CHAPTER – IV
4. Summary and conclusions

The consumption of fossil fuel has been increasing day-by-day and it is speeding up the rate of global warming. Thus the necessity for renewable energy sources became an important subject in order to slow down the rate of global warming. Several recently published reports showed that the solar energy in particular, photovoltaic systems play a major role in the transition from electricity production by fossil fuels to energy conversion by renewable energy sources. But the cost of the photovoltaic system is the main hurdle in achieving the mentioned goals. EU and German government reports show that the cost of photovoltaic system by 2030 will become significant. In 2050, it will amount to 20% and by the year 2100 solar energy will be the major energy source. The actual solar module, which converts sunlight into electricity, casts about 50% of the cost of a photovoltaic system. To reduce this cost thin film solar cells are of the alternative choice. Thin films can deposited with a cheaper, pure and on flexible substrates.

4.1. Conclusions:

In order to improve the performance of current optoelectronic device technology, this thesis explored the effects of growth conditions on the physical properties (electrical resistivity and optical/visible transmittance etc.) of the CdZnO thin films. A recipe for “minimizing the resistivity and maximizing the transparency using reactive dc magnetron sputtering technique” is given for the growth on glass substrates and nanostructures. Reactive dc magnetron sputtering technique has been chosen to grow CdZnO films for maintaining the pure environment, a perfect control over growth parameters (substrate temperature, post sputter annealing temperature, oxygen flow rate, sputter power etc.). The grown films are ex-situ characterized by several techniques, such as, XRD, FESEM,
EDX, AFM, UV-vis-NIR spectroscopy etc. The electrical properties of the films were characterized by Hall measurements system in Van der Pauw configuration. The major conclusions have been presented at the end of each sub-chapter of chapter-III. Here we have made a summary of highlights obtained during the research work.

CdZnO thin films were prepared using dc magnetron sputtering technique at various substrate temperatures from room temperature to 300 °C and the dependence of structural, micro-structural, optical and electrical properties of CdZnO thin films on substrate temperature has been systematically studied. The GAXRD studies confirm the single phase hexagonal wurtzite structure with (002) orientation along c-axis i.e. normal to the substrate surface. Structural and morphological investigations indicated that the films deposited at 200 °C had higher crystallite size of 42.47 nm, minimum stress of -0.0438 GPa and minimum dislocation density of 5.54×10^{14} cm^{-2}. The AFM results revealed that the texture of the films has uniformity with clear grains and minimum roughness of 10 nm at 200 °C of substrate temperature. The optical and electrical studies reveal that the films deposited at substrate temperature of 200 °C showed good transmittance of 86 % and lower electrical resistivity of 1.44 × 10^{-2} Ω cm.

CdZnO films were deposited on glass substrates by dc magnetron sputtering technique at different post sputter annealing temperatures (350, 400, 450, 500 and 550 °C) and the effect of post sputter annealing temperature on structural, micro-structural, optical and electrical properties of CdZnO thin films was studied in detail. The GAXRD study revealed that all the CdZnO films had c-axis orientation and hexagonal wurtzite structure without any impure phase. The minimum FWHM, maximum crystallite size, minimum stress and minimum dislocation density were observed at 500 °C of post
annealing temperature as \(0.171^\circ\), 54.0 nm, -1.2985 GPa and 3.430E+14 cm\(^2\), respectively. The morphological studies revealed that the crystallite size and grain size increased with post annealing temperature and it is confirmed with GAXRD studies in terms of FWHM and c-axis constant. The optical and electrical studies confirmed the CdZnO films post sputter annealed at 500 °C have very good transparency (~90 %), low electrical resistivity (0.3 × 10\(^1\) Ω cm) and high carrier mobility (0.501 cm\(^2\)/V s).

