CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1 THEME OF THE WORK

This work is concerned with the preparation and characterization of Ni-Mn-Ga and Ni-Fe-Ga thin films on a rigid substrate. The present work focuses on the effect of post annealing, substrate temperature and film thickness of phase formation, microstructure, thermo-magnetic phenomena and mechanical properties in Ni-Mn-Ga and Ni-Fe Ga thin films. These FSMA films have been investigated both from fundamental and applied points of view. The main objectives are: (i) to investigate the phase structure, microstructure, magnetic and mechanical behavior of the Ni-Mn-Ga and Ni-Fe-Ga thin films with respect to different post deposition annealing (TA ≤ 873 K), film thickness (TH 100 nm to 1 μm) and substrate temperatures (TS ≤ 873 K). (ii) To understand the magneto-structural transitions, microstructure, magnetic properties and their correlations with grains growth. The purpose of this work is to understand some of the fundamental aspects of the aforementioned FSMAs thin films and to establish process – property – performance correlations necessary for MEMS applications.

5.2 CONCLUSION

The main scientific contributions of the thesis are summarized in the following list:

- Ni-Mn-Ga and Ni-Fe-Ga thin films are synthesized with (i) Different post annealing (TA ≤ 873 K) (ii) Different substrate temperature (TS ≤ 873 K) and (iii) Different film thickness (TH 100nm to 1μm) by using UHV DC magnetron sputtering system on Si substrate
The evolution of phase and crystal structure are characterized using XRD and TEM
- Microstructural investigation and their correlation with the phase structure are also studied
- Phase analysis and evaluation of microstructure and magnetic properties of films with different thickness are also studied
- The post deposition annealing was found to influence the crystalline phase, microstructure and magnetic properties of the as-deposited Ni-Mn-Ga films on Si (100) substrate
- A mixture of both austenite and martensite phases were observed in the 873 K annealed film which can be attributed to the bimodal size distribution of grains
- By adjusting the annealing temperature (873 K), magnetically ordered Ni-Mn-Ga films exhibiting a Curie temperature above room temperature were obtained
- The elastic modulus and hardness of the film changes with the heat treatment conditions. After the heat treatment the hardness increases from 0.863 GPa to 6.42 Gpa.
- Irrespective of film thickness the as-deposited films exhibited quasi-amorphous structure having paramagnetic nature at room temperature.
- At low film thickness (< 300 nm), the annealed films exhibited a phase mixture of cubic austenite (L2$_1$) and martensite while at a thickness greater than 1000 nm an L1$_2$ ordered phase structure was observed.
- The HRTEM image taken from one of the grain in the dark field image clearly indicates the presence of twin structure corresponding to the martensite phase. The presence of both austenite and martensite phases at room temperature in the annealed films suggest that the
martensitic transformation is incomplete which can be attributed to the nanocrystalline grain size of the austenite phase

- Thermo-Magnetic studies of Ni-Mn-Ga thin films by (SQUID) techniques confirms the magnetic transitions are varied with the substrate temperature and thickness of the films

- The presence of L1₂ ordered phase adversely affects the magnetic properties of the film. The Curie temperature of the L1₂ ordered NMG4 film cannot be determined in the present study, nonetheless M-H curves at 4 K and room temperature indicates that ferromagnetic ordering is very feeble in this structure

- Understanding the correlation between the phase structure, magnetization and Curie temperature (T_C) of the film prepared at different substrate temperature

- An analysis of XRD patterns reveals that variation in substrate temperature leads to change in the phase structure. A small changes in the composition of Mn and Ga results in the structural transition from cubic to tetragonal and orthorhombic

- The change in grain morphology from strongly faceted pyramidal structure to non faceted spherical structure confirms the change in phase structure from cubic to orthorhombic

- The HRTEM image clearly indicates the presence of twin structure corresponding to the martensite phase appears at room temperature

- Deposition of films at higher temperature (823K) results in formation of silicides or oxides leading to a degradation of the magnetic properties

- The mechanical properties (elastic modulus and hardness) of the film are calculated by using Nanoindentation techniques and it shows that prepared films are having good mechanical strength
- The hardness and elastic modulus of Ni-Mn-Ga films prepared at different substrate temperature are reduced by the enlargement of grains, consistent with the “Hall-Petch” effect.
- The observations of martensitic microstructure, high Curie temperature and ferromagnetic magnetization feature demonstrate Ni-Mn-Ga/Si(100) thin films as a promising candidate of ferromagnetic shape memory applications.
- Annealing treatment can strongly affect the phase structure of the Ni-Fe-Ga thin films. The low temperature annealing induces the L2₁ cubic austenite phase, subsequent annealing at higher temperature (773 K) provokes the martensite structure.
- Sputtering technique is capable of preventing the formation of secondary ‘γ’ phase, which shifts phase transformation to higher temperature and imposes the positive effect on magnetic properties of the Ni-Fe-Ga thin film.
- The Ni-Fe-Ga thin films annealed at 773 K exhibited the low coercivity and high saturation magnetization of 18 Oe and 434 emu/cc, respectively. The degradation of the magnetic moment in high temperature annealed film (873 K), is attributed to the existence of nonmagnetic γ phase.
- Compared to Ni-Mn-Ga thin film, the higher values of hardness and elastic modulus are obtained for Ni-Fe-Ga thin film. Hence, Ni-Fe-Ga thin films have been reported as good alternatives to Ni-Mn-Ga thin film for their better mechanical behavior.
- The observed results highlights that the Ni-Mn-Ga and Ni-Fe-Ga films post annealed at optimized temperature exhibits higher resistance to deformation and larger stiffness which find considerable importance for using them in device kind of applications. The observations of martensitic microstructure at room temperature, lower coercivity and high Curie temperature feature demonstrate both the FSMA thin films make them a promising candidate for high temperature ferromagnetic shape memory applications.