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Impact of Doping with MWCNT on Electrical Properties of Bi_2O_3 Thin Film Photodetectors

The pulsed laser deposition technique has been used to prepare thin films of pure Bi_2O_3 and doped with multi-wall carbon nanotube (MWCNT) with weight ratios of 0.5, 1, and 2 wt% on glass substrates. Photodetectors were fabricated from these structures and the electrical characteristics were studied under dark and light using 632nm laser. Also, photoconductivity was studied using a tunable monochromatic light source in the wavelength range of 200–800nm. The performance of the fabricated photodetectors was evaluated throughout the spectral responsivity, quantum efficiency, noise equivalent power, and specific detectivity. It was concluded that adding MWCNT to the Bi_2O_3 films led to improving the properties of the photodetector.

Keywords: MWCNTs; Nanocomposites; Photodetectors; Photoresponse; Sensitivity
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1. Introduction

Nanoparticles are structures ranging in size from 1 to 100 nm. They are among the most promising elements of a new era in science and technology. Numerous industries, including biomedical applications, electronics and computers, photocells, and photodetectors, are seeing rapid growth in the market for nanoparticle-based products [1,2]. Bismuth trioxide (Bi_2O_3) is one of the important metal oxide nanoparticles that have gained attention recently due to their various and distinctive physicochemical characteristics [3,4]. So, many researchers have been interested in nanostructured Bi_2O_3 thin films because of their characteristic parameters, such as availability and easy production, photoconductivity, refractive index, transparency, and mechanical strength [5,6]. Also, Bi_2O_3 has a wide energy gap (1.73-3.98 eV), which makes it a protruding filter for use in solar cells [2,7]. So, when this material is exposed to a photon beam of the same or greater energy, it produces electron–hole pairs, producing free radicals that undergo secondary reactions [8].

The properties of Bi_2O_3 films can be improved to extend the range of their applications to include battery electrodes, field emitters, nanoelectronics, and nanoscale sensors, throughout adding other functional materials such as carbon nanotubes (CNTs). Lately, multi-walled carbon nanotubes (MWCNTs) have garnered a lot of global attention because of their exceptional mechanical qualities as well as their electrical and thermal conductivities. This makes them a promising option for a number of applications, such as field emission display [9], photocatalysis, photovoltaic devices, and dye-sensitized solar cells [10-12]. The electrical characteristics of this material are dependent on the graphene arrangement. They may be either semiconductors or superior conductors with conductivity 1000 times higher than that of copper [13]. In addition, the thermal conductivity can reach 3500 W/m.K of a single nanotube [14,15]. Also, they are stronger than steel, lighter than aluminum, and more conductive than copper [16,17].

2. Experimental Part

In this work, pulsed-laser deposition technique was used to prepare MWCNTs-doped Bi_2O_3 thin films. It is considered one of the best techniques used in preparing thin films because it gives the largest number of films in record time by controlling laser energy and the number of pulses. For preparing thin films, Bi_2O_3 nanopowder was used as a target material with a weight of 2 g to obtain pure Bi_2O_3 thin films, and MWCNTs were used as a dopant for preparing MWCNTs-doped Bi_2O_3 thin films at concentrations of 0.5, 1, and 2 wt.%. The samples were pressed using a hydraulic compressor for 10 min to obtain circular discs (target). An Nd:YAG laser beam has been used with a wavelength of 1064 nm, frequency of 6 Hz, number of pulses 300 pulses, and laser energy of 400 mJ at the angle of 45° inside the deposition chamber under vacuum pressure of 10^{-3} Torr. The glass substrates were placed on a holder in front of the target surface. After that, the films were annealed at 400°C for one hour. After preparing MWCNTs-doped Bi_2O_3 thin films on glass substrates and studying their properties to determine the optimum ones [18], Ohmic contacts are made on both the prepared film and glass substrate by depositing thick Al films using certain masks to investigate the photoresponse behavior of the photodetector using a 632nm laser light source.

