## Supplementary Information

# Cd-reduced Hybrid Buffer Layer of CdS/Zn(O,S) for Environment-friendly CIGS Solar Cell

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**Table S1**. Electrical parameters of solar cells with Zn(O,S) buffers fabricated by using different rf powers to the ZnO and ZnS targets; 40 W (A), 30W (B), 20W (C) and 15W (D) were applied for ZnO targets and rf power for ZnS target was kept constant at 15W.

| Samples | $V_{OC}$ (V) | $J_{SC}$ (mA/cm$^2$) | F.F (%) | η (%) |
|---|---|---|---|---|
| A | 0.21 | 26.12 | 49.90 | 2.72 |
| B | 0.29 | 18.79 | 56.27 | 3.09 |
| C | 0.44 | 23.65 | 50.37 | 5.34 |
| D | 0.58 | 22.05 | 44.83 | 5.73 |

**Table S2.** Defect levels in CIGS solar cell reported in articles.

| Defect energy (meV) | Characterization method | Assignments | References |
|---|---|---|---|
| 73 | DLTS | $In_{Cu}$ | 1 |
| 8.4 | DLTS | $Cd_{Cu}$ | 1 |
| 440 | DLTS | Foreign impurity | 1 |
| 470, 340, 340 | DLTS | $In_{Cu}(+/++)$ | 2 |
| 320, 250, 240 | DLTS | $In_{Cu}(0/++)$ | 2 |
| 300 | AS | $V_{Se}+V_{Cu}$ | 3 |
| 300 | TPC | $V_{Se}+V_{Cu}$ | 4 |
| 25 | AS | $V_{Cu}$ | 5 |
| 110 | AS | $(In, Ga)_{Cu}$ | 5 |
| 60, 70 | AS | $V_{Se}$ | 6 |
| 250 | AS | $In_{Cu}(0/++)$ | 6 |


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Crystal structure of fabricated ZnO, ZnS and Zn(O,S) thin films. Here, thin films were deposited on soda lime glass for longer time to get thick films (~500nm) for XRD and Raman signal.

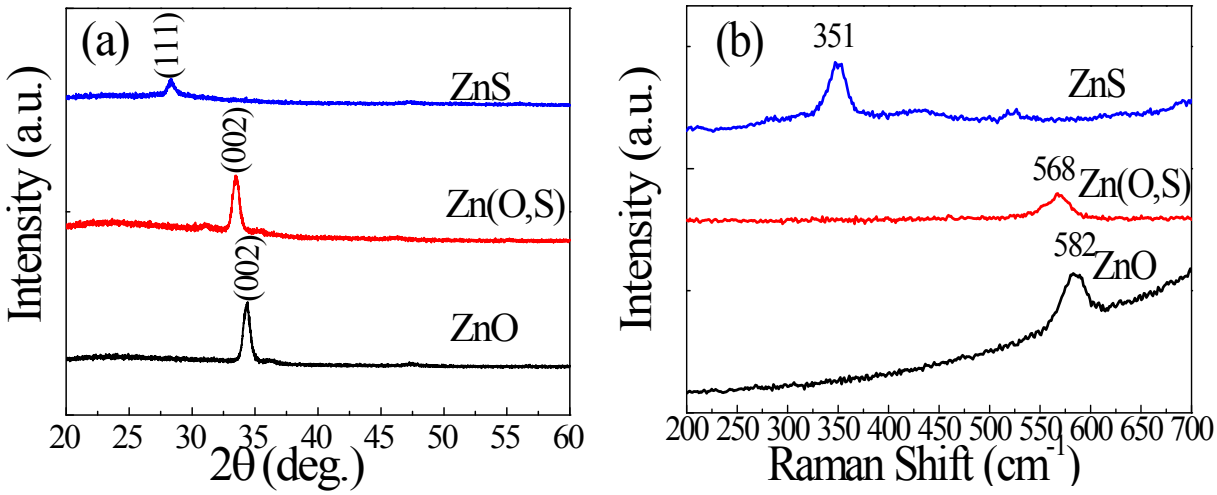


**Figure S1.** XRD spectra of thin films deposited by sputtering of ZnO, ZnS and Co-sputtering of both targets (a) and their Raman spectra (b).

