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A Novel Design of MSM Photodetector and the Investigation of Two-Top Contacts Spacing Effects on Detection Speed and Transient Response

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Highlights

- A novel microstructure of the Metal Semiconductor Metal photodetector is designed
- The designed MSM consists of an absorbing layer of semiconductor and two metal electrodes
- The transient response of the detector for the various distance between the electrodes is analyzed
- In the optimum state, the response rate is 57 ps and the maximum instantaneous current is 3.27 nA
- The shorter the distance between the two upper detector electrodes, the faster the detection speed

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Abstract

The photodetector is one of the main components of the optical communication systems that converts optical signal to electrical signal. Metal Semiconductor Metal photodetector is one type of photodetector with a high coefficient of quantum efficiency and high speed while having a simple structure. In this paper, a novel microstructure of the Metal Semiconductor Metal photodetector consisting of an absorbing layer of semiconductor and two metal electrodes which act as two back-to-back Schottky diodes is designed and simulated. Incident light is absorbed by the active area between the two top electrodes and generates electron-hole pairs which are collected by electrodes and then an electric current is generated. Therefore, by determining the transient response of the detector for the various distance between the electrodes, we can find out the effect of the distance on the detection speed and detector response. In the best case, the response rate is 57 ps and the maximum instantaneous current is 3.27 nA. The shorter the distance between the two upper detector electrodes, called the empty area, the faster the detection speed increases, and the total light current decreases due to the reduction of the light flux descending on the surface.

1. Introduction

One of the most practical methods of sending information and data in today's world is optical telecommunications. In the past, the communication link in telecommunication systems is copper wire, while today, optical fibers are used as communication links in optical telecommunication systems. In a simple optical connection, in addition to fiber optics [1], a light generator at the transmitter is needed to produce coherent light, and an optical detector at the receiver to convert the optical signal into electricity. So, the optical detector [2] is one of the main parts of an optical telecommunication system [3]. An optical detector absorbs light energy and converts it into electrical energy, which is detected as an electric current.

Stages of the detection process: 1-absorption of light energy and production of electrons and holes, 2- transfer of carriers produced by light, from across the absorption or transition region, and 3- a collection of carriers by connections and production of light current. Semiconductor optical detectors are the most suitable

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choice for optical communications due to their suitable spectral range, fast response, and good sensitivity. Among the various types of semiconductor detectors that exist, detectors with Metal-Semiconductor-Metal (MSM) Photodetector are a good choice for a receiver due to their ease of construction, simple structure, and low capacitance [4,5]. This detector has two metal connections on a semiconductor surface that are responsible for applying voltage and sending an electrical response to the outside environment. The metal connections on the detector surface are of the Schottky type, and this part is electrically similar to two Schottky diodes connected back-to-back [6,7]. The positive and negative poles of the joints are absorbed, respectively. The answer, the detector is collected as an electric current from the two above connections.

Over the past decades, the design and fabrication of MSM detectors are received considerable attention due to their high speed in integrated electronic-optical systems, high bandwidth, integration with field-effect transistors (FET), and low noise. Due to the very low capacitance of MSM detectors, their response speeds are usually in the range of a few tens of Picoseconds, which is very important [8]. Therefore, considering the role of metal-semiconductor metal detectors in optical telecommunications and their appropriate response speeds, this s structure as the target structure has been investigated in this dissertation. During various research to improve the performance of optical detectors, detectors with different dimensions, various semiconductor materials, and various metal electrodes are designed and installed in various structures. The diversity of manufacturing reports, the use of new materials, and efforts to improve the performance of metal-semiconductor metal detectors are strong reasons why simulation and efforts to improve MSM performance are of fascinating issues in optical telecommunications [9,10].

