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Simulation & Fabrication of Tungsten Trioxide based photodetectors for opto-electronic applications

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Abstract

This work focuses on the design, simulation, and fabrication of a tungsten trioxide (WO_3)-based thin film photodetector for ultraviolet (UV) optoelectronic applications. WO_3 is a promising metal oxide semiconductor due to its wide bandgap, excellent chemical stability, and strong UV absorption characteristics, making it suitable for environmental monitoring, flame detection, and optical sensing applications. The work initially involves modeling and simulation of the WO_3 photodetector using COMSOL Multiphysics to analyze charge transport, optical absorption, and electrical characteristics under UV illumination. Key performance parameters such as responsivity, current–voltage (I–V) behavior, and carrier dynamics are evaluated to optimize device performance. Experimentally, the device fabrication is carried out using a silicon (Si) substrate coated with silicon dioxide (SiO_2), providing electrical insulation and structural stability. A WO_3 thin film is being deposited over the SiO_2 layer to act as the active sensing material. The next phase includes deposition of silver (Ag) electrodes to form efficient metal-semiconductor contacts, followed by ultraviolet (UV) characterization to evaluate photodetection performance, including photocurrent response and sensitivity under UV illumination. The proposed structure aims to achieve a low-cost, CMOS-compatible, and high-sensitivity UV photodetector. The integration of simulation and experimental validation establishes a scalable approach for developing efficient WO_3-based optoelectronic devices suitable for next-generation sensing applications.

Keywords: *Index Terms—Tungsten, Silicon, Silver, Ultra-Violet.*

1. Introduction

Thin films are ultrathin layers of materials with thickness ranging from nanometres to a few micrometres. When deposited on substrates, these films exhibit unique physical, chemical, electrical, and optical characteristics distinct from their bulk counterparts due to surface effects, reduced dimensionality, and quantum confinement. Thin-film technologies enable precise tailoring of optical absorption, conductivity, surface roughness, and crystallinity, making them indispensable across electronics, sensors, photodetectors, solar cells, and flexible devices. Modern fabrication techniques such as Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), Sol-Gel processing, Sputtering, and Atomic Layer Deposition (ALD) allow engineers to achieve accurate control over film properties. These ultrathin structures are integral to memory devices, microelectronic circuits, interference coatings, energy storage systems, and biomedical devices. Their exceptional sensitivity and fast response make thin films particularly suitable for UV photodetectors, where rapid photon-to-electron conversion is essential. Photodetectors, which convert incident photons into electrical signals, form the backbone of optoelectronic systems used in biomedical imaging, environmental monitoring, industrial automation, optical communications, flame detection, radiation sensing, and digital imaging. Thin-film photodetectors—especially those based on metal oxide semiconductors such as WO_3—offer compactness, energy efficiency, low fabrication cost, and compatibility with flexible substrates. WO_3

(Tungsten Trioxide) is a wide-bandgap n-type semiconductor exhibiting strong UV absorption, oxygen vacancy–based conductivity, photochromism, and excellent thermal and chemical stability. These properties make WO_3 thin films highly suitable for UV sensing applications. Through COMSOL Multiphysics simulation and design optimization, this project aims to model, analyze, and evaluate WO_3 thin-film UV photodetectors to understand charge carrier behaviour, optical absorption, and electric field distribution under illumination [1] .

2. Overview

Thin films have become a core technology in microelectronics and photonics. Their use spans

- Sensors: gas sensors, UV sensors, biomedical sensors
- Electronics: ICs, MOSFET gates, memory devices
- Optics: anti-reflective coatings, interference filters
- Energy: solar cells, supercapacitors, photoelectrochemical devices
- Nanotechnology: flexible electronics, OLEDs, displays [2]

When thinned down to nanometre scale, quantum confinement alters their band structures, increasing sensitivity to photons and external stimuli. This makes them perfect for photodetectors detecting specific wavelengths (UV, IR, visible). The history of thin films dates back to ancient Egypt where mercury-assisted gold coating was used on jewelry. Modern thin-film technology accelerated after the invention of vacuum deposition (1900–1950), followed by sputtering, CVD, PLD, and ALD methods. Today, thin films are central to optoelectronics, sensors, electrochromic devices, and UV photodetectors. WO_3 thin-film photodetectors operate based on photon absorption → electron excitation → charge separation → electrical signal generation. Their ability to detect UV wavelengths with high sensitivity is due to their bandgap and oxygen-vacancy–enhanced conductivity. Thin-film WO_3 devices also offer excellent stability, low fabrication cost, and compatibility with silicon technology, making them suitable for large-area sensor integration. Their tunable morphology—nanorods, nanoflakes, or porous films—further enhances surface reactivity and photon absorption. As a result, WO_3-based UV photodetectors are emerging as strong candidates for next-generation environmental monitoring and wearable sensing platforms. With continued advancements in deposition techniques and defect-engineering, these devices can achieve even higher responsivity and faster response times, strengthening their role in modern optoelectronic systems. The Fig. 1 gives the tungsten trioxide thin film photodetector structure.

