

Self-Powered, High-Speed Photodetection Using Sn (5%) Doped Nanocrystalline CdS Thin Films Deposited by Vacuum Evaporation on FTO

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Abstract This work presents the fabrication and comprehensive characterization of a self-powered, high-speed photodetector based on an FTO/nanocrystalline CdS:Sn 5% heterojunction. Tin-doped CdS thin films were deposited onto FTO-coated glass substrates using thermal evaporation coupled with inert gas condensation. XRD analysis revealed the polycrystalline nature of the nc-CdS:Sn 5% thin films with peaks corresponding to the hexagonal CdS phase. Raman spectroscopy showed characteristic phonon modes of CdS, while FE-SEM displayed densely packed grains with uniform morphology. EDAX confirmed the elemental composition with Cd, S, and Sn in the desired stoichiometric ratios. The resulting device exhibited pronounced rectifying behavior in the dark, alongside significant photovoltaic effects under illumination. Key device metrics included a sensitivity of 0.25, a responsivity of 1.62 $\mu\text{A/W}$, and a detectivity of 1.51×10^6 Jones at zero bias, measured under white light irradiation. Dynamic response evaluation revealed reproducible operation up to 700 Hz, with fast rise and fall times of 0.07 μs and 2.56 μs , respectively. These findings underscore the promising potential of the FTO/CdS:Sn 5% heterojunction for high-speed optical communication, self-powered optical switching, and advanced optoelectronic applications.

Keywords: nanocrystalline CdS, FE-SEM, heterojunction, self-powered photodetector, optoelectronics

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1. Introduction

Photodetectors, which convert optical signals into electrical outputs, are vital components in a wide range of optoelectronic systems, including optical communication, environmental monitoring, biomedical imaging, and information security. The rising demand for devices that offer high-speed, low-power, and broadband photodetection has led to increased research focus on photodetectors that integrate superior sensitivity, high-speed response, and self-powered operation. Self-powered photodetectors, in particular, are highly valued for their ability to function without an external bias, facilitating autonomous operation and paving the way for compact, energy-efficient device integration in next-generation technologies [1,2].

Cadmium sulfide (CdS), by virtue of its direct band gap, high optical absorption, and chemical stability, has long been investigated as a candidate material for visible-light photodetectors. Doping CdS with metal ions such as tin (Sn) introduces defect states and tailors the optoelectronic

properties, offering pathways to enhance device performance and extend photoresponse characteristics. Nanocrystalline CdS based heterojunctions fabricated on transparent conductive substrates, particularly those employing fluorine-doped tin oxide (FTO), have exhibited promising rectifying behaviour, high responsivity, and rapid dynamic characteristics, positioning them at the forefront of modern photodetector research [3,4].

Despite notable progress, achieving simultaneous improvements in speed, sensitivity, and energy autonomy remains a challenge. This work reports the synthesis and comprehensive characterisation of a self-powered, high-speed photodetector utilising a nanocrystalline CdS:Sn 5% thin film deposited on FTO glass [5]. The device is systematically investigated in terms of structural, optical, morphological, electrical, and photoelectrical properties, demonstrating rapid and reproducible real-time photodetection under zero-bias conditions. These results underpin the potential of FTO/nc-CdS:Sn 5% heterojunctions for deployment in optoelectronic switching and high-speed optical communication systems, paving the way toward practical self-powered optoelectronics [6].

2. Material and Method

2.1. Material Synthesis and Thin Film Deposition

The CdS material was prepared using the melt-quenching technique. Constituent elements were weighed according to their atomic percentages and sealed in quartz ampoules under a vacuum of 2×10^{-5} mbar [7]. The sealed ampoules were heated to 1200 °C in a furnace at a rate of 2–3 °C/min and held at the highest melting point temperature of the components for 24 hours to ensure a homogeneous melt. Subsequently, the ampoules were quenched in ice-cold water [8].

Thin films were deposited on well-degassed, transparent fluorinated tin oxide glass substrates using thermal vacuum evaporation combined with the inert gas condensation method. The entire deposition process was conducted at a base pressure of 2×10^{-5} mbar at room temperature. To achieve thermodynamic equilibrium, the as-deposited thin films were kept in a dark deposition chamber for 24 hours before characterisation [8].