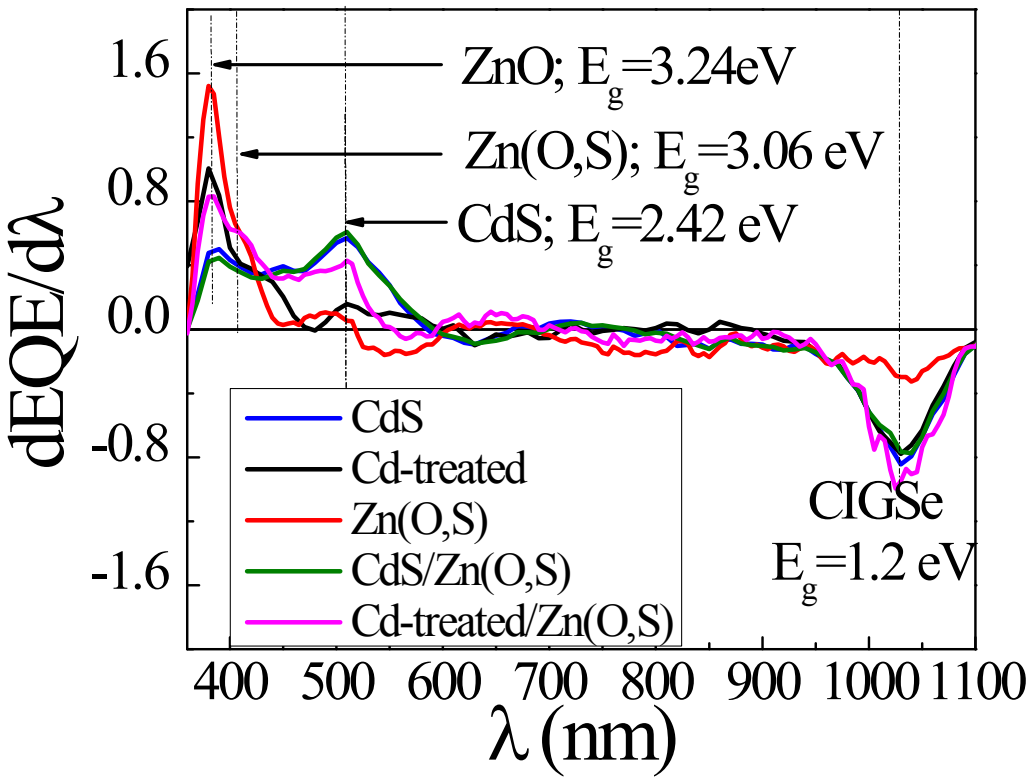


**Figure S2.**The first derivative of the EQE spectra with respect to wavelength.

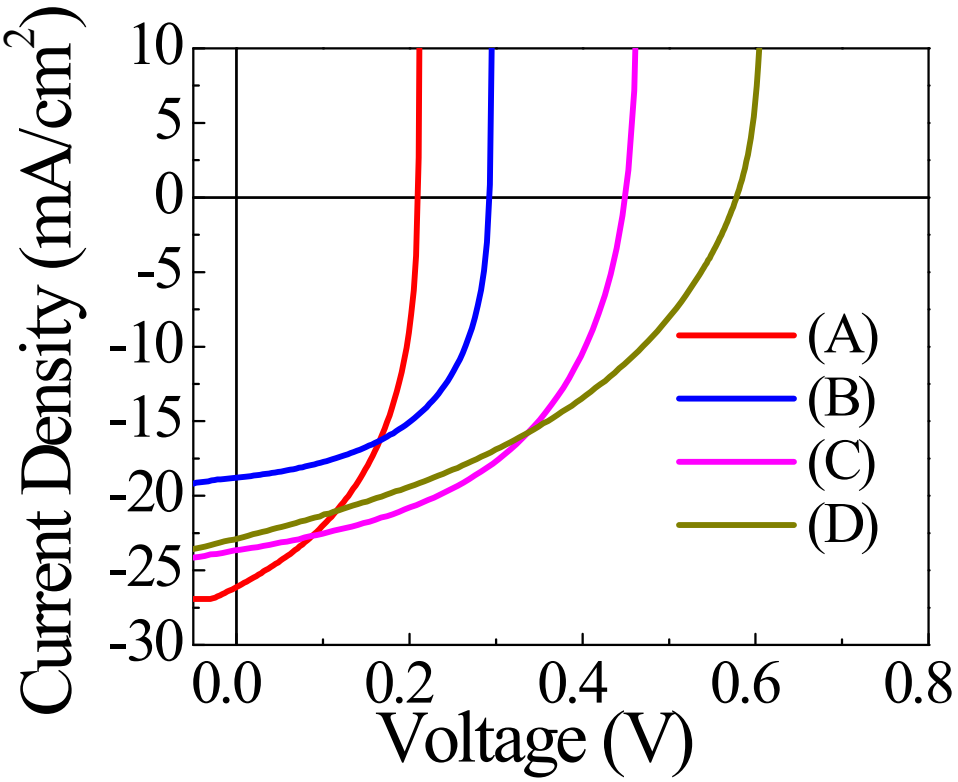


**Figure S3.** J-V characteristics of solar cells with Zn(O,S) buffer fabricated by using different rf powers; 40 W (A), 30W (B), 20W (C) and 15W (D) were applied for ZnO targets and rf power for ZnS target was kept constant at 15W.