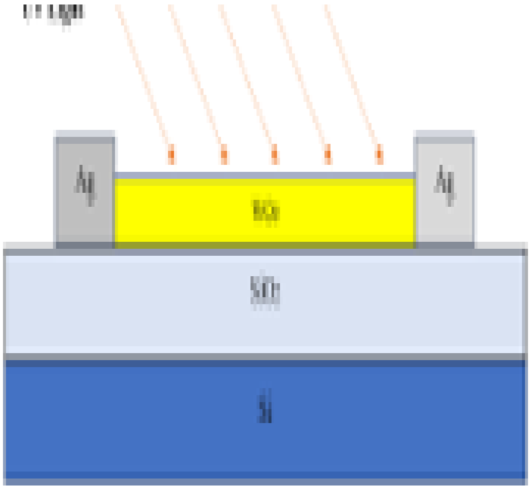

Figure 1 Tungsten Trioxide Thin Film Photodetector Structure

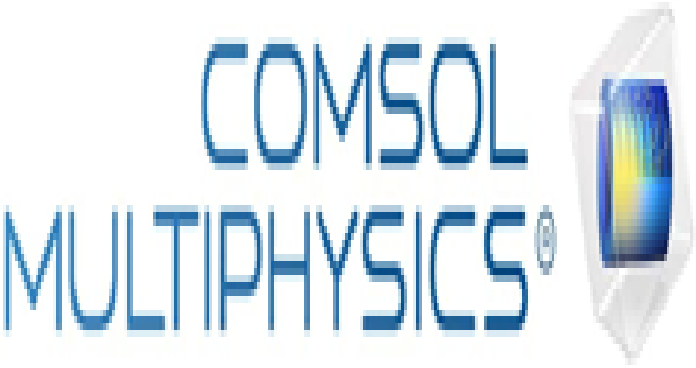

Figure 2 COMSOL Multiphysics Tool

3. Problem Statement

Ultraviolet (UV) photodetectors play a significant role in areas such as environmental monitoring, flame detection, space research, and military surveillance. Although several semiconductor materials—including Si-based, GaN, and ZnO—are widely employed, they still face notable performance limitations. Conventional UV photodetectors often exhibit high dark current, slow temporal response, limited wavelength selectivity, high fabrication costs, and inadequate stability when exposed to harsh environments. These drawbacks hinder their effectiveness, especially in long-term outdoor and industrial applications. In response to these limitations, tungsten trioxide (WO_3) thin films have emerged as a highly promising material for UV photodetection. WO_3 exhibits a wide bandgap ranging from 2.4 to 3.2 eV, enabling strong UV absorption and enhanced photon-to-electron conversion efficiency. Furthermore, its oxygen-vacancy–mediated conductivity plays a vital role in boosting the photodetector's sensitivity. WO_3-based fabrication processes are comparatively cost-effective and demonstrate excellent environmental and chemical stability, making the material suitable for rugged conditions and sustainable device development. Despite these advantages, further optimization is still necessary to fully exploit the potential of WO_3 thin-film photodetectors. Critical design factors—such as film morphology, thickness uniformity, electrode spacing, and controlled regulation of oxygen vacancy concentration directly influence device performance. Additionally, improving both response and recovery times remains a key challenge for practical real-time applications. Therefore, the present project is focused on analyzing, designing, and simulating WO_3 thin-film UV photodetectors to overcome the identified limitations, thereby enhancing detection efficiency, stability, and overall device reliability.

