

## List of Figures

**Fig.1.1: Solar PV generation capacity (gigawatts, cumulative installed capacity) and (b) Renewables generation by sources (terawatt-hours).**

**Fig.1.2: Spectral distribution of solar energy (a) at various zenith angle and (b) ASTM standard AM 1.5 G with different irradiation.**

**Fig. 1.3: Performance report of various highly efficient solar cells**

**Fig. 1.4: Schematic of CIGS Solar cell module using a laser scribing process.**

**Fig. 1.5: Transmittance spectra of substrate-Soda Lime Glass (Marienfeld, Germany)**

**Fig.1.6: Band alignment of CIGS solar cell device having SLG/Mo/CIGS/CdS/i-ZnO/AZnO structure under various deposition parameters. Here ‘ $E_c$ ’ is the conduction band, ‘ $E_F$ ’ is Fermi Energy and ‘ $E_v$ ’ is the valence band. The conduction band and its corresponding valence band are represented by the same numerical notation. Few valence band results are not mentioned here as data is not available in the respective literature. Possible losses in device (a) diffusion, (b) thermionic emission, (c) non-radiative, (d) trap-assisted tunneling, (e) CIGS/CdS interface and (6) radiative at bulk, p-n junction, and interfaces.**

**Fig. 2.1: Photograph of Vacuum Coating Unit for multilayer deposition of thin films.**

**Fig. 2.2: Photograph of Direct Current (DC) sputtering power supply.**

**Fig. 2.3: Photograph of Radio Frequency sputtering power supply and impedance RF Match-Box.**

**Fig. 2.4: Soda Lime Glass (SLG) cleaning Process (a) Organic cleaning and (b) Plasma Cleaning.**

**Fig. 2.5: (a) Schematic of Fabrication process of 50 x 50 mm CIGS solar cell module, (b) photograph of sputtering targets used for deposition of Mo/CIGS/CdS/i-ZnO/AZO layers, and (c) Annealing furnace (front view).**

**Fig. 2.6: Schematic diagram of the mechanism of X-Ray Diffraction technique.**

**Fig. 2.7: Schematic diagram of the Scanning Electron Microscope, (JSM-5410, JEOL, USA).**

**Fig. 2.8: Schematic diagram of the operation of Atomic Force Microscopy.**

**Fig. 2.9: Optical arrangement for Raman Spectroscopic analysis.**

**Fig. 2.10: Optical instrumentation of Photoluminescence spectroscopy with low-temperature arrangements.**

**Fig. 2.11: Graphical representation of resistivity measurement-Vander Pauw (no  $\vec{B}_x$ ) method (blue color) and Hall-Voltage measurement (yellow color).**

**Fig. 2.12: Pictorial representation of (a) Dark I-V, (b) Light I-V, and (c) Spectral Response measurement.**

**Fig. 2.13: Optical -setup for UV-Vis-Near Infrared Spectroscopy.**

**Fig 3.1: XRD analysis of Mo thin films deposited at (a) 10 mTorr (bottom), (b) 1 mTorr (Top) and (c) 10 mTorr (bottom) and 1 mTorr (Top) at RT with different DC power.**

**Fig 3.2: Reflectivity spectra of Mo thin films deposited at pressure (a) 10 mTorr and (b) 1 mTorr (top) and (c) 10 mTorr (bottom) and 1 mTorr (top).**

**Fig 3.3: AFM images (a, c, e, g) 2D view and (b, d, f, g) 3D view of bilayer Mo thin films deposited at sputter power (a, b) 50 W, (c, d) 100 W, (e, f) 150 W and (g, h) 200 W.**

**Fig. 3.4. SEM images (a, c, e, g) top view and (b, d, f, g) cross-sectional view of bilayer Mo thin films deposited at sputter power (a, b) 50 W, (c, d) 100 W, (e, f) 150 W and (g, h) 200 W.**

**Fig. 3.5: XRD analysis of Mo thin films deposited at (a) 10 mTorr, (b) 1mTorr, and (c) 10 mTorr (bottom) and 1 mTorr (Top) at ST 215 °C with different DC power.**

**Fig. 3.6: Reflectivity spectra of Mo thin films deposited at pressure (a) 10 mTorr and (b) 1 mTorr (top) and (c) 10 mTorr (bottom) and 1 mTorr (top) ST 215 °C with different DC power.**