3. Results and Discussion

Figure (1) shows the current-voltage characteristics (I-V) for the devices made from Bi_2O_3 and MWCNTs-

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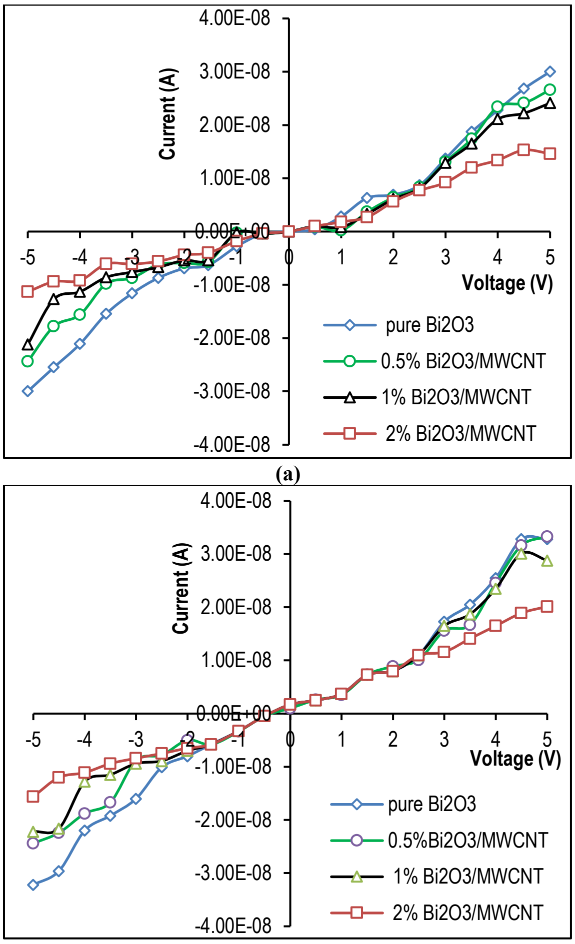
doped Bi_2O_3 thin films at forward and reverse biasing conditions.



(a)

(b)

Fig. (1) I-V characteristics for pure Bi_2O_3 and MWCNTs-doped Bi_2O_3 thin films in (a) dark and (b) light

It is obvious from the results, in the forward bias, the current show an exponential behavior with increasing applied voltage, as it is generated due to the flow of majority carriers and voltage inject majority carriers, which leads to a decrease in the width of the depletion layer. While in case of applying reverse bias, we notice that the increase of current is very slight. This behavior is one of the most important features of semiconductor heterojunctions where the applied voltage causes the depletion region's width to increase, separating the electron-hole pairs and subsequently increasing the photocurrent. Moreover, an increase in incident light intensity raises photocurrent because more photons are incident, which in turn raises the number of photogenerated charge carriers that flow in the depletion and diffusion carriers region [19].

The results also clearly show that when the applied voltage is increased and adding the MWCNTs, smaller current is produced for MWCNTs-doped Bi_2O_3 films than pure Bi_2O_3 films [20]. The optical transparency and electrical conductivity of MWCNTs-doped films are affected by their distribution of MWCNTs because there are more routes for the electrons to pass through, and the resistance decreases as the concentration of MWCNTs increases. Thus, the current decreased as a result of MWCNTs aggregation as it is known that the nearby MWCNTs improves electrical conductivity quality through the quantum tunneling effect. It drops exponentially as the separation between the MWCNTs increases [21,22].

Two critical characteristics for determining a photodetectors' response speed are the rise and fall times. They were calculated for the photodetectors fabricated from pure Bi_2O_3 and MWCNTs-doped Bi_2O_3 thin films using the Origin Program (2021), as shown in Fig. (2). From Fig. (2a), we notice the rise time is smaller than the fall time, which indicates that the detector sensitivity was fast for the photodetector fabricated from pure Bi_2O_3 thin films when compared to the MWCNTs-doped Bi_2O_3 thin film photodetectors, where MWCNTs increase the photoconductivity produced by incident light on MWCNTs-doped Bi_2O_3 thin film and generate an electron-hole pair [23]. The decrease in responsivity is due to concentrations, position, and the creation of a connected structure of MWCNTs [24].

