. [205-206] Thus, the authors claim that temperature sensors of ambient conditions are in heavy demand. The authors have also emphasised wider use of thermistor sensors because of their advantages like small size, high accuracy and resolution, highest sensitivity, low cost, least power dissipation etc. However, presently available thermistor products are still far from fully meeting the market needs. The present market requires thermistors to achieve further reductions in cost, high precision, better interchangeability, and realise a wider measurable temperature range by going lower in the materials constant among various other requirements. Most of the above mentioned
aspects for the improvement of thermistors are investigated in the present thesis.

The main aim of the thesis is development of high performance NTC thermistors. This requires an interdisciplinary approach of ceramics technology, solid state chemistry, electronics, hardware and software techniques. The global growth economics presented in chapter 1 justifies the importance of investigation on this topic. The same is further strengthened by presenting the good number of applications. Various thermistor configurations are also compared with a conclusion that the device specifications are more dependent on the fabrication technology rather than the style or geometry. The chapter justifies the main objectives of research work and systematic plan to improve various characteristics and specifications.

The follow-up of the importance of materials synthesis technique is persuaded in the chapter 2. At the outset, the choice of the material (i.e. nickel manganite) is justified and supported with research based on investigations of other researchers. Various synthesis techniques with their pros and cons are presented. Fabrication of nickel manganite based disc type NTC thermistors are reported in the first part of this chapter. One of the technique used in part I (i.e. oxalic precursor route) is extended to tailor the room temperature resistance of the thermistors varying the stoichiometry. The details are given in part II. The part III of this chapter,
presents the device fabrication aspects and an improved method of lead attachment.

Instrumentation systems for test and characterisation for the thermistors fabricated are presented in depth in chapter 3. The details of automated characterisation set-up to record the characteristics like resistance Vs temperature, current Vs voltage is presented. The time constant and dissipation constant are also calculated by using various other set-ups described here. The details of effects of moisture on samples is also reported and is followed by the listings of the software used for various characterisation.

The development of silicon micromachined sensors enables physical transducers to be integrated with control and signal processing electronics in a single, compact package. This type of "smart" sensors have revolutionised the design of sensor systems, making them more reliable, better packaging, which provide higher performance than traditional systems. These benefits are gained by embedding computing resources on the sensor itself. Chapter 4 presents three architectures of smart sensor design, namely, modified Schmitt trigger transducer, non-linear ADC and a low power ASIC.

5.2 Results and Conclusions:

From the present studies following results and conclusions drawn:

1. Despite the many drawbacks associated with NTC thermistors, their development is expected to continue on a larger pace, and the market
appears to be promising. Several emerging research trends contribute to such a perspective: (i) better understanding of sensing mechanisms due to increased efforts in basic studies in recent years; (ii) new and improved materials synthesis and device fabrication techniques; (iii) application of hardware and software techniques to minimise the drawbacks; (iv) developing sensor with embedded signal processing modules for more specific or focused applications.

2. The carboxylate precursors of nickel manganite were prepared by using fumarate, succinate, oxalate, tartarate and malonate. The XRD studies reveal a good agreement of observed d-values with the standard ones reported in JCPDS file [189]. This confirms the formation of NiMn$_2$O$_4$. The lattice parameter values calculated are in the range of 8.37 to 8.39. This is in good agreement with the reported values of 8.37 to 8.41 for NiMn$_2$O$_4$. The calculation of bond lengths ($R_A$ and $R_B$) and site radii ($r_A$ and $r_B$) shows no remarkable change in their values for the fabricated samples. The percentage of Nickel and Manganese was found out by using AAS and agrees with the stoichiometric ratio in NiMn$_2$O$_4$. The TG/DTA studies show that the total decomposition of different carboxylate precursor takes place between 325°C to 400°C. Dehydration of the carboxylate precursors takes place below 250°C.