Ternary CdZnO thin films with highly preferred (002) orientations were deposited on glass substrates by dc magnetron sputtering technique with different oxygen flow rates (1.0 to 2.5 sccm) and the effect of distinct oxygen flow rate on structural, micro-structural, optical and electrical properties of CdZnO thin films was investigated in detail. When the oxygen flow rate changed from 1.0 to 2.0 sccm, the FWHM of the films deposited on glass substrate decreased (from 0.34°) and reached a minimum value of 0.26° at the flow rate of 2.0 sccm. At oxygen flow rate of 2.0 sccm, at which the strongest reflection from c-plane is observed, the crystallite size has reached its maximum (34 nm) due to the smallest FWHM. The above results indicate that there is an optimum oxygen flow rate where the film showed relative stronger texture and better nano-crystallinity. Surface morphology showed that the films were uniformly deposited and have minimum roughness. The optical measurements revealed that, the band gap decreased gradually (from 3.12 eV) and reached a minimum value of 2.94 eV at the oxygen flow rate of 2.0 sccm. The electrical measurements showed semiconducting nature of the CdZnO films. The minimum resistivity, maximum carrier concentration and higher electron mobility were observed at oxygen flow rate of 2.0 sccm.
By maintaining the optimized oxygen flow rate and substrate temperature, the CdZnO films were deposited on glass substrates by dc magnetron sputtering technique at different Cd sputter powers (0, 87, 90 and 93 W) and studied its influence on structural, micro-structural, optical and electrical properties of ternary CdZnO thin films. The GAXRD study confirmed the single peak hexagonal wurtzite structure with complete (002) orientation along c-axis. The structural and morphological investigations indicated that the films deposited at 90 W Cd sputter power had largest crystallite size, grain size, minimum stress and roughness. The electrical resistivity sharply decreased with increase in Cd sputter power and the minimum resistivity of $8 \times 10^{-1}$ Ω cm was observed at 90 W of Cd sputter power. At Cd sputter power of 90 W, properties of low electrical resistivity of $8 \times 10^{-1}$ Ω cm, high mobility of 0.48 cm$^2$/V-s, high carrier concentration of $9.8 \times 10^{19}$ cm$^{-3}$ and high transmittance of 78 % with an optical band gap of 3.08 eV were achieved.

The irradiation of CdZnO samples with 100 MeV O$^{7+}$ ions has significant changes in their structural, optical and electrical properties. The GAXRD data obtained for these samples has been analyzed successfully to extract the different structural parameters like crystallite size, stress and dislocation density. These structural parameters have been found to vary significantly with the variation of the irradiation fluences. The AFM studies confirmed that, the surface RMS roughness decreased after irradiation from 19 to 11.24 nm. The decrease in surface roughness is attributed to discontinuous tracks that may lead to amorphization. Variation in optical transmittance and band gap energy was also observed as a result of the ion irradiation and this could be associated to the change in the crystallite size and the formation of trap levels. The estimated optical constants ($n, k$) showed strong dependence on the irradiation of O$^{7+}$ ion fluence. The electrical resistivity
of pristine CdZnO films increased with ion irradiation from $2.45 \times 10^{-2}$ to 1.87 Ω cm. Hall mobility of pristine film decreased from 176 to 0.04 cm$^2$/V s with ion fluence due to increase in carrier concentration and grain boundary scattering with decreased mean free path.

The effect of SHI on the properties of CdZnO thin films was studied using 100 MeV Au$^{7+}$ ions. The irradiation (from $1 \times 10^{11}$ to $5 \times 10^{12}$ ions/cm$^2$) of the films caused considerable grain growth (from 21.81 to 34.22 nm) and subsequent a decrease of the dislocation density (from $2.194 \times 10^{15}$ to $8.939 \times 10^{14}$ cm$^{-2}$) and strain (from 0.96 to 0.54 GPa). The results from the GAXRD and AFM revealed that at lower fluence, the film quality improved and roughness decreased due to strain relaxation among the grains. The maximum transmittance (~85 %) and minimum electrical resistivity of $1.3 \times 10^{-3}$ Ω cm have been achieved by the 100 MeV Au$^{7+}$ ion irradiation. The CdZnO films irradiation at fluence of $5 \times 10^{12}$ ions/cm$^2$ showed good physical properties from this study. So, these films are suitable for device applications.

### 4.2. Scope of future work:

In order to further optimize the device performance, adjustments in magnetron sputtering conditions and in post-deposition treatments are proposed for future research. A better understanding of the vapor phase and film surface reactions during the growth of ZnO and CdZnO layers by dc magnetron sputtering is desirable. Future research could be directed towards further optimization of structural, electrical and optical properties simultaneously by combining results from the present thesis. The research work of present thesis opens up various new areas of research. Some of these are:
(i). Use of high mobility films for the fabrication of field effect transistors. In particular, the top gate geometry can be explored.

(ii). We have investigated the CdZnO films on glass substrates, and they have electrons as charge carriers, on can also deposit the films having holes as charge carriers by sputtering and investigate the charge transport.

(iii). CdZnO films grown on flexible substrates like n-Si (100), the efficiency of the solar cell can be improved. For further research on both ZnO and CdZnO optimization, a promising path is the search for morphologies that efficiently scatter the light, while at the same time allow the deposition of high quality amorphous and microcrystalline silicon. Especially for the understanding of the relation between TCO surface morphology and light scattering, and in particular the angular distribution of the scattered light, further research is necessary. This knowledge should allow the fabrication of thin-film silicon solar cells with high fill factor and open circuit voltage, which can thus take full advantage of the high photocurrent as a result of their optimized light trapping properties.

(iv). To investigate the properties of the CdZnO thin films by dc magnetron sputtering on different substrates (sapphire, Mica, n-Si, GaN, ITO etc) and compare the device performance in terms of fill factor, efficiency etc.