4. Objective

The proposed project focuses on the design and simulation of a WO_3 thin-film UV photodetector using COMSOL Multiphysics with the goal of enhancing device performance while maintaining cost-effectiveness and environmental reliability. The study involves a comprehensive evaluation of the photodetector's characteristics, including responsivity, quantum efficiency, I–V behaviour, and transient response under varying UV illumination conditions. Additionally, the optical behaviour of WO_3 will be examined using wave-optics-based simulation to understand absorption dynamics and carrier generation mechanisms. A key aspect of the project is the optimization of structural and material parameters to improve sensitivity and operational speed. This includes analyzing the effects of film thickness, electrode geometry, and oxygen-vacancy concentration on photocurrent generation and signal stability. The final objective is to establish a robust modelling framework that can be used to develop a cost-efficient and reliable WO_3 thin-film photodetector suitable for environmental sensing and broader optoelectronic applications [3].

- To simulate and evaluate the electrical and optical performance of a WO_3 thin-film UV photodetector using COMSOL Multiphysics.
- To investigate the effects of structural and material parameters—including film thickness and electrode geometry—on sensitivity and device response.
- To develop an optimized and practical model for a cost-effective WO_3-based UV photodetector suitable for environmental and optoelectronic applications [4].

5. Problem Analysis & Design - Requirement Analysis - Functional Requirements

The primary functional requirement of the proposed WO_3 thin-film photodetector is its ability to accurately detect ultraviolet (UV) radiation, particularly around the wavelength of 365 nm, which is widely used in environmental monitoring and flame detection applications. The device must be capable of generating a measurable photocurrent when exposed to UV illumination, ensuring that the generated signal is sufficiently strong and distinguishable from the dark current. This performance is crucial for achieving high sensitivity and reliable UV detection. Furthermore, the photodetector is required to deliver a stable and linear output response over repeated measurement cycles, allowing consistent performance under varying UV intensities. The device must also exhibit fast response and recovery times when subjected to ON/OFF UV cycles to support real-time sensing and rapid signal processing. Meeting these requirements is essential for the development of a practical, high-performance UV sensing system suitable for modern optoelectronic and environmental applications [6].

6. Problem Analysis & Design - Requirement Analysis - Non-Functional Requirements

The non-functional requirements of the proposed WO_3 thin-film UV photodetector emphasize performance attributes that ensure its reliability and suitability for long-term practical deployment. One of the key expectations is that the device should exhibit a response time of less than 1 ms, enabling rapid detection and real-time signal processing. Additionally, the dark current must remain below 1 µA to maintain a high signal-to-noise ratio and to ensure that the generated photocurrent is not masked by background electrical noise. Low intrinsic noise is critical to achieving accurate and precise readings even under low-intensity UV exposure. Beyond electrical performance, the photodetector is expected to deliver long operational stability and low power consumption to function efficiently in continuous or remote monitoring environments. Stability over extended periods reduces the need for recalibration or frequent maintenance, making the device suitable for harsh ambient conditions and outdoor applications. Low power consumption supports integration into battery-operated, portable, or IoT-based platforms. Collectively, these non-functional requirements ensure that the final design is not only sensitive and fast, but also energy-efficient, robust, and suitable for modern optoelectronic systems.

7. Chemicals And Hardware Required

The materials required are - WO_3 nano powder, SiO_2 substrate, Ag metal, UV LED (365 nm), Source meter. In this work, WO_3 nano powder is used to form the main sensing layer of the UV photodetector. This thin film is deposited on a SiO_2 substrate, which provides a smooth and stable surface for proper film formation and prevents electrical interference from the base material. After the WO_3 thin film is formed, silver (Ag) is added to create the electrodes. These metal contacts help collect charge carriers efficiently and allow the device to be connected to external measurement equipment. For testing and performance evaluation, a UV LED with a wavelength of 365 nm is used to provide controlled ultraviolet illumination. This makes it possible to observe how the detector responds when the UV light is turned ON and OFF. A precision source meter is then used to record the current–voltage characteristics and monitor the photocurrent changes in real time. Together, these components allow the fabrication and complete testing of the proposed WO_3-based UV photodetector [5].

8. Software Requirements

Simulation software COMSOL Multiphysics 5.6 as shown in the Fig. 2 allows users to study and simulate a wide range of physical processes in a unified environment. These processes include chemical reactions, heat transport, fluid dynamics, structural mechanics, and electromagnetics. When investigating complicated real-world systems with interrelated physical consequences, this unified method shines. Modelling procedures are made easier by the software's user-friendly graphical user interface. You may build geometry, give materials qualities, describe the laws of physics, establish boundary conditions, and configure solvers. From simple single-physics applications to intricate multi-physics scenarios, this modular framework enables the methodical creation and adaptation of models An indispensable tool for both academic studies and industrial applications, COMSOL Multiphysics offers a user-friendly graphical user interface (GUI), scripting capabilities through the COMSOL Application Builder, and the ability to integrate with external programming environments like MATLAB. Users can customize simulations through parameter sweeps and other means[7].