The optical response of a metal-semiconductor metal detector is an important parameter for detection. Important detector properties such as quantum effect and response time are related to the detector geometry, range, and width of the electrodes [11]. The effect of the dimensions and geometry of the detector on the performance of the metal-semiconductor metal detector is less studied and this causes the limitation and lack of progress of this type of detector. In a semiconductor metal structure detector, the smaller the distance between the two high connections, the faster the detection speed increases by reducing the drive time of the carriers, and the response decreases the amount of light flow relative to a radiated light power [12,13]. Therefore, in this paper, the detector response to the distance between the electrodes is simulated and investigated, and by determining the detector response to the distance between the electrodes, a balance can be established between the detection speed and the detector response so that both the speed of detection and response is satisfactory. Optical simulation is important to save time and money and optimize their performance. In line with the main purpose of the paper, we balance the detection speed and the appropriate response, change the distance between the connections and obtain the electrical response. The response rate of a piece to a pulse of light is usually calculated at the full width at half the maximum (FWHM). By examining the response to the distance between the electrodes, the optimal response and the appropriate distance will be determined.

In the reference [14], an improved metal semiconductor metal photodiode is investigated. In particular, it is an optical detector with high sensitivity and bandwidth in which anodes and cathodes of different materials and in different dimensions are used. Using an opaque anode and a transparent cathode reduces the surface reflections of the opaque electrode, absorbing lighter in the active area and at the same time keeping the transition distance to a minimum for slower carriers. Thus, the long sequence in response is minimized due to the collection of cavities so the bandwidth increases. Also in 2014, Habibpour and colleagues studied the temporal response of a BG MSMPD1 detector as a function of the equilibrium radiation reflection position. The results show that the detector response rate varies when the pulse position is shifted relative to the active region. This means that when the beam is shone in the middle of the active region, it has the lowest current and when it approaches the joints, the response of the part increases. The magnitude of the current near the cathode is exactly equal to the magnitude of the current near the anode [15]. According to the said content and to develop the research done; in this paper, a novel microstructure of the Metal Semiconductor Metal photodetector consisting of an absorbing layer of semiconductor and two metal electrodes that act as two back-to-back Schottky diodes is designed and simulated.

The remainder of this paper is organized as follows. How to extract and calculate basic semiconductor equations and the process of production and recombination of carriers is shown in section 2. In section 3, the proposed structure in terms of size and materials used is introduced and reviewed. In section 4, the desired structure is simulated and the transient and response speed of the metal-semiconductor metal in different modes are discussed. Section 5 also the conclusion and general report of the design and simulation results.

2. Theory and Mathematics

Metal Semiconductor Metal photodetector is another optical detector that is a simpler structure than APD and PIN while having a high quantum coefficient and speed. The detector consists of a semiconductor absorber layer and two metal electrodes arranged back-to-back like two Schottky diodes. External voltage is applied between the connections in such a way that one of them is direct and the other is inverse. The light shines into the active area between the two electrodes and, depending on the amount of light absorbed, several electron pairs and holes are produced, and these carriers move under the influence of an electric field caused by the output voltage and are collected by the electrodes. Since one of these electrodes is always biased backward, it has less dark current than other types of detectors [16,17]. In the MSM detector, the connectors can have a simple pattern, that mean in the form of two parallel electrodes or with an intermediate pattern (finger electrodes) [18]. The reason for using this finger pattern for electrodes is that the short distance between the electrodes Decreases and somehow increases the speed of response [19,20].

2.1. Quantum Efficiency

Quantum efficiency is equal to the number of electron pairs of holes produced per the number of photons emitted. If each photon ideally produces a pair of electrons and a hole, then the quantum efficiency is 100%. In practice, however, factors such as poor recombination and absorption, and reflection make η less than 100. Mathematical relation of quantum efficiency as:

$$\eta = \frac{Ne - h_G}{P_C} \tag{1}$$

where h_G is the number of holes produced, Ne is the number of electrons, and P_C is the number of colliding photons. On the other hand, the quantum efficiency is expressed as the following equation:

$$\eta = \frac{I}{q\varphi} = \frac{I}{q}\left(\frac{hv}{P_r}\right) \tag{2}$$

where ϕ is the Photon flux, and Pr is the Decreasing light power. Quantum efficiency depends on the absorption coefficient of the material and the thickness of the adsorption region. As mentioned, not all photons produce light carriers. Some photons fail to absorb due to the possible nature of the adsorption process. Some photons may be reflected from the detector surface. Absorbed power in an area of width w as:

$$P = P_r(1 - e^{-aw})(1 - R) \tag{3}$$

Where a is the absorption coefficient of the semiconductor material and R is the input reflectance of the detector. So, the light current will be equal to:

$$I = \frac{q}{hv} P_r(1 - e^{-aw})(1 - R) \tag{4}$$

And quantum efficiency by the relation:

$$\eta = (1 - e^{-aw})(1 - R) \tag{5}$$

Equation (4) means that a lot of light must be absorbed to achieve high quantum efficiency, so the width of the empty region must be large enough [21]. By reducing the reflectance at the diode surface, increasing the absorption in the active region, and preventing carriers from being lost in the semiconductor, quantum efficiencies can be increased to some extent.

2.2. Dark Current

The amount of current produced by the reverse bias of an optical detector without applying an optical signal is called dark current (I_{dark}). This current is an unwanted current that is added to the system as noise and is a function of the detector and temperature components. To minimize dark current, a long barrier is desirable, which is achieved by selecting the appropriate metal and cleaning the semiconductor surface properly before depositing the metal on it.

There are several mechanisms for generating dark currents. The mechanism of heat-ion diffusion in the metal-semiconductor interface (metal and insulation) and the mechanism, the tunneling current, are dark. The potential generated by the metal is adjacent to it. The dark current due to the thermal process is calculated according to Eqs (6) and (7).

$$I_0 \propto exp\left[\frac{-q(\varphi - \Delta\varphi)}{KT}\right] \tag{6}$$

$$\Delta\varphi = \sqrt{\frac{qE}{4\pi\varepsilon}} \tag{7}$$

Where q is the electron charge, φ is the potential barrier height for the electrons from the Fermi level of the metal to the semiconductor conductivity level, K is the Boltzmann constant, and T is the room temperature. $\Delta\varphi$ is the expression of the Schottky effect, and ε is shown to be the dielectric constant [22]. The tunneling phenomenon occurs due to the electric field inside the discharge zone. Due to this electric field, the electron is detached from the bond and goes from the capacitance band to the conduction band, thus creating a dark current.

2.3. *Response Rate*

One of the most important parameters of an optical detector is the response rate ($R0$). Response according to eq (8):

$$R_0 = \frac{I_P}{P_r} \tag{8}$$

The ratio of the detected current in amperes divided by the power of the incoming light is defined in watts. According to Eqs (4) and (5), the response in terms of wavelength and efficiency is Eq (9):

$$R_0 = \frac{\eta q}{h} = \frac{\eta q \lambda}{hc} \tag{9}$$

The response is a function of wavelength and detector components. At longer wavelengths, the photons do not have the energy needed to overcome the energy gap of the semiconductor material, so the semiconductor becomes transparent to this beam. Therefore, the energy of radiant photons must be greater than the energy gap to be absorbed and cause an electric current by producing a carrier.

3. MSM Photodetector

As shown in Figure 1, the proposed MSM Photodetector are two contacts made of gold and with thickness and length equal to T_G=100 nm, L_G=L_A=L_C= 20 µm, respectively. GaAs with different doping are used in the lower layers and substrate layer. An air gap is created between the cathode and anode contacts with a thickness of T_{air} = 1.1µm, and the length of this gap is L_{air} = 10µm. The layers below the contacts are used to absorb more light, which is doped with a high-density n-type = 4e18 and a thickness of T_G = 1µm. This causes the structure to be activated by a slight impact of light rays on high-density electrons. In the middle layer, the intensity of doping for the smooth movement of electrons after the impact of light rays is reduced by n-type = 1e18. The same layer of GaAs is used substrate layer, but the doping has changed to p-type with a density of 4e18. This change in doping controls the path of electrons and on the other hand, the holes are absorbed towards the relevant contact, which can lead to less response time and fewer losses in the path of combining and recombining electrons and holes.