2.2. Characterisation Techniques

Structural parameters for the FTO/nc-CdS:Sn 5% sample were determined via X-ray diffraction (XRD) using a Spinner 3064 XPERT-PRO diffractometer (CuK α , $\lambda = 1.54056$ Å) over a 2θ range of 17°–70°, with a scanning speed of 0.02° s⁻¹. Raman spectra were acquired using a Spex Ramalog 1403 double monochromator equipped with an RCA 31034A photomultiplier tube [7,9]. Crystallite size was calculated from the XRD peak broadening using the Debye–Scherrer equation, and micro-strain was derived from peak positions and widths using standard strain formulas.

Optical absorption and transmission measurements were performed using a computer-controlled UV/VIS/NIR spectrophotometer across the wavelength range of 460–2500 nm at room temperature. The acquired spectral data enabled determination of the optical band gap by applying the conventional Tauc's method, while the absorption coefficient was quantitatively estimated using Lambert–Beer's law.

Surface morphology and elemental composition of the thin films were comprehensively characterized using a Hitachi SU-8000 field emission scanning electron microscope (FE-SEM, Model: HI-0876-0003) coupled with Energy Dispersive Analysis of X-ray (EDAX), providing high-resolution visualization of grain size distribution, microstructural features, and film homogeneity as well as enabling semi-quantitative determination of elemental distribution within selected regions of the film.

Electrical characterization was conducted using a Keithley 6517A electrometer, which functioned as both a voltage source and current meter. Photodetector devices were fabricated by forming Ag point contacts on nc-CdS:Sn 5% films using silver paste, establishing a heterojunction with the conductive FTO substrate. Key diode parameters, including series resistance (R_s), ideality factor (n), reverse saturation current (I_0), and Schottky

barrier height (Φ_B), were extracted from the measured I–V curves based on the thermionic emission model. Photovoltaic performance metrics such as open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), fill factor (FF), and maximum output power (P_{max}) were derived from illuminated I–V characteristics.

For dynamic response analysis, an Nd:YAG laser ($\lambda \approx 1064$ nm, pulse width ≈ 10 ns, power ≈ 10 mJ) served as the excitation source for measuring rise and fall times. To enhance signal-to-noise ratio, the sample was mounted in a custom-designed metallic holder. Electrical current under applied bias and during photonic excitation was recorded with a Digital Phosphor Oscilloscope, enabling precise determination of device speed and suitability for high-frequency photonic applications.

3. Results and Discussion

3.1. Structural Properties

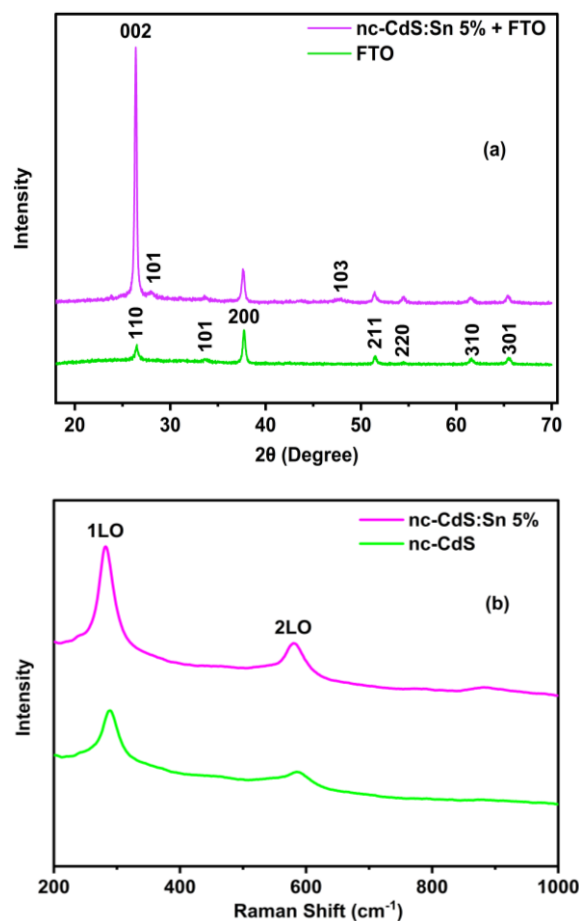


Figure 1. (a) X-ray diffraction patterns (b) Raman spectra of nc-CdS:Sn 5% thin film