9. Constraints

During the fabrication of the WO_3 thin-film UV photodetector, achieving proper film uniformity is a critical consideration, as any inconsistency in thickness or surface morphology can influence UV absorption efficiency and carrier transport. Likewise, the photodetector must be designed to operate within safe UV intensity limits to prevent material degradation and saturation effects that could distort the device response or shorten its operational lifetime. In addition to technical factors, practical constraints also influence the development process. The budget available for deposition tools determines the selection of fabrication techniques and directly affects scalability and cost-effectiveness. Furthermore, the thermal stability of the chosen substrate must be ensured, as it needs to withstand the deposition temperature and any heat generated during device operation without compromising structural or electrical integrity. The flow-chart for the system that is to be designed is shown in the Fig. 3

10. Design System – Flowchart

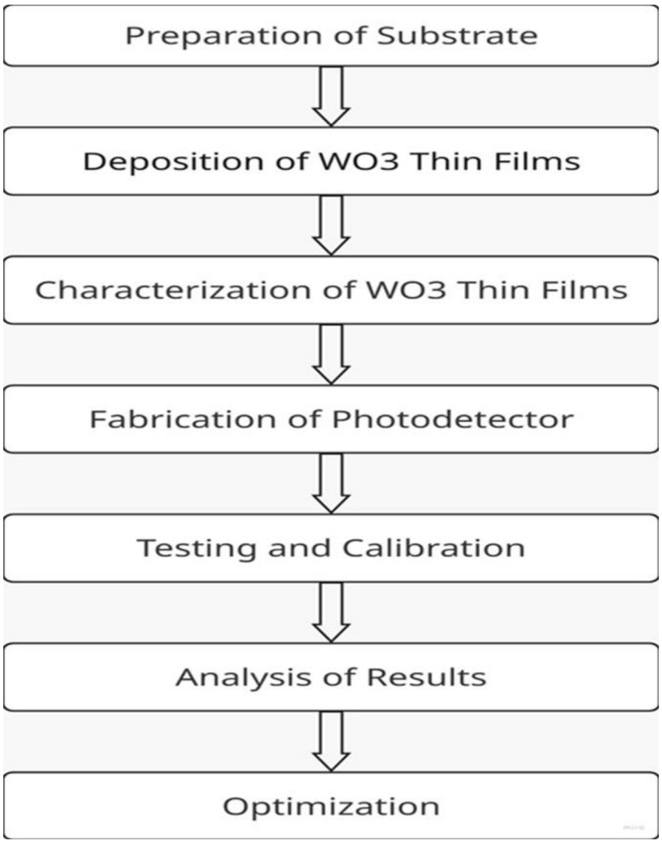

Figure 3 **Flow Chart**

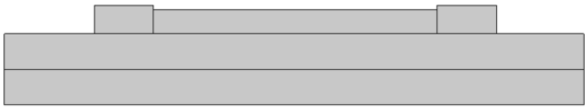

Figure 4 **Geometry of WO3 device structure**

11. Design Of Device Structure

Photodetectors based on tungsten trioxide (WO3) thin-films use silver electrodes as electrical contacts and a WO3 semiconductor layer on top of a silicon dioxide substrate. Because of its high photoconductivity and significant absorption, WO3 an n-type semiconductor with a broad bandgap is perfect for ultraviolet light detection. The geometry of the of WO3 device Structure is shown in the Fig. 4. The SiO2 foundation offers mechanical support and electrical insulation, creating a solid platform for the deposition of WO3 thin-films. The WO3 surface is equipped with silver electrodes, which allow for effective charge collection via ohmic connections with low resistance. The photogenerated carriers are extracted by this metal-semiconductor-metal (MSM) combination, which, when exposed to ultraviolet light, produces detectable photocurrents. Charge carrier density and photo-response are both improved by oxygen vacancies in WO3 films. Optimal UV absorption and carrier transport are achieved by optimizing the film thickness. An efficient UV photodetector may be achieved using this structure's combination of WO3 sensitivity, SiO2 substrate, and Ag (Silver) electrodes [8].