**Fig. 3.7: AFM images 2D (a, c, e, g) view and 3D (b, d, f, g) view of bilayer Mo thin films deposited at ST 215 °C with sputter power (a, b) 50 W, (c, d) 100 W, (e, f) 150 W and (g, h) 200 W.**

**Fig. 3.8: SEM images (a, c, e, g) top view and (b, d, f, g) cross-sectional view of bilayer Mo thin films deposited at ST 215 °C with sputter power (a, b) 50 W, (c, d) 100 W, (e, f) 150 W and (g, h) 200 W.**

**Fig. 3.9: XRD analysis of bilayer Mo thin films with a thickness of (a) 300 nm, (b) 500 nm, and (c) 1000 nm.**

**Fig. 3.10: Optical reflectivity of bilayer Mo thin films with a thickness of 300 nm, 500 nm, and 1000 nm.**

**Fig. 3.11: Scanning Electron microscopy top and cross-sectional images of Mo bilayer thickness (a, b) 300 nm, (c, d) 500 nm, and (e, f) 1000 nm.**

**Fig 3.12: Triangular shockwave due to laser beam interaction with the Mo layer.**

**Fig: 3.13: Representation of distance between two consecutive laser pulse spots at center.**

**Fig 3.14: Laser Scribing unit.**

**Fig 3.15: Laser scribing process steps**

**Fig 3.16: (a) Mo thin Film, (b) Heat distribution at the surface, (c) train of pulse, melting Mo surface, (d) evolution of layer from inside layer, and (e) complete removal of Mo layer.**

**Fig 3.17: P1 laser scribing at 150 mm/s, 2 pass, 1.9 W, 10 sec pass delay, 39.1 mm-Z focus and pulse repetition rate (a) 10, (b) 25, (c) 100 and (d) 450 kHz.**

**Fig. 3.18: P1 laser scribing at 450 kHz, 2 pass, 1.9 W, 10 sec pass delay, 39.1 mm - Z focus with scribing speed (a) less than 25 (b) 25, (c) 30, (d) 35, (e) 40, (f) 50, (g) 100 and (h) 150 mm/s.**

**Fig. 3.19: P1 laser scribing at 450 kHz, 150 mm/s speed, 2 pass, 1.9 W, 39.1 mm-Z focus and pass delay (a) 0.1, (b) 1, (c) 2 (d) 5, (e) 10, (f) 15, (g) 20 and (h) 25 seconds.**

**Fig. 3.20: P1 laser scribing at 450 kHz, 150 mm/s speed, 2 pass, 39.1 mm - Z focus, pass delay 10 sec and power (a) 0.65 W, (b) 1.08 W, (c) 1.4 W, (d) 1.9 W, (e) 2.45 W and (f) 2.85 W.**

**Fig. 3.21: P1 laser scribing at 450 kHz, 2 pass, 150 mm/s speed, 1.9 W power, pass delay 10 seconds and Z-Focus (a)  $\Delta Z = 37.1$  mm, (b)  $\Delta Z = 38.1$  mm, (c)  $\Delta Z = 39.1$  mm, (d)  $\Delta Z = 40.1$  mm, and (e)  $\Delta Z = 41.1$  mm.**

**Fig 3. 22: P1 laser scribing at 20 kHz, 3500 mm/s speed, power (a) 0.22 W (b) 0.65 W, (c) 1.08 W, (d) 1.4 W, (e) 1.9 W, (f) 2.45 W, (g) 3.41 W, (h) 4.45 W, (i) 5.46 W, and (j) 5.58 W.**

**Fig 3. 23: P1 laser scribing at power 1.4 W, 3500 mm/s speed, pulse repetition rate 20 kHz, (b) 40 kHz, (c) 50 kHz, (d) 100 kHz, (e) 250 kHz and (f) 450 kHz.**

**Fig 3. 24: P1 laser scribing at power 1.4 W, pulse repetition rate 20 kHz and Galvo scan speed (a) 100, (b) 500, (c) 1000, (d) 2000, (e) 3000, (f) 3500, (g) 4000, (h) 5000 (i) 7500 (j) 10,000 and (k) 20,000 mm/s.**

