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Modeling of Avalanche Photodiodes Performance under Thermal and Radiation Effects

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Abstract* - Radiation-induced damage in Avalanche Photodiode (APD) was shown to result from the dark current and a change of the effective doping concentration occurring within the photodiodes. In this paper a model to reveals the effect of ionizing radiation and temperature on the performance of APDs is built by using Vissim environment. This proposed model provides a mean to control the properties of APD when they are selected to operate in thermal radiation environments. Efficiency, sensitivity, responsitivity, and signal to noise ratio are modeled. The temperature effects are combined with radiation effects to formulate a rigours treatment for the APD behavior. The results are validated against published experimental work in temperature case and show good agreement.

***Keywords*– Avalanche Photodiode, Neutron Radiation, Thermal Effects, Efficiency, and signal to noise ratio.**

I. INTRODUCTION

Considering the continuous revolutions of optoelectronic and photonic components optical detectors with single photon sensitivity have been developed to achieve the highest per photon efficiency in an optical communications link. One such single photon detector is an avalanche photodiode (APD) [1]. APD is a crucial component in large part because of their use as detectors in fiber-optic communication systems where they not only exhibit higher sensitivities than PIN structures for low light level applications such as long to medium haul fiber networks but also very fast photodetectors [2], [3]. They operate by converting clusters of detected photons, associated with information-carrying pulses of light in a digital communication system, into cascades of electrons. These cascades have sufficiently high charge to be readily detected by the electronics following the APD [4]. Furthermore their high sensitivities have recently led them to be widely used in high-radiation environments [2], [5], which include reactors and the space environments. Therefore the radiation sources influence the APD properties can be neutrons, gamma, or X-rays, or a wide range of charged particles including electrons, protons, and heavy nuclei [6]. Moreover the major degradation in the photodiode properties occurs by neutron irradiation [7]. In view of the fact that in case of irradiated APDs both incident light and ionizing radiation produce electron-hole pairs, which results in a photocurrent. However, the ionizing radiation interact with the bulk material (volume effect), whereas the information carrying photons are merely absorbed in the active region [8]-[11]. Consequently this leads to increase dark current as well as noise and thus raise the minimum detectable light power [12]-[15].

Thus, it is essential to be acquainted with the thermal radiation influences on APDs properties in the radiation environment, and how we can optimize these properties in order to improve APDs characteristics. Consequently, we are concerned with radiation effects on device efficiency, responsitivity, sensitivity that enables us to calculate the degradation that occurs in APDs performance under irradiation environment. In addition, improving the signal to noise ratio contributes in achieving maximum usage of the communication system bandwidth, and to control APDs properties when they selected to operate in radiation fields. The arising effects of radiation induced damage are decisive in designing high-bit-rate optical communication systems. The motivation of this work comes from the need to examine the competence of these devices for exploitation in the neutron irradiation environmental applications and tests. This work is done by using VisSim environment. VisSim is a visual block diagram language for simulation of dynamical systems and model based design of embedded systems. It uses a graphical data flow paradigm to implement dynamic systems based on differential equation.

This paper is organized as follows: Section II presents the basic assumptions and modeling of radiation induced performance degradation, section III describes the model results. However section IV is devoted to conclusion.

II. BASIC ASSUMPTIONS AND MODELING OF RADIATION INDUCED PERFORMANCE DEGRADATION

Avalanche photodiodes have already shown very good performance in various applications than PIN photodetectors. However, their performance is degraded drastically when they are operated in radiation environments. Radiation results in an increase in the photodiode dark (leakage) current and therefore a larger background noise level. The other important permanent damage effect from neutron irradiation is a reduction in optical sensitivity, signal to noise ratio and efficiency. In this model two APDs were used, one of effective thickness =140μm and the other is equal to 120μm and the photodiodes are assumed to overfill the fiber so that all mode groups are received. The cross sectional areas diameters of the two devices are 0.8 and 0.5 mm. Operating wavelengths of the optical sources used for transmitting data are 850 nm and 1310 nm. To illustrate the performance degradation of avalanche photodiode in radiation environment, the effect of the neutron radiation on the properties of avalanche photodiodes such as efficiency, responsitivity, sensitivity and signal to noise power has been studied under different thermal condition. Moreover neutron radiation effect has two main contributions to the dark current of an APD. The first of these is the surface dark current, generated at or near of the perimeter of the junction.

The second contribution to the dark current is bulk current, generated within the junction region, and in an APD this current component undergoes multiplication. Thus we have [16].

$$I_D = I_{DS} + MI_{DB} \quad (1)$$

Where I_D, I_{DS}, I_{DB}, and M are a the total dark current, the unmultiplied surface component of the dark current, the multiplied component of the dark current, and multiplication factor (gain) respectively. Therefore the dark current resulted from neutron effect can be also obtained as follows [17].

$$I_{Dark}neutron \cong I_{Dark}gamma - I_{Dark}proton = MI_{DB} \quad (2)$$

Therefore equation (1) can be simplified as follows:

$$I_D = I_{DS} + I_{Dark}neutron \quad (3)$$

However, under neutron fluence Φ the dark current is a volume effect, so usually the increase in the dark current I_{Dark} neutron is written as follows [18].

$$I_{Dark}neutron = \alpha v \Phi \quad (4)$$

where v, α are the volume of the detector, and a parameter which has been measured by different groups, and its value is ranging between α = (10-13)10^{-17}A/cm. In the case of Avalanche Photodiodes, the volume which is relevant for the generation of the bulk current is the area times the effective thickness of the detector [18].

$$v = A_d \times T_E \quad (5)$$

Therefore equation (3) can be rewritten as follows:

$$I_D = I_{DS} + \alpha v \Phi \quad (6)$$

Moreover one of important characteristics that are commonly used to describe photodetector performance is the quantum efficiency (η) that can be defined as the ratio of number of incident photon to the face of photodiode in unit time and is denoted as (N_P) to the number of photoexcitation photoelectron (N_e). Then the quantum efficiency η is defined as [19]:

$$\eta = \frac{N_e}{N_p} \times 100\% \quad (7)$$

Where

$$N_e = \frac{I_{ph}}{q}, \quad N_p = \frac{P\lambda}{hc} \quad (8)$$

where P is physical radiated power of the incident light, Iph is the photo-current which produced in photodiode when the radiated power is P. Thus, Substitute (8) into (7), we have [19].