12. Design Calculations - Responsivity (R)

The efficiency with which an electrical gadget transforms light into current is called its responsiveness. It is more precisely described as the ratio of the power of the incident optical signal to the electrical output signal (usually photocurrent) produced by the device. When the output is current, the units of response are amperes per watt (A/W). When the output is voltage, the units of response are volts per watt (V/W). This metric measures how well photodetectors convert light into electricity and is sensitive to parameters like incoming light wavelength and device material characteristics. Essential for sensitive photodetection applications, a high responsivity gadget delivers a strong electrical signal for a given optical input. One unit of input optical power produces a certain amount of photocurrent as $R= I_{ph}/P_0$, where R is the responsivity (A/W), I_ph is photon Current, P_o is illumination power over the effective UV detection area.

13. External Quantum Efficiency (Eqe)

The EQE of a photodetector, solar cell, or other comparable optoelectronic device is defined as the ratio of the number of photons that reach the active surface to the number of charge carriers that are effectively collected by the electrodes. It is a metric for the efficiency with which entering photons are transformed into electrical carriers. A greater EQE reflects the photon absorption capabilities of the material as well as its carrier separation, transport, and collecting processes, and a bigger proportion of absorbed photons contributing to photocurrent [9].

$$\eta = R * \frac{hc}{\lambda} * 100\%$$

where η is EQE, R is the responsivity (A/W), h is Planck's constant, c is the speed of light, q is the elementary charge, lambda λ is the incident light wavelength.

14. Methodology

The basic process of photoexcitation is what allows a photodetector composed of a thin layer of tungsten trioxide (WO3) to function. Photons that strike the film with an energy level exceeding the bandgap of WO generate holes by promoting electrons from the valence band to the conduction band. The separation and movement of these electron-hole pairs throughout the device result in a detectable photocurrent, as they serve as mobile charge carriers. This device operates as a light sensor, with the magnitude of the photocurrent being directly proportional to the amount of incident radiation. The extensive bandgap of WO3 renders it particularly responsive to the ultraviolet (UV) segment of the electromagnetic spectrum, making it an excellent candidate for this application. Its selective response to ultraviolet light makes it suitable for biological sensing, environmental monitoring, and flame detection. WO3's fascinating photochromic and electrochromic properties enable its use in reconfigurable and multifunctional devices, enhancing its versatility. As a desirable material for applications such as UV and visible light photodetectors and photocatalysis, WO3's optical response and photocatalytic efficiency are derived from its photoexcitation. The metal oxide semiconductor WO3 can absorb both ultraviolet and visible light due to its moderate band gap, which ranges from approximately 2.4 to 2.8 eV. In WO3, the initial photoexcited state is highly transient, occasionally lasting less than 500 femtoseconds. Intermediate states may develop as the excitation advances, resulting in more stable charge carriers and facilitating improved charge separation. Gaining a deeper knowledge of transition metal oxide semiconductors and designing more efficient WO3-based optoelectronic and photocatalytic devices are both facilitated by investigating WO3's photoexcitation at ultrafast timeframes. Furthermore, WO thin-films have great potential as a bridge between basic sensing and practical and sophisticated optoelectronic applications; this is because they are compatible with flexible substrates, making them ideal candidates for the next generation of lightweight and bendable photodetectors [10].

15. Geometry Creation

A UV photodetector based on WO3 thin film geometry designed in COMSOL Multiphysics requires an accurate model of the real device to be built in the virtual one. An even layer of silicon dioxide, shown here as a rectangular slab or block of the exact same size as the actual device, serves as the foundation. To accurately capture optical absorption and charge transport events, the WO3 thin film is represented as a thin layer with a thickness that corresponds to experimental or design criteria. Electrodes made of silver (Ag) are fabricated by depositing metallic domains or surfaces over a WO3 layer, thereby simulating the real metal arrangement. For the simulation results to be significant, the geometry has to be dimensionally precise. Layer thickness, length, and breadth may be precisely controlled in COMSOL Multiphysics.

16. Material Property Selection

A few of the material features of WO3 thin film are as follows: electrical conductivity (both in the dark and when exposed to UV light), bandgap, and relative permittivity. Determine the appropriate electrical conductivity of silver electrode materials. Table I summarizes the material parameters of WO3, Table II of SiO2, and Table III of Si, which were used in this investigation shown in Table 1 and 2.