**Fig 3. 25: P1 laser scribing at power 1.4 W, pulse repetition rate 20 kHz and Galvo scan speed 3500 mm/s and depth of focus  $\Delta Z = -0.8$  mm to  $+0.8$  mm.**

**Fig 3.26: Photo (using back light) of bi-layer molybdenum thin film on 60 x 60 mm square SLG using P1 scribing process with the optimized parameter of Nd:YAG fiber laser.**

**Fig 3.27: Adhesion Test of bilayer Mo thin film deposited at 150 W DC power by (a) Nd:YAG (1064 nm) Laser, and (b) 6M of  $\text{NH}_4\text{OH}$  solution.**

**Fig: 4.1: Pseudobinary phase diagram of Chalcopyrite CIGS phase.**

**Fig. 4.2: Image of (a) Twin bowl planetary ball mill system (M/s. Insmart System, Hyderabad), and (b) Cold Press Machine.**

**Fig. 4.3: Optical image (a) Ball milled CIGS powder and (b) cold press (c) vacuum sintered CIGS target at 500 °C for one hour.**

**Fig. 4.4: XRD spectra of (a) Ball milled CIGS powder and CIGS target; CIGS thin films deposited at various (b) pressure, (c) RF power, and (d) annealing under vacuum environment.**

**Fig. 4.5: XRD spectra of (a) Ball milled CIGS powder and CIGS target, CIGS thin films deposited at various (b) pressure, (c) RF power, and (d) annealing under vacuum environment.**

**Fig. 4.6: 2D and 3D topographical (AFM) images of CIGS thin films deposited at various (a) pressure [10 mTorr (a, b), 15 mTorr (c, d), and 20 mTorr (e, f)], (b) RF power [125 W (g, h), 150 W (i, j), and 175 W (k, l)], and (c) annealing [150 °C (m, n), 200 °C (o, p), and 250 °C (q, r)] under vacuum environment.**

**Fig. 4.7: Scanning Electron Microscopic images of CIGS thin films deposited at various (a) pressure [10 mTorr-(a), 15 mTorr-(b), and 20 mTorr-(c)], (b) RF power [125 W-(d), 150 W-(e), and 175 W-(f)], and (c) annealing [150 °C-(g), 200 °C-(h), and 250 °C-(i)] under vacuum environment.**

**Fig. 4.8: Optical Transmittance of CIGS thin films deposited at different (a) pressure, (b) power, and (c) Annealing under vacuum environment.**

**Fig 4.9: Plot of  $(\alpha h\nu)^2$  versus energy (E) of CIGS thin films deposited at various deposition conditions.**

**Fig 4.10: (a) Dependence of Ga content on optical bandgap and (b) Urbach Energy of CIGS thin films deposited at various deposition conditions.**

**Fig. 4.11: (a) Rapid Thermal Annealing (RTA) Profile for CIGS phase formation, (b) Rapid Thermal Annealing setup for the annealing process.**

**Fig. 4.12: X-ray diffraction spectra of different Rapid Thermal Annealing (RTA) Profiles for SLG/Mo/CIGS phase formation.**

**Fig. 4.13: (a) Reflectivity X-ray spectra and (b) Optical Bandgap of different Rapid Thermal Annealing (RTA) Profiles for SLG/Mo/CIGS phase formation.**

**Fig. 4.14: Raman Spectroscopic Analysis of different Rapid Thermal Annealing (RTA) Profiles for SLG/Mo/CIGS phase formation.**

**Fig. 5.1: Chemical Bath Deposition process for CdS thin film deposition.**

**Fig. 5.2: X-ray analysis of CdS thin films deposited by (a) thermal evaporation at different ST, (b) CBD at different S/Cd ratio, and (c) RF sputtered.**

**Fig. 5.3: Optical Transmittance spectra and Optical Bandgap (inset) of CdS thin films deposited by (a) thermal evaporation at different ST, (b) CBD at different S/Cd ratio, and (c) RF sputtered.**

**Fig. 5.4: Photoluminescence spectra of CdS thin films deposited by (a) thermal evaporation at different ST, (b) CBD at different S/Cd ratio, and (c) RF sputtered.**

**Fig. 5.5: Scanning Electron Microscopic images of CdS thin films deposited by (a) thermal evaporation ST-150 °C, (b) CBD at different S/Cd ratio, and (c) RF sputtered.**