$$\eta = \frac{I_{ph}hc}{q\lambda P} \times 100\% \quad (9)$$

Where λ, h, q, and c is incidence light wavelength, Planck constant (6.626×10^{-34}J·S), electric charge, and light velocity respectively. Furthermore from equation (9) we obtain the relationship between photogenerated current Iph and optical power P in photodiode [19]

$$I_{ph} = \frac{\eta q \lambda}{hc} P \quad (10)$$

In addition when the wavelength of incident light (light source) and photosensitive device (material) are fixed the value of (ηqλ/hc) is constant. Consequently we can write the photodiode sensor's responsivity S_R as in the following equation [19]

$$\frac{I_{ph}}{P} = \frac{\eta q \lambda}{hc} \quad (11)$$

So we can suppose that [19]

$$S_R = \frac{\eta q \lambda}{hc} \quad (12)$$

Substitute S_R into (10), then we obtain [19]

$$I_{ph} = S_R P \quad (13)$$

Thus, the responsivity is essentially a measure of the effectiveness of the detector for converting electromagnetic radiation to electrical current or voltage. Furthermore equation (9) can be written as the following [19]

$$\eta = S_R \frac{hc}{q\lambda} \quad (14)$$

Moreover, the quantum efficiency η, can be also calculated from the formula [3]

$$\eta = S_I \frac{hc}{q\lambda} \quad (15)$$

Where S_I is the primary photoelectric sensitivity of avalanche photodiodes which can be calculated from the equation [3]

$$S_I = \frac{I_{ph}}{P} = \frac{\eta q \lambda}{hc} \quad (16)$$

Consequently, from equations (12), (16) we can conclude that

$$S_I = S_R \quad (17)$$

However, the total sensitivity is related to the primary sensitivity by the following equation [3]

$$S_T = MS_I \quad (18)$$

Furthermore, from equation (17) the total sensitivity is related to the responsivity by the following equation

$$S_T = MS_R \quad (19)$$

So that responsivity gives a measure of the detector's sensitivity to radiant energy. Moreover another important characteristic used to describe photodetector performance is the signal to noise ratio (S/N ratio) that can be determined for APDs by the equation [20]:

$$\frac{S}{N}(M) = \frac{M^2 I_{ph}^2}{2qB\left[I_{ph}M^2F(M) + \left(I_{DS} + I_{DB}M^2F(M)2^{(T-300)/10}\right)\right] + \frac{4kTB}{R_L}} \quad (20)$$

Where k, T, B, R_L, and F(M) are the Boltezman,s constant, temperature, load resistance, and excess noise factor respectively. However the excess noise factor may be calculated using the model developed my McIntyre which considers the statistical nature of avalanche multiplication. Thus the excess noise factor is given by [16]

$$F(M) = K_{EFF}M + [1 - K_{EFF}]\left(2 - \frac{1}{M}\right) \quad (21)$$

Where K_{EFF} is the effective k-factor for an APD, whereas k-factor is the carrier ionization ratio. Furthermore in equation (20) the first component in the denominator describes the shot noise (N_{sh}) but the second one the thermal noise (N_{th}) of the load resistance. So that from equation (20) the shot noise can be calculated from the equation [20]

$$N_{sh} = 2qB\left(I_{ph}M^2F(M) + I_{DB}M^2F(M)\right) \quad (22)$$

Moreover shot noise is present in all photon detectors due to the random arrival rate of photons from the source of radiant energy under measurement and background radiation. This

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shot noise is the true ultimate limitation to detector performance. However, the thermal noise can be calculated from the equation [20]

$$N_{th} = \frac{4kTB}{R_L} \quad (23)$$

It occurs in all conducting materials. It's a consequence of the random motion of electrons through a conductor. The electrons are in constant motion, but they collide frequently with the atoms or molecules of the substance. Each free flight of an electron constitutes a minute current. The sum of all these currents taken over a long period of time must, of course, be equal to zero. But their ac component is thermal noise. Therefore the total noise (N_T) can be calculated from the following equation [20]

$$N_T = N_{sh} + N_{th} \quad (24)$$

Moreover a substantial characteristic for an avalanche photodiode is dependence of a multiplication factor (M) on its reverse bias voltage. Therefore an empirical relationship describes this characteristic for parametrically variable temperature is given by [20].

$$\mathrm{M}(V,\Phi,\mathrm{T}) = \frac{\mathrm{H}}{V_b + [0.18(300-\mathrm{T})] - V_R} \quad (25)$$

Where V_b, V_R, T are the breakdown voltage, and the reverse bias voltage, and ambient temperature respectively. In addition an approximate universal expression of the breakdown voltage for all semiconductors studied can be given as follows [21].

$$V_b = a\left[\frac{E_g}{1.1eV}\right]^{3/2}\left[\frac{N_{eff}}{10^{16}cm^{-3}}\right]^{-3/4} \quad (26)$$

Where E_g, N_{eff} are the bandgab energy of silicon, and the effective doping $N_{eff} = 1.53\times10^{15}\exp[-1.139\times10^{-15}\Phi]$ concentration respectively.

Furthermore, defects generated during irradiation cause changes in the effective doping concentration which are macroscopically modeled as a function of the radiation particle fluence, Φ given by [21].

(27)

III. Results and Discussion

We have demonstrated the optical performance of APDs in thermal irradiation environment. We illuminate the effect of those environments on the optical efficiency and signal to noise ratio of APDs and how we can reduce the neutron effect in those devices. The results showed that the key to reducing thermal radiation effect would expect in minimizing the active device volume and increase reverse bias voltage. These results are considerable in designing optoelectronic systems, requiring immunity to the permanent and transient effects of thermal ionizing-radiation. The reference values of these parameters are shown in Table 1. These values of the calculations are taken from [3], [20-21].

Table 1 Operating parameters used in our proposal model.

Symbol	Operating parameter	Value
Φ	Radiation Fluence	$1\text{x}10^{11}$ n/cm^2-$5\text{x}10^{12}$ n/cm^2
T	Ambient Temperature	300 K - 400 K
P	Incident Power	1 nW - 10 nW
B	Bandwidth	1 MHz – 2 MHz
λ	Incidence light Wavelength	800 nm – 1100 nm
S_0	Detector Initial Sensitivity	0.5 A/W – 0.75 A/W
Eg	Energy gap of Silicon	1.15 eV
v	Detector Volume	$2.5\text{X}10^{-5}$cm^3 - $7.0\text{X}10^{-5}$cm^3
k	Boltzman's Constant	$1.38\text{x}10^{-23}$ J/K
R_L	Load Resistance	4 KΩ - 5 KΩ