The X-ray diffraction (XRD) patterns of the FTO glass substrate and the nc-CdS:Sn 5% thin film deposited on the substrate at 300 K are shown in Figure 1(a). The XRD pattern of the FTO substrate corresponds well to the standard cubic phase of SnO₂. The nc-CdS:Sn 5% thin film exhibited diffraction peaks attributable to both CdS and FTO. Besides the characteristic FTO peaks, the CdS film showed prominent reflections at 2θ values of 26.38°, 27.92°, and 47.84°, indexed to the (002), (101), and (103)

planes, respectively. These reflections confirm the hexagonal crystal structure of CdS, indicating the polycrystalline nature of the film with a preferred orientation along the (002) plane. All diffraction peaks were well indexed, and no secondary or impurity phases were detected, evidencing the high phase purity of the deposited film.

The interplanar spacing for the (002) plane, d_{002} , was calculated using Bragg's law, $\lambda = 2d_{002} \sin \theta$, yielding a value of 3.353 Å. The crystallite size D along the (002) plane was estimated by the Debye–Scherrer equation,

$$D = \frac{0.94\lambda}{\beta \cos \theta}$$

where θ is the Bragg angle, λ the X-ray wavelength, and β the full width at half maximum (FWHM) in radians. The calculated crystallite size was approximately 19 nm [10]. The microstrain ε was estimated using

$$\varepsilon = \frac{\beta \cos \theta}{4}$$

and found to be $0.001926 \text{ Lines}^{-2}\text{m}^{-4}$. This analysis confirms the high-quality polycrystalline nature of the FTO/nc-CdS:Sn 5% thin film with well-defined structural parameters.

The Raman spectrum of the nc-CdS:Sn 5% thin film is presented in Figure 1(b). Two prominent peaks appear at 282 cm^{-1} and 582 cm^{-1} , corresponding respectively to the first-order and second-order longitudinal optical (LO) phonon modes of CdS [7]. These characteristic phonon modes indicate that the nc-CdS:Sn 5% thin film retains a crystal structure similar to bulk CdS, confirming its high crystallinity and phase purity.

3.2. Optical Properties

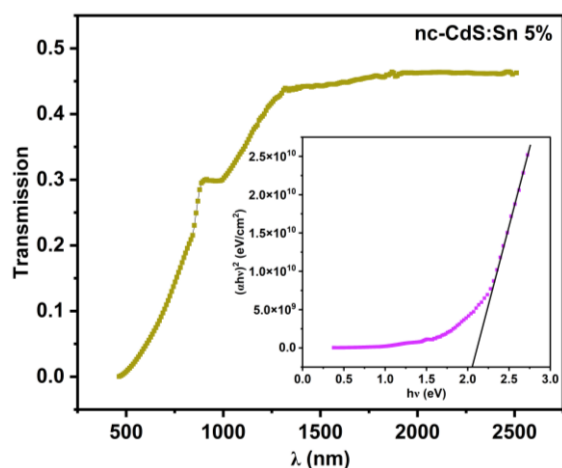


Figure 2. Optical transmission spectra for the nc-CdS:Sn 5% thin films deposited at room temperature (300 K). The inset shows the graph plotting $(\alpha h\nu)^2$ against $h\nu$

Figure 2 displays the optical transmission spectrum of the nc-CdS:Sn 5% thin film deposited at room temperature. The transmittance (T) and absorption coefficient (α) are related through Lambert–Beer's law as $T = e^{-\alpha d}$, where d is the film thickness. For direct-bandgap semiconductors, the optical band gap (E_g) is determined using Tauc's relation:

$$(h\nu\alpha)^2 = A(h\nu - E_g)$$

where h is Planck's constant, ν the photon frequency, and A a constant independent of photon energy. The band gap is found by extrapolating the linear region of the $(\alpha h\nu)^2$ vs. $h\nu$ plot to $\alpha=0$ [11]. The optical band gap of nc-CdS:Sn 5% was estimated to be 2.06 eV, lower than that of bulk CdS. This reduction is attributed to defect-induced band tailing, an intrinsic effect in nanocrystalline films produced under rapid quenching and high-vacuum conditions. Such defects create localized states near the band edges, acting as trap centers that alter optical absorption and reduce the observed band gap.

