Supplementary document for

Synergistic Enhancement of Charge Transfer and Catalytic Activity in CNT@rGO@Cu₂S Composite Counter Electrodes for High-Performance Quantum Dot-Sensitized Solar Cells

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Experimental Procedures for Device Fabrication

S1. Quantum Dot-Sensitized Solar Cell Fabrication Procedure

FTO Cleaning: FTO glass (7 Ω /sq) was sequentially ultrasonicated in acetone, ethanol, and deionized water for 15 min each and dried under nitrogen.

TiO₂ Layer: A commercial TiO₂ paste (Dyesol 43T) was screen-printed onto the cleaned FTO and sintered at 450 °C for 30 min to form a mesoporous layer (\sim 1 µm thick).

CdS Sensitization (SILAR): TiO₂ films were alternately immersed in $0.1 \text{ M Cd}(\text{NO}_3)_2$ and $0.1 \text{ M Na}_2\text{S}$ (both in methanol) for 3 cycles (30 s each), rinsing with methanol between dips.

CdSe:Cu Sensitization: A Cd^{2+}/Cu^{2+} precursor solution $(Cd(CH_3COO)_2 \cdot 2H_2O)$ and $CuCl_2 \cdot 2H_2O$, 0.3 molar ratio) was used in combination with Se²⁻ from Na₂SeSO₃ (prepared by refluxing Se powder and Na₂SO₃). Films were dipped for 3 cycles (30 s each) with ethanol rinses.

ZnS Passivation: Films were immersed in 0.1 M Zn(NO₃)² and 0.1 M Na₂S (ethanol) for 2 cycles to deposit a ZnS overlayer.

Electrolyte: Polysulfide electrolyte containing 0.1 M S, 0.1 M Na₂S, and 0.1 M KCl was dissolved in water and stirred until fully mixed.

Counter Electrode (CE): CNT/rGO@Cu₂S powder (30 mg) was mixed with 5 mL ethanol and 0.5 g polyethylene glycol to form a slurry. This was screen-printed onto cleaned FTO, dried at 60 °C, and annealed at 350 °C for 30 min.

Device Assembly: The photoanode and CE were assembled face-to-face with a Surlyn spacer (25 μ m), and the electrolyte was injected through predrilled holes.