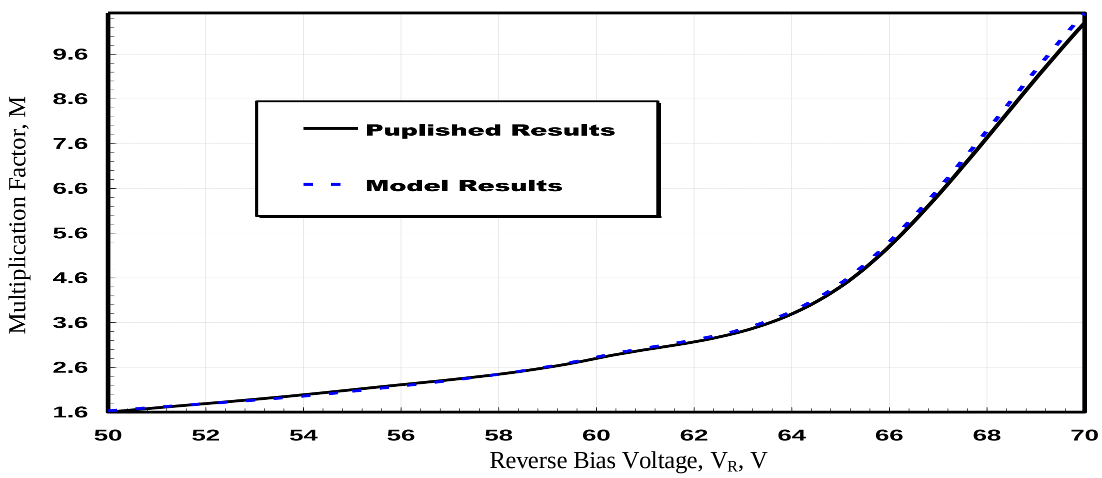

Fig.1. Variations of the multiplication factor (M) against reverse bias voltage (V_R) with T=300K, P=10nW, B=1MHz, Φ=$1\text{x}10^{11}$ n/cm^2, λ=850nm, and R_L=4.5 KΩ.

In figure (1) the typical computed values for the Multiplication Factor (M) against reverse bias voltage (V_R) under thermal effect, and experimental values are represented in the above figure that shows a good agreement between the resulted curve and published experimental curve.

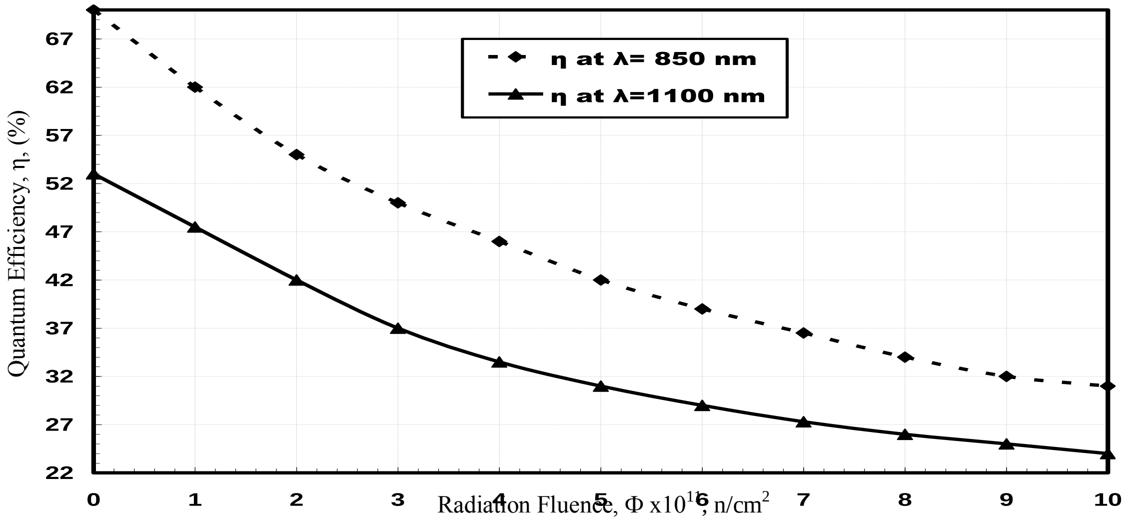

Fig.2. Variations of the quantum efficiency (η) against radiation fluence (Φ) at different optical signal wavelength (λ) with T=320K, P=10nW, B=1MH, and R_L=4 KΩ.

Figure (2) reveals the relation between quantum efficiency and radiation fluence at different incidence light wavelength. The figure illustrates that as the radiation fluence increases the device quantum efficiency is decreases. This can be explained by the fact that if the energy of neutron irradiation is high enough (above several hundred keV) the pair generation occurs. The energy spectrum of the energetic electrons is called"slowing spectrum". The energetic electron interacts with a lattice atom. As a result, the lattice atom is displaced from lattice site. This is so called Primary Knock on Atom (PKA). Interstitial (PKA), vacancy, and complex of them form a deep level in bandgap. This is so-called the generation-recombination centre [22]. Moreover these defects created throughout the optically active volume tend to decrease the overall collection efficiency of optically generated minority carriers by reducing the minority carrier diffusion length [23]. Consequently the photocurrent decrease and hence, the device quantum efficiency decreases. In addition quantum efficiency decreases with increase incidence light wavelength. This can be explained by examining some basic material properties and the photocurrent generation mechanism. For indirect bandgap semiconductors, such as silicon, the optical absorption coefficient is usually relatively small for photons with energies only slightly larger than the material bandgap. This results in the creation of infrared (0.8 pm - 1.1 pm for Si) generated minority carriers farthest from the front optical surface and usually farthest from the electrical junction [23].

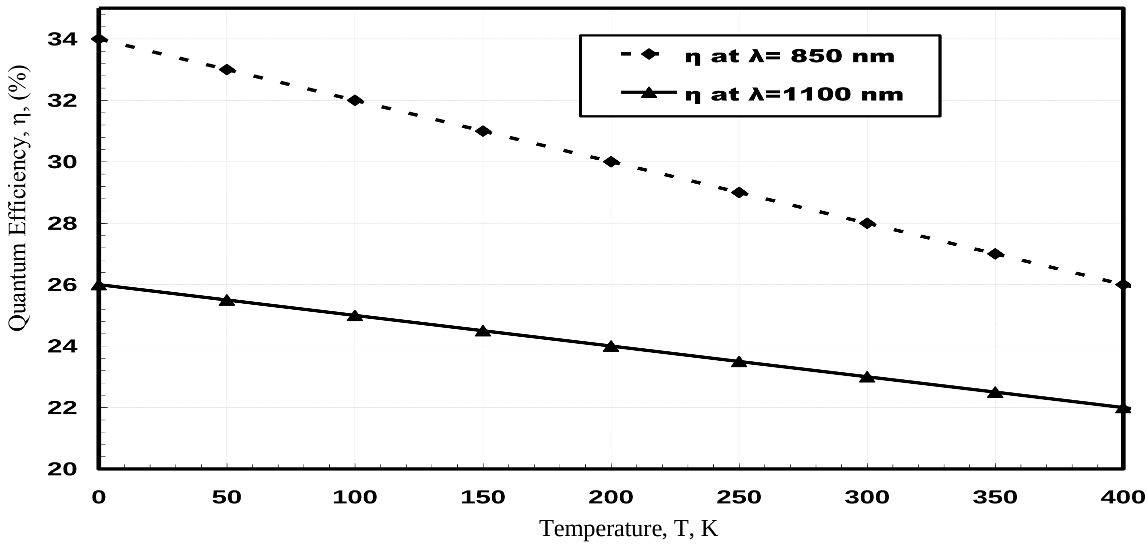

Fig.3. Variations of the quantum efficiency (η) against temperature (T) at different optical signal wavelength (λ) with Φ = $1x10^{11}$ (n/cm^2), P=10nW, B=1MH, and R_L=4 KΩ.