Table 1. Material Properties Of Wo3

Parameter	Value
Relative permittivity	11.7
Electron affinity	4.05V
Band-gap	1.42V
Effective density of states, conduction band	2.8*10^25 m^{-3}
Effective density of states, valence band	1.04*10^25 m^{-3}
Mobility of electrons	0.05m^2/(V·s)
Mobility of holes	0.145m^2/(V·s)

Table 2 Material Properties Of Sio2

Parameter	Value
Relative permittivity	9
Electron affinity	4.07V
Band-gap	8.9V
Effective density of states, conduction band	3*10^24 m^{-3}
Effective density of states, valence band	1*10^25 m^{-3}
Mobility of electrons	0.015m^2/(V·s)
Mobility of holes	0.003m^2/(V·s)

17. Select And Define Physics Interfaces

- To model the transfer of charges, one may use the Semiconductor Module in COMSOL. Incorporate Electrostatics
- The field of electron-hole dynamics known as drift-diffusion physics.
- To mimic the effects of ultraviolet light absorption and photogeneration of carriers, use the Wave Optics Module or the mechanics of electromagnetic waves into your model.
- As a function of the wavelength and intensity of incoming UV light, determine the rates of electron-hole pair production.

Using COMSOL's physics interfaces, the UV photodetector is precisely simulated. By recording the tungsten trioxide thin film's charge transport phenomena, the Semiconductor Module computes the mobilities, concentrations, and recombination processes of carriers. To provide a comprehensive description of electron-hole dynamics, the model is connected with Drift-Diffusion physics and Electrostatics. The integration of the Wave Optics Module or the Electromagnetic Waves interface represents the interaction between the semiconductor and UV radiation. This paves the way for modelling the thin film's optical energy distribution and light absorption at targeted ultraviolet (UV) wavelengths. The rate at which electron-hole pairs are generated from absorbed photon energy is dependent on the wavelength and intensity of the input ultraviolet light. By integrating these interfaces, one can reliably forecast the device's performance by describing optical excitation and electrical response.

18. Boundary Conditions And Initial Conditions

- Using electrical contact boundaries, connect two electrodes: one that is biassed (e.g., grounded or has a voltage applied) and the other that is grounded or left floating.
- The direction, intensity, and wavelength of the UV light source are defined as the border and domain source terms.

In order to mimic the UV photodetector realistically, the simulation setup specifies boundary and beginning conditions. Metal contacts at the device's electrodes provide electrical boundaries, allowing for the modelling of current flow, carrier injection, and collection. Interfaces between semiconductors use surface recombination parameters to measure the probability of electron-hole pairs recombining at boundaries and defects in the material. The optical excitation process requires precise UV illumination parameters, such as the direction of propagation, the intensity of the light, and the wavelength. An exact relationship between external excitation, internal charge dynamics, and quantifiable device response can only be achieved with precise boundary and starting condition definitions.

19. Mesh The Geometry

- Making a mesh that works for wave optics and semiconductor physics, and using a finer mesh to provide accurate results around electrodes, thin film areas, and interfaces.
- Verifying that the mesh components are sufficiently tiny in relation to the film's thickness and the UV wavelength.

Numerical precision in the fields of linked semiconductor and wave optics physics is ensured by discretizing the geometry of the UV photodetector through the creation of a mesh. Charge transfer and optical absorption serve as examples of nanoscale processes that must be accurately represented by the mesh. The initial structure is a physics-controlled mesh, followed by enhancements in critical areas such as semiconductor interfaces, regions near electrodes, and thin film layers, where optical fields, significant spatial gradients in potential, and carrier concentration are known to exist shown in Figure 5.

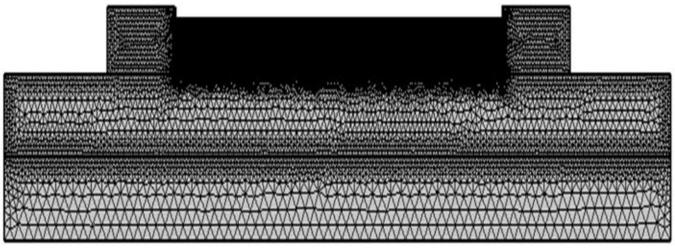

Figure 5 Meshing of WO3 device

The Fig 5 gives the meshing of WO_3 device. Mesh components must be smaller than both the thickness of the film and the wavelength to accurately capture the interaction between the device and the film when exposed to UV light. Consequently, the calculations for photogeneration efficiency, wave propagation, and absorption profiles are assured to be accurate. To optimize the mesh while minimizing resource consumption, it is essential to find a balance between computational efficiency and precision. When the mesh is well-designed, convergence is reliable, and the insights gained into device performance are substantial shown in Figure 6.