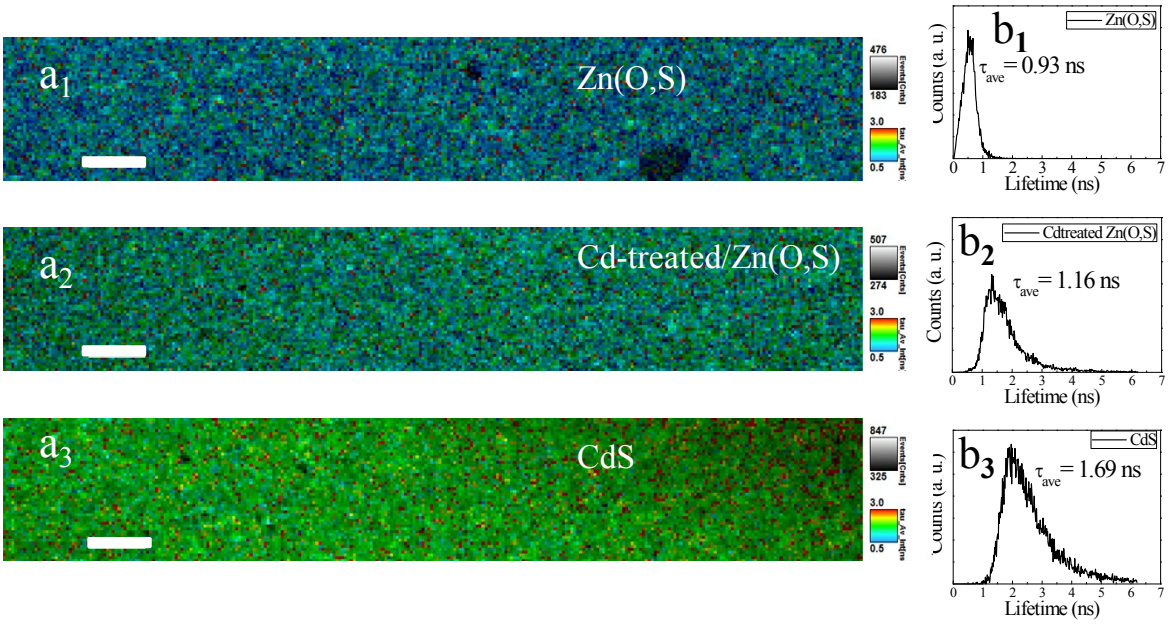


**Fig. S4** Results of **c**arrier lifetime measurement for CIGS/Zn(O,S)/i-ZnO, CIGS/Cd-treated/Zn(O,S)/i-ZnO and CIGS/CdS/i-ZnO: ($a_1$-$a_3$) TRPL life time mapping and ($b_1$-$b_3$) histograms of average life time. The scale bar in TRPL mapping image is 20 μm.