Figure (3) reveals the relation between quantum efficiency and temperature at different incidence light wavelength. The figure shows that as the temperature increases the device quantum efficiency decreases. This can be attributed to the fact that temperature plays a significant role in the number of reactions that take place during/after irradiation as a rise in 10^0C can double the reaction rates (Berejka and Cleland, 2011) [24]. Therefore this duplication of defects created throughout the optically active volume tends to decrease the overall collection efficiency of optically generated minority carriers by reducing the minority carrier diffusion length [23]. This is the reason of why dark current increases by a double of its value for each rise in temperature of 10^0C [20]. In addition, the avalanche process statistics generate current fluctuations these fluctuations increases with the temperature, and APD efficiency degraded [16].

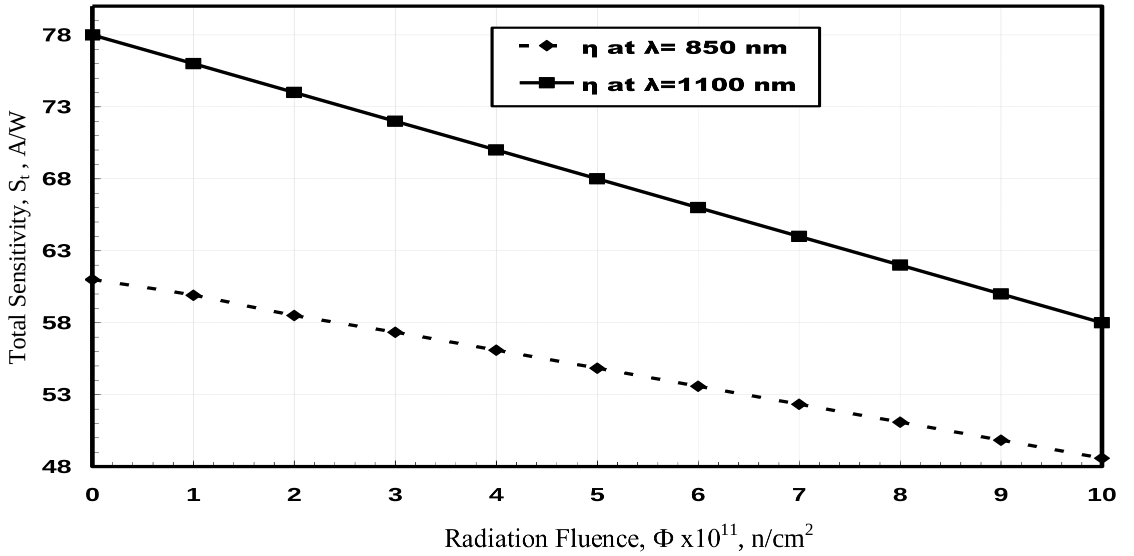

Fig.4. Variations of the total sensitivity (S_t) against radiation fluence (Φ) at different optical signal wavelength (λ) with T=320K, P=10nW, B=1MHz, and R_L=4 KΩ.

Figure (4) reveals the relation between total sensitivity and radiation fluence. It shows the reduction in optical sensitivity with increasing neutron radiation. This is because radiation induced defects created throughout the optically active volume tending to decrease the overall collection of optically generated minority carriers by reducing the minority carrier diffusion length. The crystal damage clusters serve as recombination sites causing optically generated hole-electron pairs to recombine before they can contribute to junction current [23]. In addition sensitivity is limited by photon shot noise which increases with increase dark current in the radiation field [16]. Moreover the shorter the wavelength of incident radiation is the higher noise current I_N and lower the gain M for I_N = const is. Worsening of photodiode properties for shorter wavelengths results from the increase of number of holes participating in total current flowing through the avalanche region. Therefore from equation (20) this will reduce total sensitivity at shorter wavelengths [22].

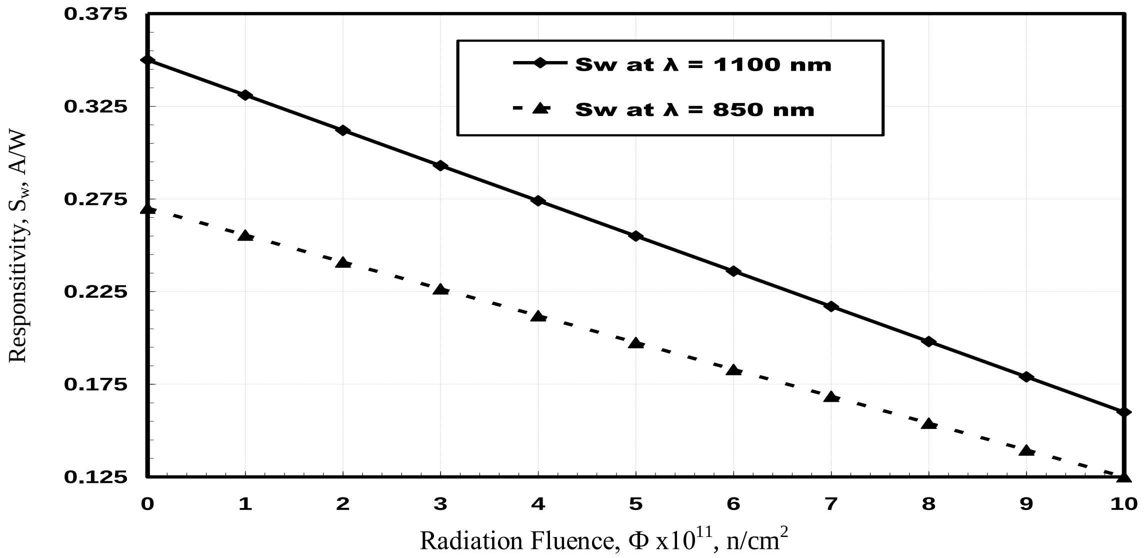

Fig.5. Variations of the responsivity (S_W) against radiation Fluence (Φ) at different optical signal wavelength (λ) with T = 320 (K), P=10nW, B=1MHz, and RL=4 KΩ.

Figure (5) reveals the relation between responsivity and radiation fluence. Responsivity gives a measure of the detector's sensitivity to radiant energy. The rapid decrease in infrared responsivity can be explained by neutron irradiation is believed to cause large clusters of disorder in the crystal lattice due to the relatively large energy transfer associated with neutron scattering. These disorder clusters in the crystal lattice create generation sites in the depletion region of the semiconductor junction. This results in an increase in the photodiode dark (leakage) current and therefore a larger background noise level. These internally generated noise of a photodiode is one of the main factors affecting the minimum optical power an optical detector can sense [23]. Moreover collection efficiency for infrared generated minority carriers far from the junction region is determined by minority carrier lifetime that will degrade under radiation effect. So the decrease in infrared responsivity can be explained as a consequence of radiation-induced minority carrier lifetime degradation and at the same time increasing of dark current level [25]. However high values of APD responsitivity can be obtained by using avalanche multiplication phenomenon [20]. In addition the reverse bias range can be used to increase the photodiode speed of response [23].

