

Effects of annealing temperature on  $\text{Cu}_2\text{ZnSnS}_4$  (CZTS) films formed by an electro-spray technique

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The electro-spray technique is a simple and inexpensive method for producing high-quality  $\text{Cu}_2\text{ZnSnS}_4$  (CZTS) films under low temperature conditions. The effects of annealing temperature for the as-deposited CZTS films were investigated. All the as-grown CZTS films exhibited a kesterite structure with a preferred orientation of (112), (220) and (312). And there was no phase transition according to annealing temperature. In addition, all samples exhibited a CZTS characteristic peak in the Raman spectra centered at  $336\text{ cm}^{-1}$ , which indicated the CZTS phase was established during the film depositions. The grain size of the CZTS films increased substantially in the range of  $300 - 450\text{ }^\circ\text{C}$ , and the optical band-gap ( $E_g$ ) of the CZTS films under different annealing temperatures decreased from  $1.71\text{ eV}$  to  $1.42\text{ eV}$ . The blue shift in  $E_g$  was strongly related to the grain size due to the quantum confinement effects. It is found that the annealing process improved the crystallinity and optical properties of the films, making them suitable for photovoltaic applications.