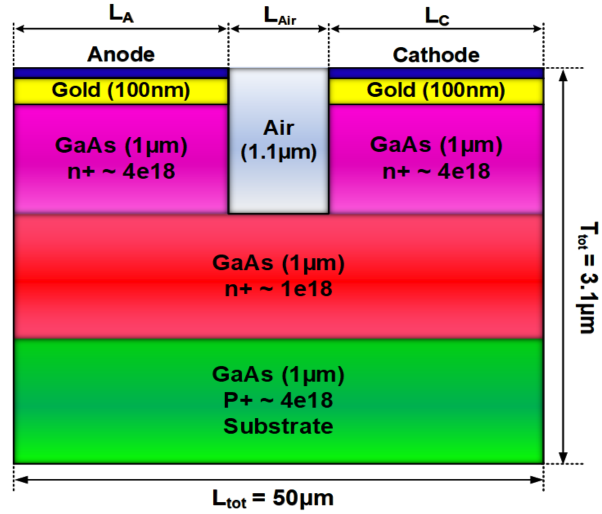

Fig. 1. Cross-section of the proposed device.

As can be seen, a cross-section of the structure is created, showing a two-dimensional view, and so the light beams shine on the structure from above, causing the structure to function. On the other hand, the beam shines on the whole structure. While no beam passes through the gold layer and enters the detector. Along with changing the length of the active area, the beam profile must be adjusted so that the radiation is the same in all cases.

4. Result and Discussion

In this simulation section, five different modes for the distance between the connections and the cathode are considered, with the distance between the two upper connections varying between 10, 20, 30, 40, and 50µm while the other parameters are the same in all cases. Figure 2 shows the current for the case where the distance between the contacts is L_{Air} = 10µm, the detector is below 6 volts and the light from above shines vertically on the whole structure. Since the mobility of electrons is greater than that of holes. The resulting electric current has a rapid rise due to electrons and a long descent time due to the movement of holes. The peak of electric current in the electric current diagram in terms of time is 7.75×10^{-10} A, and the response speed by calculating the amount of FWHM from the diagram in MATLAB software is 57ps. The number of carriers that pass through the surface unit of this detector per unit of time is approximately $n=5\times10^{8}$.

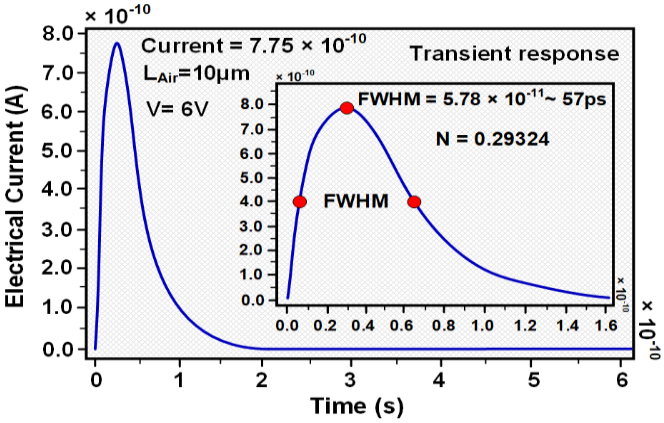

Fig. 2. Shown transient response and FWHM width LAir = 10μm

If the peaks of transient response diagrams are plotted in terms of increasing the distance of the electrodes in the MSM detector, the maximum changes in the amount of electric current with the change in the distance of the electrodes in figure 3 are well visible. As can be seen from this figure, the rate of increase in electrical current decreases with increasing distance, so that the maximum difference between the electrical currents in the two initial states is a distance of 10um compared to 0.20 nA, while for the structure 40μm is 0.2 nA compared to 50μm. This decrease in the slope of the changes is due to the increase in the recombination rate of carriers in the active region.