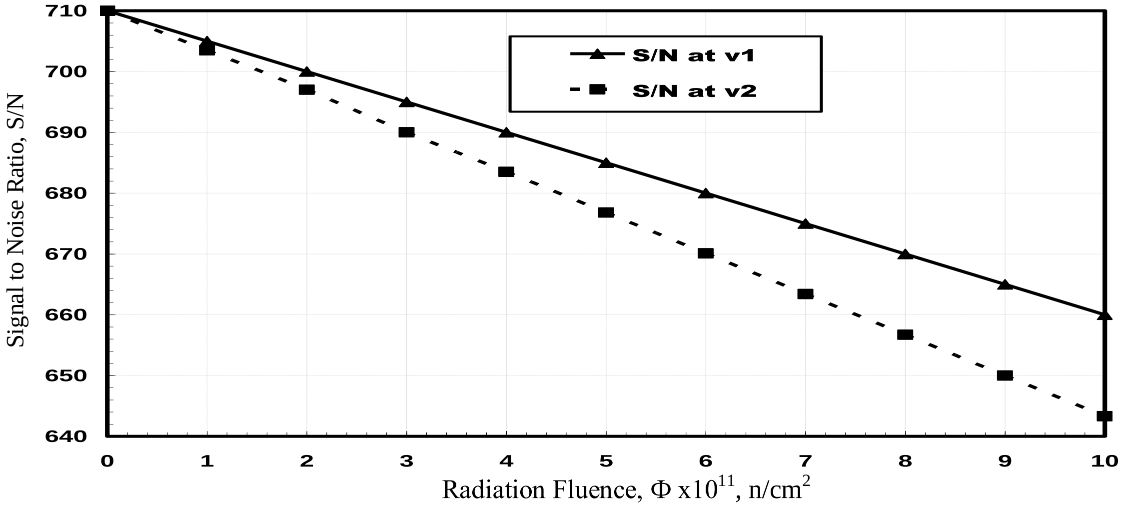

Fig.6. Variations of the signal to noise ratio (S/N) against radiation fluence (Φ) at different active volume (v) where (v_1= 2.4x10^{-5} cm3, v_2 = 7x10^{-5} cm^3) with T=320K, P=10nW, B=1MHz, and RL=4 KΩ.

Figure (6) reveals the relation between signal to noise ratio and radiation fluence. The instantaneous photocurrent generated in photodiodes during exposure to a pulse of ionizing radiation is a result of a combination of Compton scattering effects and the photoelectric effect, depending on the energy of the ionizing-radiation photon. Both mechanisms create excited electrons which generate many electron-hole pairs as the excited electrons move through the crystal lattice. These electron-hole pairs can contribute to the device current if they are created within approximately one diffusion length of the semiconductor depletion region edge. This ionizing-radiation induced photocurrent can be significantly larger than the intended signal current component, depending on the amplitude of the ionizing-radiation field and the amplitude of the signal intensity. Moreover an increase in the photodiode dark (leakage) current results in a larger background noise level. Consequently the signal to noise ratio decrease. However by minimizing the active device volume, the magnitude of the radiation induced signal current can be reduced. Relatively short minority carrier diffusion lengths also decrease the number of ionizing-radiation induced minority carriers that contribute to the device current [23]. Small active volume photodiode structures are used to achieve low noise current during exposure to ionizing-radiation and as a result increase the signal to noise ratio [25].

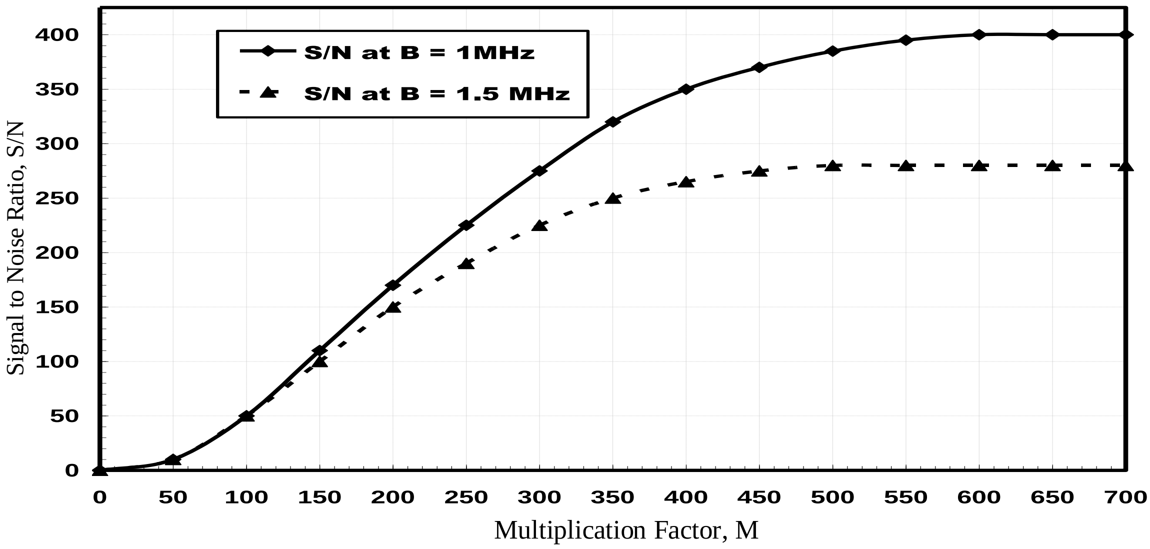

Fig.7. Variations of the signal to noise ratio (S/N) against multiplication factor (M) at different bandwidth (B) with Φ = 1x1011 (n/cm2), P=10nW, T=320 K, and RL=4 KΩ.

Figure (7) reveals the relation between signal to noise ratio and multiplication factor at different load resistance. From the figure signal to noise ratio increases as multiplication factor increase. This can be attributed to the fact that a mechanism of internal gain causes significant increases in a signal current generated in a detector and improves the signal to noise ratio [20]. While impact ionization can improve the signal to noise ratio in APDs it still limits their bandwidth at high M because of the long multiplication chains, which takes time to build up and die away. This accompanying increase in response time with M results in a roughly constant gain bandwidth product [26]. In addition in order to have maximal value of a signal to noise ratio the high values of load resistance should be taken [20]. However high values of load resistance will restrict the photodiode frequency band which depends on the load resistance, according to the following equation [20]

$$B = \frac{1}{2\pi R_L C_t} \tag{28}$$

Where C_t is the resultant capacity of the input circuit.

