

ADVANCING INDOOR PHOTOVOLTAICS BASED ON $\text{Cu}_2\text{ZnSnS}_4$ KESTERITE: FROM RIGID TO FIRST FLEXIBLE DEVICES

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The current market landscape is shaped by the rapid proliferation of Internet of Things (IoT) devices, whose integration is estimated to reach 1 trillion by 2035. [1] These technologies predominantly rely on batteries, which present significant challenges in terms of technical viability, economic feasibility, and environmental sustainability. Indoor photovoltaic (IPV) is considered a feasible and environmentally friendly energy solution for providing sustainable power to IoT nodes. Over the last two decades, the global IPV market has undergone unprecedented expansion, driving strong interest in the development of PV technologies based on eco-friendly, earth-abundant materials combined with scalable manufacturing processes. The use of sustainable materials is particularly relevant, as IPV devices are designed for integration into everyday objects and indoor environments. Another attractive aspect is their compatibility with flexible substrates, enabling the realization of wearable and bendable devices for lightweight emerging technology platforms. [2] [3]

Kesterites, $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$, are p-type semiconductor chalcogenides mostly known as absorber materials in thin-film solar cells, and increasingly attracting interest for indoor photovoltaics. This thanks to their high absorption coefficients, a nontoxic and earth-abundant elemental composition, and a tunable direct bandgap (1.0-2.2 eV). These properties establish $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) and Ge-alloyed CZTS particularly promising candidates for IPV, owing to their bandgap compatibility with the most common indoor light spectra. [4]

In this work, the synthesis of CZTS thin films was investigated in terms of composition of the precursor ink (metal ratio, alloying and doping concentrations) and annealing conditions (temperature and time). Ink composition parameters were optimized to tune the absorber band gap for compatibility with indoor spectra and to evaluate their effect on morphological and optoelectronic properties of the resulting films; while annealing parameters were varied to assure a high crystalline quality of the kesterite material. In addition, different functional layers (MoO_x , Al_2O_3) and electron transport layers (CdS , $\text{Zn}_x\text{Sn}_{1-x}\text{O}$) were incorporated into device architectures, and heterojunction treatments were studied to assess their impact on device performances. CZTS prototype solar devices were fabricated on both Soda Lime Glass (SLG)/Molybdenum (Mo) substrates and flexible engineered Mo foil substrates, using CdS as the electron transport layer, zinc oxide (ZnO) and indium tin oxide (ITO) as transparent conductive oxides, and silver contacts. Devices were measured under AM1.5G spectrum and indoor lighting at different color temperature light spectra (2700, 3000, 4000, 5000, and 6000K) across varying intensity levels. Power conversion efficiencies exceeding 16% and 13% were achieved for rigid SLG/Mo and flexible devices, respectively, under low-light conditions, with both architectures showing good resilience of open circuit voltage and fill factor values across different illuminance levels. These results report the first ever CZTS flexible solar cell tested for indoor photovoltaics and demonstrate that further development and improvement could pave the way to develop a kesterite-based lightweight thin-film technology suitable for integrated emerging IPV applications.

[1] Hoye, R. L. Z. *et al*; *Joule* 2025, 9 (10).

[2] Grandhi, G. K. *et al*; *Nature Reviews Clean Technology* 2025, 1 (2), 132–147.

[3] Sun, Z. *et al*; *Chem. Commun.* 2025, 61 (7), 1243–1261.

[4] Gong, Y. *et al*; *Solar RRL* 2025, 9 (4), 2400756.

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