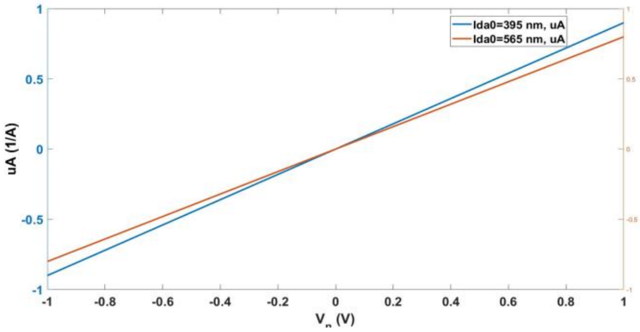

Figure 6. Current Vs Voltage

20. Implementation And Results - Iv Characteristics

The typical current-voltage (I-V) behaviour of a WO_3 photodetector is defined by its response to light conditions. In the absence of light, a minimal current is observed due to the low level of intrinsic carrier generation. When exposed to UV illumination, a significant photocurrent is generated as the creation of electron-hole pairs enhances the material's conductivity. The model is given by I_ph∝ P^θ . The power of the incoming UV light is represented by P, and the parameter θ governs the photocurrent's response to the corresponding UV light intensity. It is common for the photocurrent to increase linearly with the bias voltage until it reaches saturation, which is an indicator of efficient carrier collection. This graph illustrates the current-voltage (I-V) characteristics of a tungsten trioxide (WO_3) thin-film UV photodetector. It compares the device's performance under two distinct illumination wavelengths, 565 nm (visible light) (Red line) and 395 nm (UV light) (Blue line), against its baseline dark current.

21. Key Observations

The applied voltage (Vn) is plotted on the x-axis, spanning from □1 V to +1 V. The y-axis represents the current generated by the device, measured in microamperes (µA). The graph displays two distinct lines corresponding to illumination at 565 nm and 395 nm, which are compared against the implied dark condition where no light is present. The Fig 5 gives the sim result of the current Vs voltage.

22. Interpretation

Both curves display a nearly linear response, which signifies Ohmic behaviour where the current varies linearly with the applied voltage, a characteristic feature of photoconductive devices. For any given voltage, the current generated under 395 nm (UV) illumination is marginally greater than under 565 nm (visible light), indicating more effective photogeneration of charge carriers at higher photon energies.

Conclusion & Scope For Future Work

In this work, the performance of Tungsten Trioxide (WO3) thin film photodetectors for ultraviolet (UV) light detection was systematically studied through COMSOL Multiphysics simulations. By combining semiconductor physics, optical absorption, and electric field distribution into a single framework, the model allowed for a detailed investigation of the device's photo-response under UV illumination. Results confirm WO_3 thin-films hold major potential as cost-effective, sensitive, durable materials for ultraviolet detection. Study demonstrates optimization of device parameters film thickness, electrode configuration, doping concentration, applied bias can greatly boost photocurrent generation, responsivity. Findings emphasize critical role of computational approaches; these provide efficient means to evaluate performance improvements before experimental fabrication. Here, Multiphysics modelling acts not only as predictive framework but also as diagnostic tool guiding design of high-performance UV photodetectors. Present work rests mostly on idealized material properties. In real situations, surface roughness, grain boundaries, oxygen vacancies, electrode-film interfaces exert large influence on detector performance. Looking ahead, several paths for advancement appear obvious. Development of innovative device architectures heterojunction-based photodetectors, nanostructured WO_3 films offers potential for further improvements in sensitivity, response speed. Doping engineering, defect control present opportunities to tailor bandgap properties, carrier lifetimes, boost efficiency. Ultimately, experimental fabrication, validation of computationally optimized designs will prove indispensable in turning theoretical insights into deployable, high-performance UV photodetectors. This project establishes WO3 thin-films as highly attractive candidates for next-generation UV photodetectors, combining sensitivity, robustness, and cost-effectiveness. The results not only confirm their potential in areas like environmental monitoring, flame detection, and aerospace applications but also lay a strong foundation for future research that integrates simulation, material engineering, and practical validation into a unified development cycle.

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