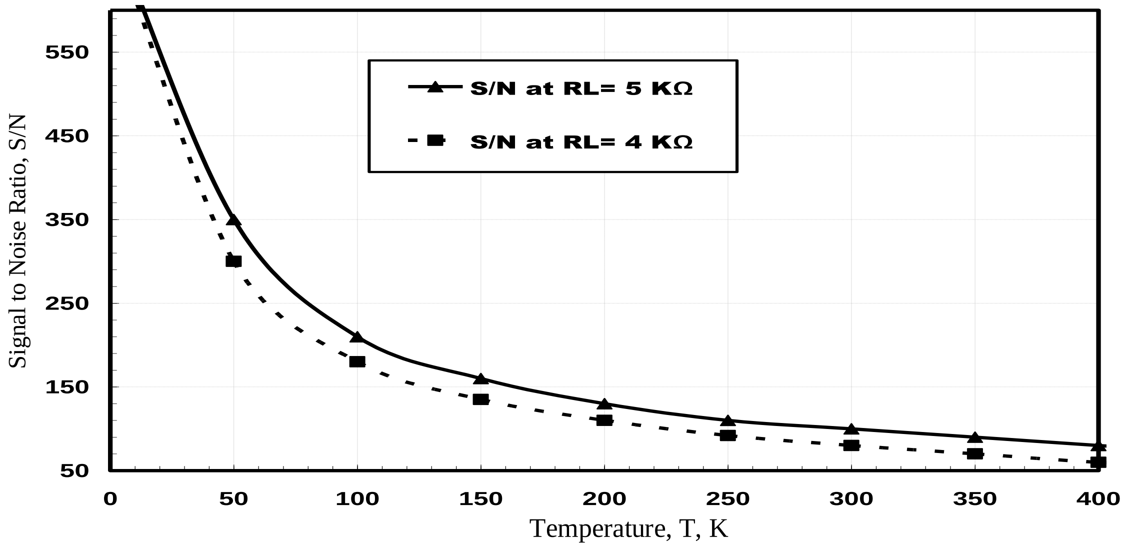

Fig.8. Variations of the signal to noise ratio (S/N) against temperature (T) at different load resistance (R_L) with $\Phi = 1x10^{11}$ (n/cm^2), P=10nW, B=1MHz, and R_L=4 KΩ.

Figure (8) reveals the relation between signal to noise ratio and temperature at different load resistance. From the figure signal to noise ratio decreases as temperature increase. This can be attributed to the fact that temperature plays a significant role in the number of reactions that take place during/after irradiation as a rise in 10^0C can double the reaction rates (Berejka and Cleland, 2011) [24]. Therefore this duplication of defects created throughout the optically active volume tends to increase photodiode dark current and therefore photodiode noise power level [23]. So the signal to noise ratio decrease with temperature. Moreover for the higher values of a load resistance the value of thermal noise decreases. Hence, the value of signal to noise ratio increase. Therefore in order to have maximal value of a signal to noise ratio the high values of load resistance should be taken [20].

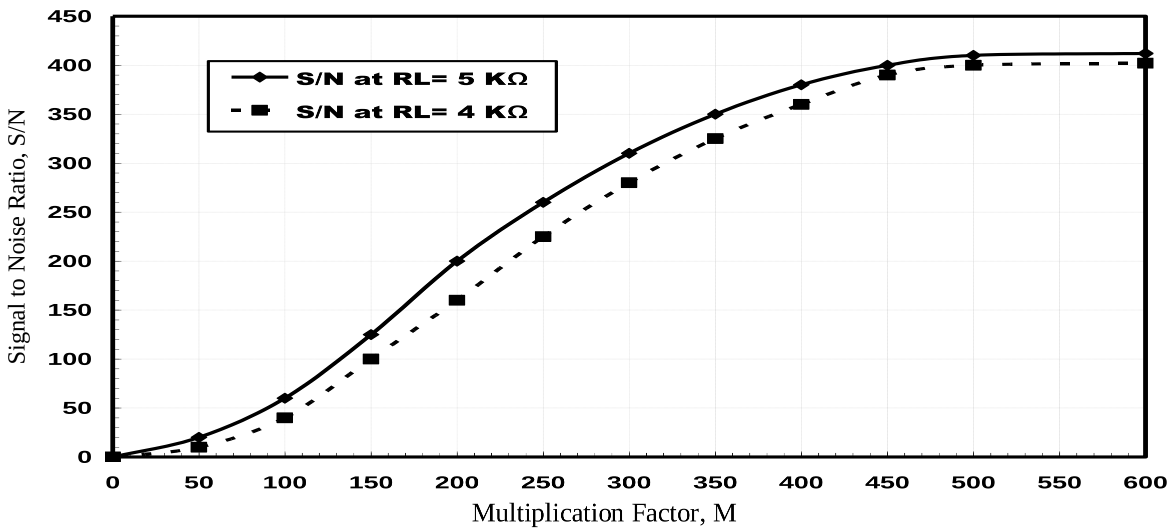

Fig.9. Variations of the signal to noise ratio (S/N) against multiplication factor (M) at different load resistance (R_L) with $\Phi = 1x10^{11}$ (n/cm^2), P=10nW, T=320 K, B=1MHz, and R_L=4 KΩ.

Figure (9) reveals the relation between signal to noise ratio and multiplication factor at different load resistance. From the figure signal to noise ratio increases as multiplication factor increase. This can be attributed to the fact that a mechanism of internal gain causes significant increases in a signal current generated in a detector and improves the signal to noise ratio. Such a mechanism, however dose not influence on the noises originated from a load resistance as will as the amplifier noises [20]. Furthermore as thermal noises decreases with increase the load resistance this will contribute in increasing the signal to noise ratio of avalanche photodiode.