**Fig. 5.6: Photographic image of CdS layer deposited by CBD technique at the different duration of deposition.**

**Fig. 5.7: Elemental dispersive x-ray analysis of CdS layer deposited by CBD technique for 8 mins.**

**Fig. 5.8: P2 scribe using 532 nm laser, pulse repetition rate 20 kHz, 40 mm/sec scribing speed and pulse energy (a) 1.5  $\mu$ J, (b) 2.1  $\mu$ J, and (c) 2.4  $\mu$ J and (d) P2 mechanically scribed.**

**Fig. 6.1: (a) Photograph and XRD (b) Pattern of 2-inch (diameter) i-ZnO Target.**

**Fig. 6.2: XRD analysis of RF sputtered i-ZnO (a, b, and c) and AZO (d and e) thin films deposited at variable deposition pressure and power, thickness, and substrate temperature.**

**Fig. 6.3: Crystallite size of RF sputtered AZO thin films (a) RT and (b) ST-215 °C thin films deposited at variable deposition pressure and thickness.**

**Fig. 6.4: Optical transmission spectra of i-ZnO thin films deposited ((a) 10, (b) 5 and (c) 1 mTorr), deposition power (50, 100 and 150 W) having thickness (50, 70 and 90 nm).**

**Fig. 6.5: Optical transmittance and Bandgap spectra of AZO thin films deposited (15 (a and b), 10 (c and d), 5 (e and f) and 1 (g and h) mTorr), deposition power 100 W having a thickness (300, 400 and 500 nm).**

**Fig. 6.6: Burstein-Moss shift of AZO thin films (a) RT and (b) ST-215 °C.**

**Fig. 6.7: Urbach Energy ( $E_U$ ) of RF sputtered AZO thin films (a) RT and (b) ST-215 °C thin films deposited at variable deposition pressure and thickness.**

**Fig. 6.8:** AFM analysis of i-ZnO thin film deposited at (a and b) 10 mTorr, (c and d) 5 mTorr, (e and f) 1 mTorr), 150 W and thickness 500 nm and AZO thin film at RT, (g and h) 300 nm, (i and j) 400 nm and (k and l) 500 nm) and ST-215 °C, (m and n) 300 nm, (o and p) 400 nm and (q and r) 500 nm.

**Fig. 6.9:** Scanning Microscopic image of AZO thin film (a) RT, (b) ST-215 °C and i-ZnO thin films (c) 10 mTorr, (d) 5 mTorr and (e) 1mTorr.

**Fig. 6.10:** Photoluminescence (PL) emission spectra of i-ZnO thin films deposited ((a) 10 (b) 5 and (c) 1 mTorr), and AZO thin films ((d) RT and (e) ST-215 °C).

**Fig. 6.11:** Raman spectra emission spectra of i-ZnO thin films deposited (a) (10, 5 and 1 mTorr), AZO thin films at (b) RT and (c) ST-215 °C.

**Fig. 7.1:** Schematic of the stack of multilayer SLG/Mo/CIGS/CdS/i-ZnO/AZO CIGS solar cell.

**Fig. 7.2:** Fabrication steps of CIGS thin-film Solar Cells.

**Fig. 7.3:** Photograph of 50 μm, 100 μm, and 200 μm in size Al Finger grid on multilayer SLG/Mo/CIGS/CdS/i-ZnO/AZO CIGS solar cell.

**Fig. 7.4:** FESEM image of multilayered CIGS solar cell.

**Fig. 7.5:** Schematic of the cell to module process of CIGS solar cell module.

**Fig. 7.6:** Fabrication steps of Monolithic integrated CIGS Solar Cell Module.

**Fig. 7.7:** Close view of P1 laser patterned, P2 and P3 mechanical scribed multilayered CIGS solar cell module.

**Fig. 7.8:** Experimental Set-up for performance analysis of multilayered CIGS solar cell module.

**Fig. 7.9:** Dark and under-illumination I-V curve of (a, b)-CdS by a different deposition technique, (c, d)-CdS-CBD for different duration of deposition, and (e, f)-i-ZnO layer with different thickness.

**Fig. 7.10:** (a) Dark, (b) Under-illumination I-V curve, and (c) Quantum Efficiency of CIGS Solar Cell module.