A tunable monochromatic light source in the wavelength range of 200–800 nm was used to determine the optimum photoconductivity behavior. By plotting the incident wavelength against the average $<R/R_0>$, the best active wavelength was identified, where R and R_0 denote the resistance of the samples in light and dark, respectively. As shown in Fig. (3), it shows that films achieved the lowest value of $<R/R_0>$ in the visible region at around 500 nm. Also, it shows an increase in the $<R/R_0>$ value when MWCNTs are added to Bi_2O_3 thin films and this result could be the result of light absorption, as previously mentioned, by which MWCNTs increase the photoconductivity due to incident light [23,25].

The most important parameters required to evaluate the photodetector's performance are spectra responsivity (R), specific detectivity (D^*), noise equivalent power (NEP) and quantum efficiency (η). The spectral responsivity represents the photocurrent produced per unit area per unit illumination intensity and is determined by the following relation:

$$R_\lambda = I_{pc}/AP_{in} \quad (1)$$

The specific detectivity (D^*) represents a minimum power that can be detected by the photodetectors. It is calculated by the following relation:

$$D^* = RA^{1/2}/2eI_{dc} \quad (2)$$

The noise equivalent power (NEP) is a way to quantify the noise in the detector and determined by the following relation [26]:

$$NEP = I_n/R_\lambda \quad (3)$$

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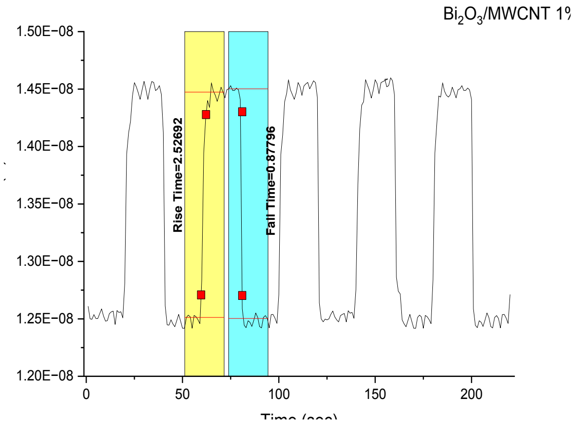
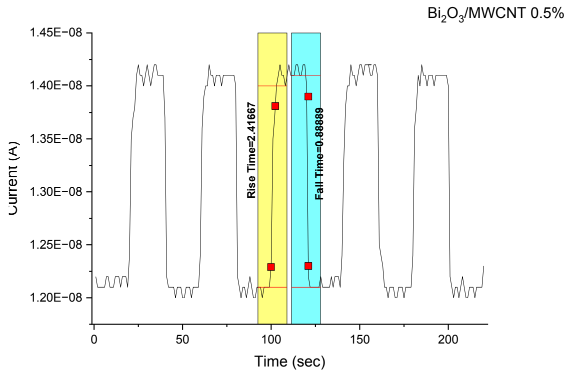


(a)



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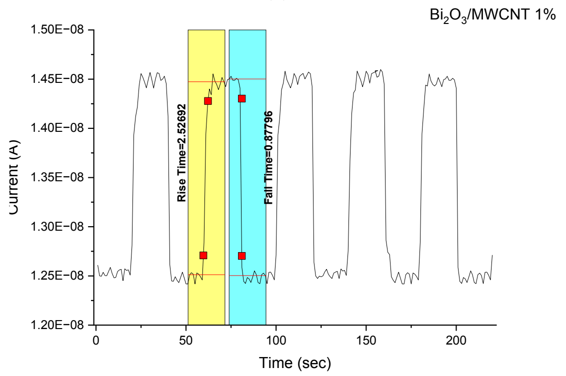
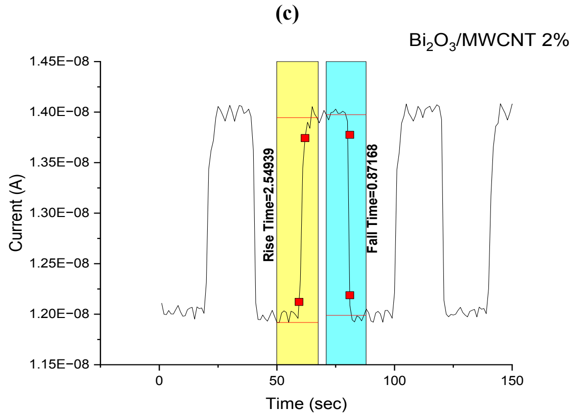