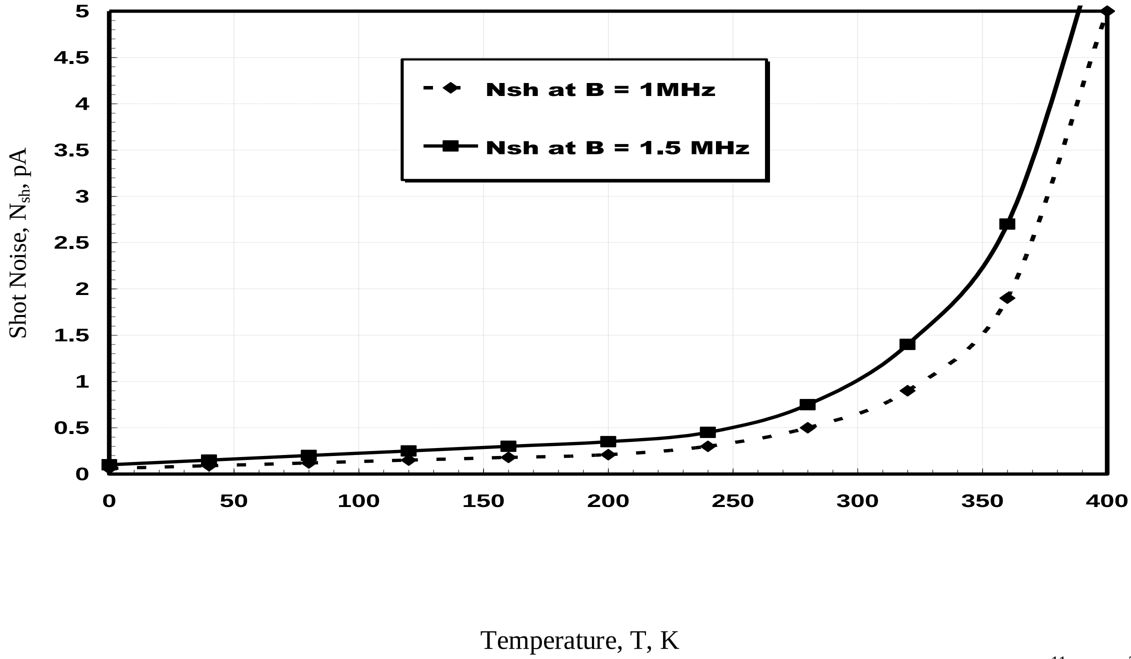

Fig.10. Variations of the shot noise (N_{sh}) against temperature (T) at different Bandwidth (B) with T=320K, $\Phi = 1x10^{11}$ (n/cm^2), P=10nW, and R_L=4 KΩ.

Figure (10) reveals the relation between shot noise and temperature at different load resistance at different bandwidths. From the figure shot noise increases as temperature increase. This result can be credited to the shot noise derives from the random statistical Poissonian fluctuations of the dark current [16]. Since dark current increases by a double of its value for each rise in temperature of 10^0C [20]. Therefore this change in diode dark current results in increasing the shot noise value as the temperature increases. Moreover in higher bandwidth the number of photons that have random arrival rate from the source of radiant energy will increase. Consequently the shot noise will increase.

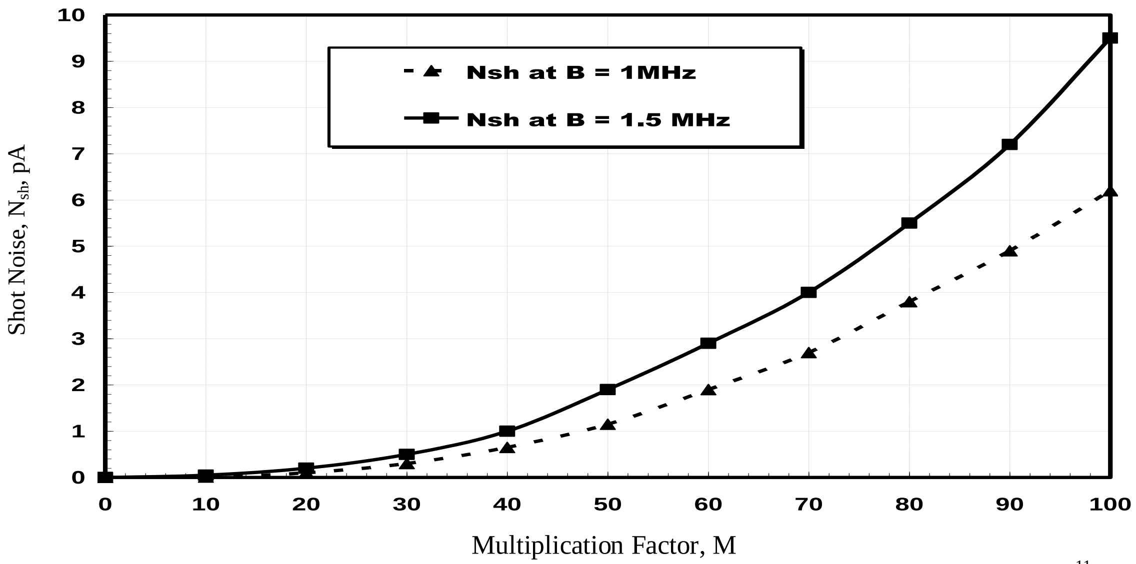

Fig.11. Variations of the shot noise (N_{sh}) against multiplication factor (M) at different Bandwidth (B) with $\Phi = 1x10^{11}$ (n/cm^2), P=10nW, T=320 K, B=1MH, and R_L=4 KΩ.

Figure (11) reveals the relation between shot noise and multiplication factor at different bandwidths. From the figure shot noise increases as multiplication factor. This result can be credited to the avalanche gain causes both, an increase in the noise originated from a dark current and in the quantum noise. It is due to the fact that a random mechanism of carriers multiplication causes additional noises which are the shot noises with the values overcoming values resulting from primary generation of the unbalanced carriers. The dominant source of noises in avalanche photodiode is the shot noise multiplicated similarly to a signal multiplication [20]. Furthermore increase of shot noise in higher bandwidth can be attributed to higher bandwidth contain larger number of photons that have random arrival rate from the source of radiant energy that are responsible in shot noise occurrence.

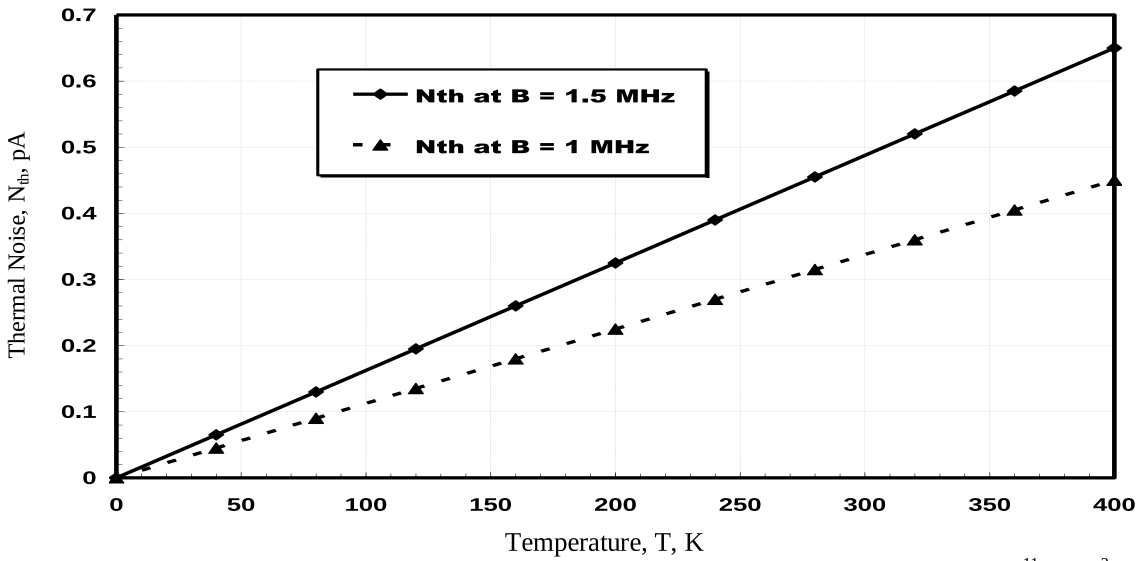

Fig.12. Variations of the thermal noise (N_{th}) against temperature (T) at different Bandwidth (B) with $\Phi = 1 \times 10^{11}$ (n/cm^2), R_L= 4 kΩ, and P=10nW.