3. Nickel manganite based disc type pellets prepared by using carboxylate precursor route, exhibited their NTC thermistor behaviour in domestic temperature range. All these thermistor samples have moderate value
of materials constant (β). The tolerance of β is in the range of ± 0.003% to ±0.009%. The resistance ratio is in the range of 5.09 to 6.31. These specifications are comparable and even better than those reported in the literature for disc thermistors. Moderate β values with minimum tolerance indicates a good measurement precision. Improved resolution is indicated by the high values of resistance ratio. This satisfies the our main objectives: optimisation for domestic applications; improving figure of merit; better resolution.

4. The precursors of nickel manganite with stoichiometry Ni$_{1-x}$Mn$_{2+x}$O$_4$ with 0 ≤ x ≤ 0.6 were prepared by using oxalic precursor route. XRD studies of the decomposed oxalic precursor at different temperature reveals the total decomposition and formation of single phase nickel manganite at 600°C. The TG/DTA analysis shows the dehydration of the precursors below 200°C and a total decomposition at 325°C. The lattice parameter values are in the range of 8.37 to 8.39, which is in good agreement with the standard reported ones. The percentage of Nickel and Manganese in the oxalic precursors was found out by using AAS and agrees with the stoichiometric ratio in NiMn$_2$O$_4$. The disk type pellets fabricated exhibited a non-linear R Vs T characterisation in the range 27°C to 170°C. Wide variation in the room temperature resistance in the range of 55.4K to 6.1K was observed with change in stoichiometry. The β values of all these thermistors are in the range of 940 K to 1834 K. The resistance ratio is in the range of 2.20 to 4.68. Thus the power
consumption may be tailored by choosing the proper composition in this series having appropriate dormant resistance, which also constitutes one of the objectives.

5. The leads are attached to the thermistors with conventional method and a new method. With the same stoichiometry and dimensions, the thermistors fabricated with the conventional method exhibited poor interchangeability of the order of \( \pm 1.5^\circ C \). The reasons attributed to poor interchangeability and ageing are poor control on the geometry, varying electrode shape and lead wire attachments from sample to sample. The new method with the modified jig, exhibited better interchangeability of the order of \( \pm 0.2^\circ C \) and less ageing characteristics. All the thermistor samples prepared by carboxylate and oxalic precursor routes were found to follow the Steinhart-hart equation.

6. Zero power resistance variation with temperature, time constant and dissipation constant influence the measured temperature. An automated set-up for resistance VS temperature characterisation of thermistors is designed. The set-up comprises of a furnace, thermocouple amplifier, AD574 based analogue to digital converter and HP34401A DMM. The furnace for materials synthesis (temperature upto 1200\(^\circ C\)) and characterisation (temperature upto 300\(^\circ C\)) are designed. A thermocouple based temperature controller controls the temperature of materials synthesis furnace within \( \pm 0.8^\circ C \). A d.c. high wattage power supply with ratings of 24 V at 3 A, 15 V at 6 A and 6V at 6A powers the
characterisation furnace. A RTD based temperature controller controls the temperature of this furnace.

7. The automated set-up designed to evaluate dissipation constant and time constant gave a dissipation constant in the range of 1.5 mW/°C to 4 mW/°C and time constant in the range of 0.5 to 1 Second. With dissipation constant known, the value of current excitation can be decided. e.g. With measurement range 25°C to 50°C, with a desired resolution ΔT of 0.1°C and thermistor room temperature of 1K and dissipation constant 4 mW/°C, the maximum power must be restricted below \( P_{\text{max}} = \Delta T \cdot D \) i.e. 0.4 mW to avoid self heating.

8. The conventional flip-flop sensor design was applied to thermistor and a modified Schmitt trigger sensor is proposed. The circuit was successfully simulated.

9. The architecture of PWM ADC was modified for thermistor applications and the same was simulated.

10. The architecture of low power thermistor based ASIC for clinical applications is proposed and simulated.

11. The above results indicate that all the objectives undertaken for the development of a high performance NTC thermistor are fulfilled.