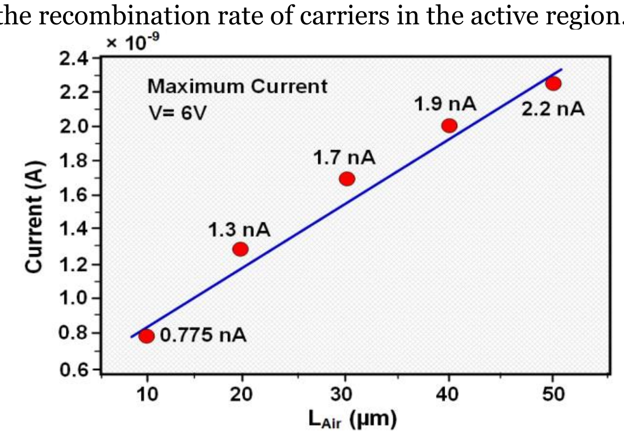

Fig. 3. Shows the changes in maximum electrical current as the distance increases (LAir).

By increasing the distance, the detection speed increases by increasing the drive time of the carriers, which is shown in Figure 4, increasing the response time. As can be seen in the figure, as long as the L_{Air} distance is increased to 30 microns ($L_{Air} \leq 30\mu m$), the FWHM value increases almost slightly. But when the distance of X is more than 30 microns ($L_{Air} > 30\mu m$), the rate of FWHM increases at twice the speed.

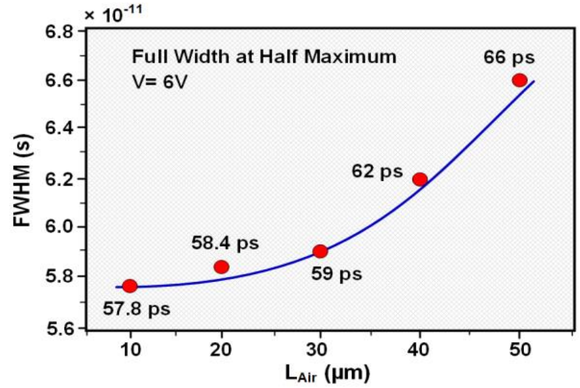

Fig. 4. Shows the changes in FWHM as the distance increases (LAir).

In this section, the effect of changing the optical power applied to the detector in the form of a Gaussian pulse is simulated and investigated. The simulation is performed for detection with a distance of 20 microns (L_{Air} = 20μm) and under a voltage of 6V. the radiant pulse power is set to 120, 200, and 300mw, and the results are obtained as shown in Figure 5. As shown in the figure, with increasing radiative power, the amount of electric current peak in the transient response also increases.

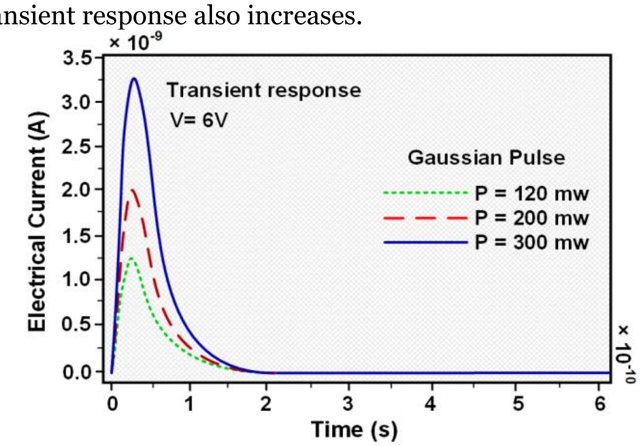

Fig. 5. Dependence of detector transient response on radiant pulse power.

In the detector under study, the change in beam power has little effect on the response speed, and the FWHM in all three cases is equal to and approximately 58 ps, but the electric current, because the beam has more penetrating power and produces more carriers, with increasing current It is an upward trend. The effect of the change in optical power of the radiation pulse on the amount of maximum current and response speed can be seen in Figure 6.