3.3. Structural Properties

The FE-SEM micrograph of the nc-CdS:Sn 5% thin film is shown in Figure 3 (a). The FE-SEM imaging revealed a densely packed, crack-free surface morphology composed of spheroid-like grains, indicating uniform nucleation and growth on the FTO substrate. The observed homogeneity in the microstructure, without any pinholes or voids, demonstrates the optimization of deposition parameters and confirms the reliability of the fabrication process in producing high-quality thin films suitable for device integration. EDAX spectra of nc-CdS:Sn 5% thin film is shown in Figure 3 (b). The composition shows that cadmium (Cd) and sulfur (S) are present in nearly equal atomic proportions, while tin (Sn) is introduced as a minor dopant. The totals for both atomic and weight percentages indicate a normalized distribution, confirming the absence of significant impurities.

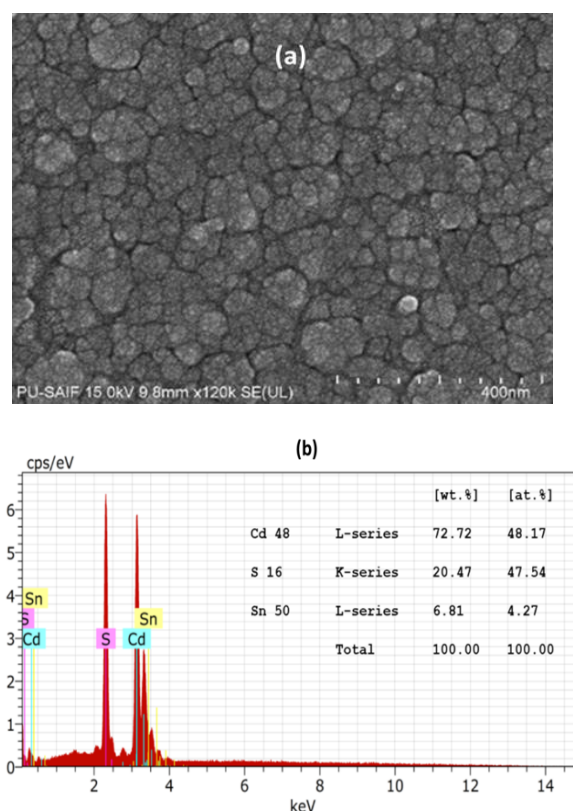


Figure 3. (a) FE-SEM image and (b) EDAX spectra of nc-CdS:Sn 5% thin film

3.4. Electrical Characteristics

Figure 4 presents the current-voltage (I–V) characteristics of the FTO/nc-CdS:Sn 5% device measured in the dark and under white light illumination. The device exhibits increased current under illumination, confirming its photoconductive behavior. The I–V curves also demonstrate rectifying behavior, with a rectification ratio of 7.68 within a ± 2 V range, indicating the formation of a Schottky-type junction between the FTO and the nc-CdS:Sn 5% thin film.

For an ideal diode, the relationship between current and voltage can be described by the following equations:

$$I = I_0 \left\{ e^{\frac{q(V-IR_s)}{nk_B T}} - 1 \right\}$$

$$I_0 = AA^* T^2 \exp\left(\frac{-q\Phi_B}{k_B T}\right)$$

Where I_0 is the reverse saturation current, R_s is the series resistance, n is the ideality factor, k_B is Boltzmann's constant, T is the Kelvin temperature, A is the Schottky contact area, A^* is the Richardson's constant, and Φ_B is the barrier height. The barrier height Φ_B is extracted from the diode characteristics according to thermionic emission theory [12,13].

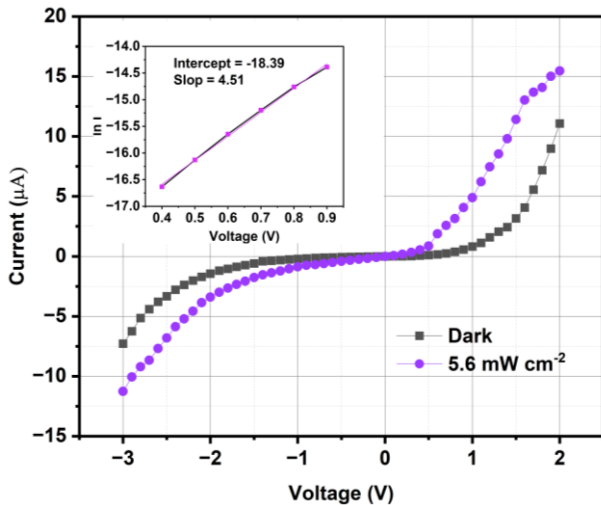


Figure 4. I-V characteristics of FTO/nc-CdS:Sn 5% Schottky diode heterojunctions measured in dark and under white light illumination. The inset shows the $\ln I$ -V plot under forward-bias condition