(c)



(d)

Fig. (2) Time-dependent photocurrent of (a) pure Bi_2O_3, and MWCNTs-doped Bi_2O_3 with (b) 0.5 wt.%, (c) 1 wt.%, and (d) 2 wt.%

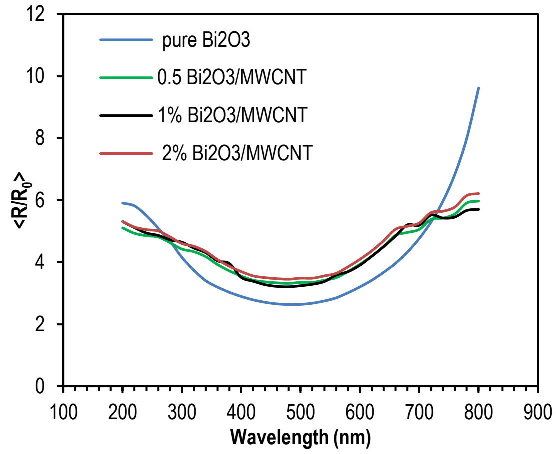


Fig. (3) Photo-behavior of the prepared pure Bi_2O_3 and MWCNTs-doped Bi_2O_3 films

The ratio of produced electrons to incident photons when light strikes the photodetector's surface in the practical region is known as quantum efficiency (η), which is related to the spectral responsivity *R(λ)* according to the following equation [27]:

$$\eta = R_\lambda \frac{1.24}{\lambda\,(\mu m)} \times 100\% \qquad (4)$$

The values of spectral responsivity, specific detectivity, quantum efficiency, noise equivalent power, and sensitivity for these photodetectors are shown in table (1). It is shown that the values are almost equal, while the NEP value was decreased. Thus, we notice an improvement in photodetectors' properties.

4. Conclusion

Thin films of pure Bi_2O_3 and MWCNTs-doped Bi_2O_3 with doping ratios of 0.5, 1, and 2 wt.% were successfully prepared by the pulsed-laser deposition technique. The effect of MWCNTs on the electrical characteristics of these films is observed. The MWCNTs produce smaller current in the MWCBTs-doped Bi_2O_3 films than that in pure Bi_2O_3 films with increasing applied voltage. Also, the electrical conductivity and optical transparency are affected by the distribution of MWCNTs. Thus, the resistance decreases and the electrical conductivity increases as the concentration of MWCNTs is increased. The detector sensitivity was faster for the photodetectors fabricated from pure Bi_2O_3 compared to the MWCNTs-doped Bi_2O_3 photodetectors. Additionally, the films achieved the lowest value of <R/R$_0$> in the visible region at around 500 nm. Also, an increase in the <R/R$_0$> value with the concentration of MWCNTs added to Bi_2O_3 thin films. Consequently, we conclude that the addition of MWCNTs to the Bi_2O_3 thin films led to improve the properties of the photodetectors fabricated form these structures.

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Table (1) Results of photodetectors for pure Bi_2O_3 and Bi_2O_3/MWCNT thin films

Sample	Sensitivity %	R_λ (mA/W)	η (λ)%	NEPx10^{-11} (W)	D*x10^{+10} (cm.$Hz^{1/2}$.W^{-1})
Pure Bi_2O_3	18.4	0.23	0.045	1.5	1.12
Bi_2O_3/MWCNT 0.5%	18.3	0.23	0.045	1.24	1.18
Bi_2O_3/MWCNT 1 %	18.28	0.23	0.045	1.22	1.18
Bi_2O_3/MWCNT 2%	18.3	0.23	0.045	1.21	1.2