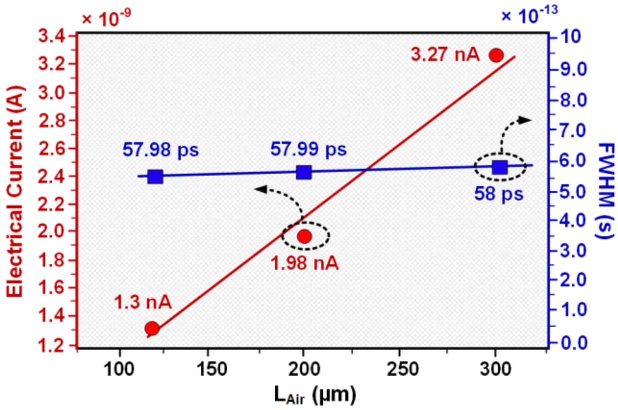

Fig. 6. Effects of Gaussian pulse power on electric current (left), and FWHM (right).

Up to this point, the effects of the distance between the contacts (L_{Air}) on the electric current and FWHM are simulated as a transient response. Now for further investigation, change the thickness or depth of the active area (air), and finally, the results are included in Figure 7 shows the effects of active area thickness on detector parameters.

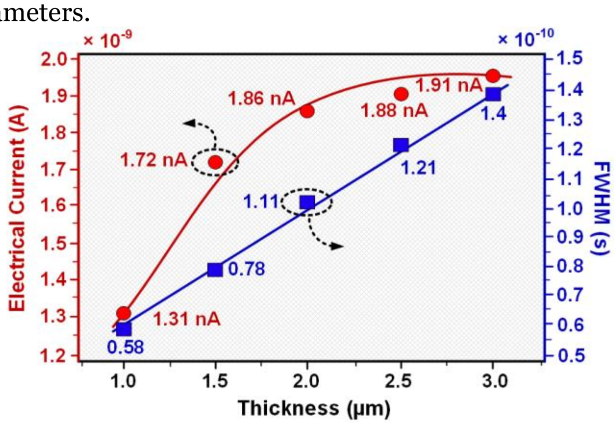

Fig. 7. Effects of active area thickness on electric current (left), and FWHM (right).

As the depth of the active area increases, more carriers are produced, which in the first place increase the electric current. On the other hand, the electric field is weaker in the deeper regions, so the time required for these carriers to reach the connections is longer than the carriers produced at the surface.

Thus, FWHM increases as a function of optical power. It should be noted that this increase in the thickness of the active area, in this structure more than 3 microns, causes an increase in response time, which is not appropriate. In the last section, to prove the superiority of the proposed structure over other similar structures, the values of important parameters are compared in Table 1.

Table 1. Comparison of important parameters of the proposed structure with other structures.

Works	Current	Response Time	Footprint (μm2)
Ref [23]	0.31 nA	0.6911 ns	-
Ref [24]	1.43 pA	0.412 ms	25
Ref [25]	0.1 pA	-	500
This Work	3.27 nA	57 ps	155

As can be seen in the table, the most important parameters in a photodiode structure are response time, current, and dimensions. The proposed structure has a high speed due to its small dimensions. On the other hand, the integrated use of substance GaAs with different and appropriate doping will increase the flow as much as possible. On the other hand, the use of gold material in contact has had a good effect on the current transmission.

5. Conclusions

In In this paper, a novel microstructure of the Metal Semiconductor Metal photodetector consisting of an absorbing layer of semiconductor and two metal electrodes that act as two back-to-back Schottky diodes was designed and simulated. The simulation results show that at a constant voltage and pulse, as the distance between the electrodes (L_{Air}) increases, the metal-semiconductor metal detection response increases. Because increasing the area of the active area increases the absorption of radiation, in other words, divergent rays are also absorbed and show better current. On the other hand, this causes changes in the detector's response time to radiation. As the results show, increasing the distance between the two connections above increases the response time by increasing the drive time and distribution of the carriers. A large increase in the length of the active region causes the recombination of carriers to dominate the propulsion and diffusion processes. In the best case, the response rate is 57 ps and the maximum instantaneous current is 3.27 nA. Therefore, the greater the distance and intensity of the light beam, the higher the parameter values.

As a future work, we can focus on the Monolayer or ultraviolet MSM Photodetectors and improve their performance.

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7. Conflict of Interest

The authors declare that they have no conflict of interest.

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