The series resistance R_s was determined from the slope of the plot of voltage against current in the high forward-bias region, which was approximately 58 k Ω . The ideality factor (n) determined by getting the slope of the natural log of current ($\ln I$) against voltage (V) was determined to be 8.57 which is much higher than the ideal value of 1-2 for a perfect Schottky diode, indicating significant non-ideal properties. These non-ideal properties may be due to interface states, defects in the nanocrystalline film, or series resistance. Nanocrystalline CdS films are known to have a higher trapped state density as well as grain boundaries that recombine charge carriers around grain boundaries to enhance the nonideal behavior of the

Schottky diode such as additional recombination and charge tunneling pathways resulting in an increase in ideality factor as shown in another study of Schottky and heterojunction photodetectors utilizing either the CdS or other wide bandgap materials [14,15]. The series resistance estimated to be roughly 58 k Ω likely contributes to the deviation from ideality via internal voltage drops in the device. These kinds of non-ideality are typical for nanostructured semiconductor devices and do not necessarily rule out high-performance photodetection. Instead, they show the complexity of charge transport mechanisms within doped nanocrystalline materials. High ideality factors reported here are also consistent with similar CdS-based photodetectors, where reported ideality values were in the range of 4 to 10 due to contributions from interfaces and defects [16,17,18]. Improvements in film quality and interface engineering could lead to reductions in effects such as these which may subsequently lower ideality factors and improve device performance.

The reverse saturation current I_0 was calculated to be 1.3×10^{-8} A. Using the standard diode equation, the Schottky barrier height Φ_B was estimated as 0.85 eV. These parameters—specifically, the high barrier height and relatively low leakage current indicate good junction quality and efficient charge transport, confirming the potential of the FTO/nc-CdS:Sn 5% heterojunction device as a photodetector with favorable rectifying and photosensitive characteristics.

3.5. Photodetector Performance

The device exhibited clear photovoltaic behavior, with an open-circuit voltage (V_{oc}) of 0.021 V and a short-circuit current (I_{sc}) of 0.37 μ A. Within the voltage range from 0 to V_{oc} , the current decreased nearly linearly with increasing voltage. The maximum power output (P_{max}) was calculated to be 2.2 nW at a voltage $V_m = 0.015$ V and current $I_m = 0.15$ μ A. Consequently, the fill factor (FF), defined as $FF = P_{max}/(V_{oc}I_{sc})$, was determined to be 28.13% [19].

Photodetector performance was evaluated in terms of sensitivity (S), responsivity (R), and detectivity (D^*). Sensitivity indicates the relative increase in current due to illumination and reflects the photocurrent gain compared to the dark current. Responsivity is the photocurrent generated per unit incident optical power per unit detector area. Detectivity represents the minimum detectable optical signal, with higher values indicating better performance in noisy environments.

These parameters are calculated by the relations:

$$S = \frac{(I_p - I_d)}{I_d}$$

$$R = \frac{(I_p - I_d)}{PA}$$

$$D^* = \frac{RA^{1/2}}{(2qI_d \Delta f)^{1/2}}$$

where I_p is the photocurrent, I_d the dark current, P the incident light intensity, A the effective device area, and q the electronic charge [20]. For the device under white light illumination of 8.5 mW cm^{-2} at zero bias, the sensitivity (S) was approximately 0.025, with a responsivity of $R \approx 1.62 \text{ } \mu\text{A/W}$ and a specific detectivity of about $D^* \approx 1.51 \times 10^6 \text{ Jones}$. While these parameters demonstrate the feasibility of self-powered photodetection, the obtained values are relatively low compared to typical reports for photodetectors, including self-driven devices. Such performance reflects limited photon-to-current conversion efficiency and a reduced signal-to-noise ratio [21].

