Investigating the Role of Selenium Ion Concentration on Opto-electronic Properties of the $Cu_2ZnSn(S_{1-x}Se_x)_4$ Thin Films

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 # Supporting information

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Table S1: Comparative XRD data of the CZTSSe thin films

A comparative experimental and standard 'd' values of the CZTSSe films were determined using relation, $\Delta d(Å) = d_{exp}(Å) - d_{jcpds}(Å)$

Sr. No.	JCPDS Data	2θ (Degree)	(*hkl*)	d_{Exp} (Å)	d_{JCPDS} (Å)	$\Delta d(Å) = d_{Exp}(Å) - d_{JCPDS}(Å)$
1		28.76	112	3.324	3.234	0.09
2	***$Cu_2ZnSn(SSe)_4$***	47.30	220	1.932	1.849	0.09
3	(26-0575)	56.43	312	1.698	1.646	0.05
4		60.99	224	1.576	1.545	0.03

Table S2: Compositional analysis parameters of the deposited CZTSSe thin films

The observed Zn/Sn, Cu/(Zn+Sn) and (S+Se)/(Cu+Zn+Sn) stoichiometric ratio and atomic percentage of elements for CZTSSe thin film as function of Se^{2-} ion concentration.

Sample Code	Cu	Zn	Sn	S	Se	$\frac{Zn}{Sn}$	$\frac{Cu}{(Zn+Sn)}$	$\frac{(S+Se)}{(Cu+Zn+Sn)}$
Se_1	24.8	13.3	12.5	49.4	0.0	1.06	1.01	0.97
Se_2	23.8	12.4	12.8	40.8	10.2	0.96	0.95	1.04
Se_3	25.2	10.8	13.7	34.6	15.7	0.78	1.02	1.01
Se_4	23.6	12.5	11.2	30.9	21.8	1.11	0.99	1.11
Se_5	22.4	12.2	11.8	27.2	26.4	1.03	0.93	1.15

Table S3: EIS parameters of the CZTSSe thin films

Values of series resistance (Rs), charge transfer resistance (Rct), double layer capacitance (Cdl), Warburg impedance and Bode phase angle for CZTSSe thin film

Sample Code	Rs (Ω/cm^2)	Rct (Ω/cm^2)	Cdl (F/cm^2)	Zw (mMho)	Bode phase angle
Se_1	32.4	465	6.53	1.76	-57.2^o
Se_2	32.6	203	7.57	10.9	-54.2^o
Se_3	26.4	124	10.5	4.26	-25.6^o
Se_4	67.9	40.4	6.19	10.9	-8.2^o
Se_5	73.7	68	107	21.4	-20.1^o

Figure S1. Photographs of the deposited $Cu_2ZnSn(S_{1-x}Se_x)_4$ (x=0.0 to 0.1 M Se) thin film

Lab scale physical photographs of hydrothermally deposited $Cu_2ZnSn(S_{1-x}Se_x)_4$ thin film with varying Se^{2-} ion concentration

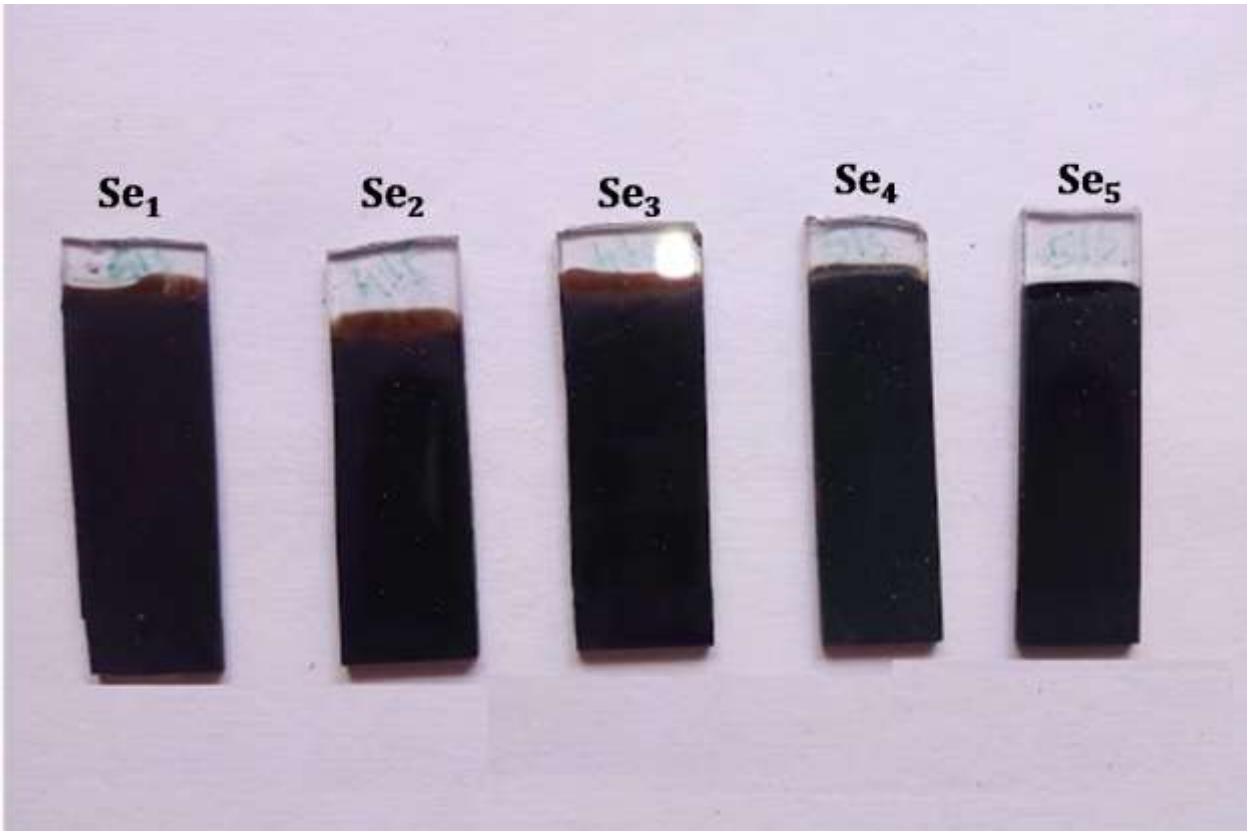

Figure S2: Thickness measurement of deposited $Cu_2ZnSn(S_{1-x}Se_x)_4$ films as a function of Se ion concentration

Thickness of deposited CZTSSe thin films were lies in the range of 425 to 545 nm with varying Se^{2-} ion concentration in $Cu_2ZnSn(S_{1-x}Se_x)_4$ films. The increase in film thickness with Se^{2-} ion concentration in CZTSSe thin films up to x=0.075 M and after that it slightly decreases.