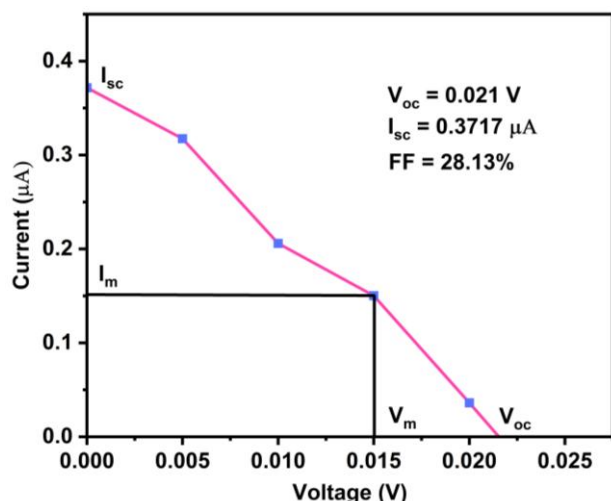


Figure 5. Shows the photovoltaic characteristics of the FTO/nc-CdS:Sn 5% Schottky diode heterojunction under halogen light illumination with an intensity of 5.6 mW/cm^2

3.6. Dynamic Response

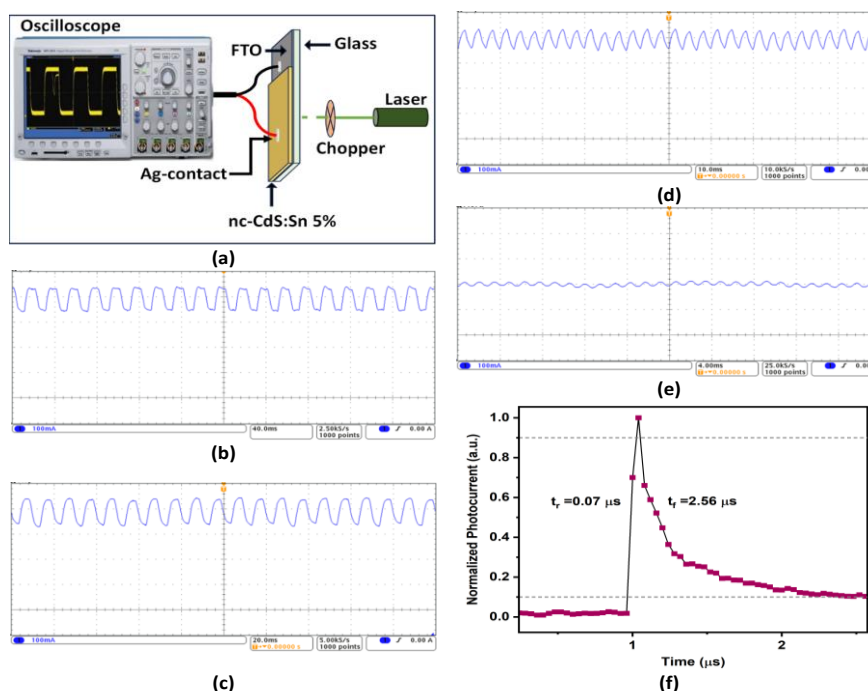


Figure 6. Schematic illustration of our experimental set-up for photoresponse detection. The photoresponse of the FTO/nc-CdS:Sn 5% device under pulsed light at frequencies of (b) 50 Hz, (c) 100 Hz, (d) 300 Hz, and (e) 700 Hz. (f) Rising and falling edges for estimating rise and fall times [22]

The fabricated FTO/nc-CdS:Sn 5% device functions as a high-speed, self-powered visible-light photodetector an essential feature for optical switch and light-wave communication applications. Under zero bias, dynamic response was investigated by modulating incident green laser light (intensity = 1 mW cm^{-2}) with a mechanical chopper, as illustrated in Figure 6(a). The time-dependent photocurrent was recorded using a Digital Phosphor Oscilloscope. Figures 6(b-e) depict the photocurrent response of the self-powered photodetector at switching frequencies of 50 Hz, 100 Hz, 300 Hz, and 700 Hz. The device displayed highly reproducible and stable operation across this frequency range, confirming its effectiveness as a self-powered signal detector operating without external power.

The photodetector's rise time (τ_r) and fall time (τ_f) characterize its temporal response. Rise time, defined as the interval for the photocurrent to increase from 10 % to 90 % of peak current (I_{peak}), and fall time, capturing the drop from 90 % to 10 % of I_{peak} , were measured using a Digital Phosphor Oscilloscope [24]. In this study, an Nd:YAG laser operating at a wavelength of 1064 nm (photon energy $\approx 1.17 \text{ eV}$), with a pulse width of $\sim 10 \text{ ns}$ and a power of $\sim 10 \text{ mJ}$, was employed as the excitation source. Although the photon energy is below the bandgap of the device (2.06 eV), a measurable photoresponse was detected. This response can be attributed to a nonlinear optical process of two-photon absorption, in which two photons of 1.17 eV combine to provide sufficient energy ($\sim 2.34 \text{ eV}$) to excite electrons across the bandgap, thereby generating electron-hole pairs. The rise and fall times were estimated to be $0.07 \text{ } \mu\text{s}$ and $2.56 \text{ } \mu\text{s}$, respectively, confirming ultrafast response capabilities suitable for advanced optoelectronic applications.

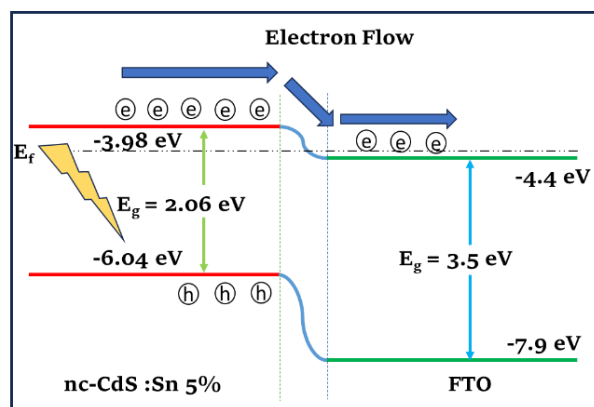


Figure 7. Energy band diagram of FTO/nc-CdS:Sn 5% device

The working mechanism of the fabricated photodetector can be understood from the energy band diagram presented in Figure 7. The nc-CdS:Sn 5% thin film exhibits a band gap of 2.06 eV, while the band positions of FTO are taken from literature reports [25]. Upon contact of FTO with nc-CdS:Sn 5%, charge transfer occurs until their Fermi levels attain equilibrium, resulting in the formation of a built-in electric field within the depletion region at the heterointerface. Owing to its high optical transparency in the visible region, the FTO layer permits incident photons to be absorbed efficiently by the nc-CdS:Sn 5% film. When photons with energy $E \geq E_g$ are absorbed, electron-hole pairs are generated in the nc-CdS:Sn layer and subsequently separated by the built-in potential. The photogenerated electrons drift toward the FTO, while the holes remain in the nc-CdS:Sn region, thus suppressing recombination losses. This carrier separation induces an open-circuit voltage across the junction. Under short-circuit conditions, the transport of electrons and holes in opposite directions through the external circuit gives rise to a measurable short-circuit current. Consequently, the device generates a photocurrent solely from the internal field, enabling self-powered operation without the necessity of external bias [26].

4. Conclusion

In conclusion, the FTO/nanocrystalline CdS:Sn 5% heterojunction photodetector fabricated in this study exhibited promising performance for self-sustained, rapid-response visible light detection. The device consistently showed good rectification behavior, pronounced photovoltaic effects, and fast response times. Its ability to operate without an external power source positions it as a strong candidate for diverse optoelectronic applications, such as high-speed optical switching and advanced light-wave communication systems. Future work aimed at optimizing the fabrication process and device architecture is expected to further enhance performance and broaden the applicability of this heterojunction for next-generation visible photodetectors.

Statement of Competing Interests

The authors have no competing interests.

List of Abbreviations

nc: Nanocrystalline
 CdS: Cadmium Sulfide
 Ag: Silver
 Sn: Tin
 FTO: Fluorine-doped Tin Oxide
 SEM: Scanning Electron Microscopy
 XRD: X-Ray Diffraction
 R_s : Series Resistance
 I_0 : Saturation Current
 Φ_B : Barrier Height
 V_{oc} : Open-circuit Voltage
 I_{sc} : Short-circuit Current
 FF: Fill Factor
 R: Responsivity
 S: Sensitivity
 D^* : Detectivity
 t_r : Rise Time
 t_f : Fall Time

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