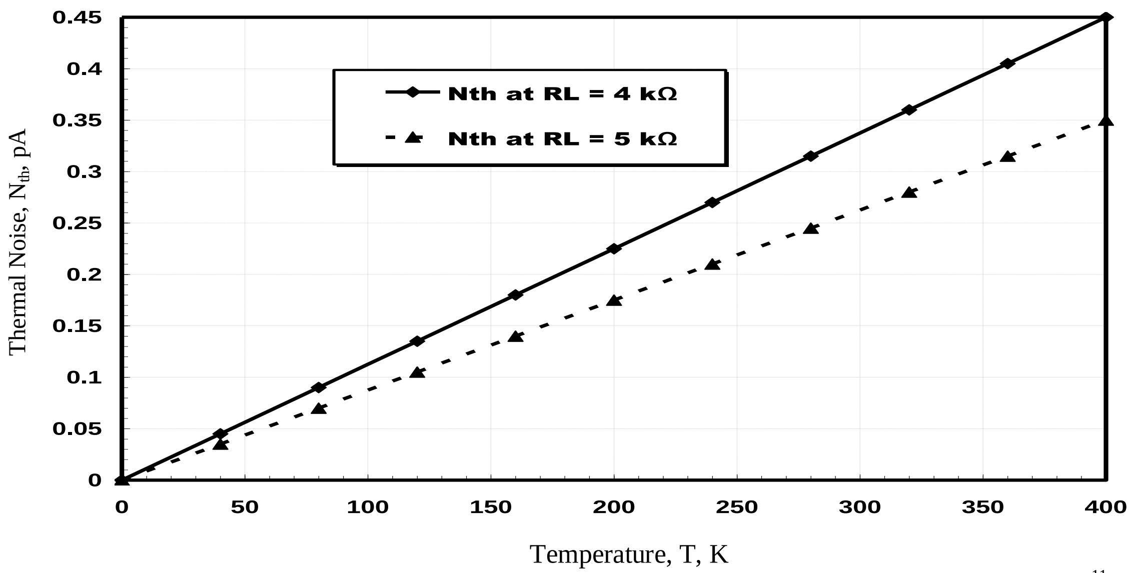

Fig.13. Variations of the thermal noise (N_{th}) against temperature (T) at different Load Resistance (R_L) with $\Phi = 1 \times 10^{11}$ (n/cm^2), B= 1MHz, and P=10nW.

Figures (12), (13) reveal the relation between thermal noise and temperature at different bandwidths and load resistance. From the figures thermal noise increases as temperature increase. This result can be credited to thermal noise is a consequence of the random motion of electrons through a conductor. The electrons are in constant motion, but they collide frequently with the atoms or molecules of the substance. Each free flight of an electron constitutes a minute current. The sum of all these currents taken over a long period of time must, of course, be equal to zero. But their ac component is thermal noise. Increasing temperature will raise the collisions number of the electrons with the atoms or molecules of the substance. Therefore thermal noise increase with temperature increment. In addition from the figure the thermal noise can be reduced by increase the load resistance. Therefore in order to have maximal value of a signal to noise ratio the high values of load resistance should be taken [20]. However high values of load resistance will restrict the photodiode frequency band which depends on the load resistance, according to the following equation [20]

$$B = \frac{1}{2\pi R_L C_t} \qquad (28)$$

Where C_t is the resultant capacity of the input circuit. For that reason in order to have minimal value of thermal noise the high values of load resistance or small values of bandwidth should be taken.

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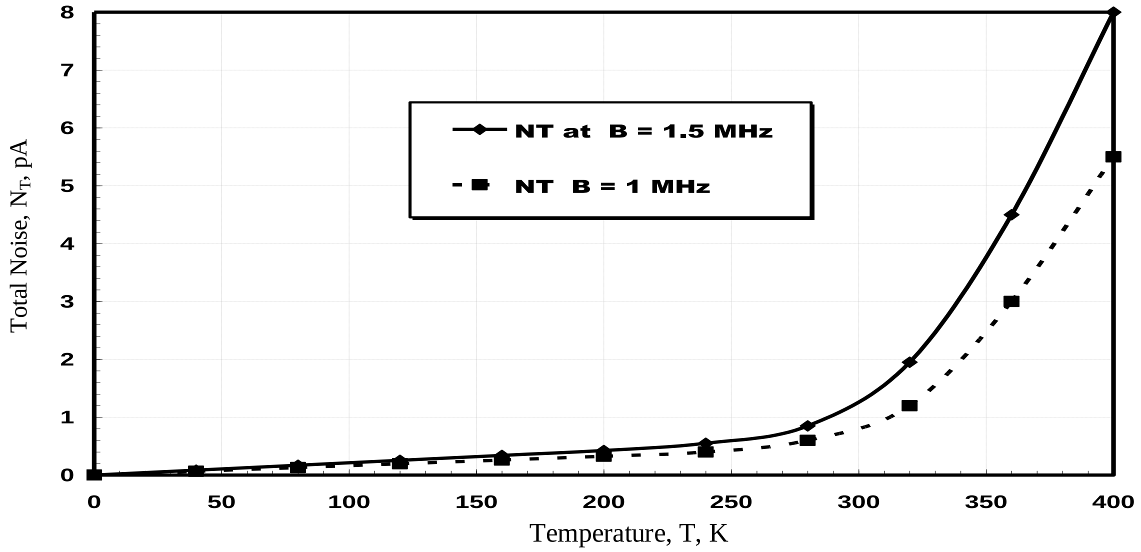

Fig.14. Variations of the total noise (N_T) against temperature (T) at different Bandwidth (B) with T=320K, P=10nW, and R_L=4 KΩ.

Figure (14) reveals the relation between total noise and temperature at different bandwidths. From the figure total noise increases as temperature increase. This result can be credited to since both shot and thermal noise increase with temperature increases. Therefore from equation (24) the total noise will increase with temperature. When the photodiode is exposed to the effects of light, then the photon energy is used to break the covalent bond releasing electrons and creating a hole in the process. If the generation of electrons and holes occurred in the depletion area, then the existing electric field removes them from that area before they get a chance to recombine. As a result, the reverse current (photocurrent) occurs. Also, the number of collisions of electrons with phonons in the semiconductor crystal lattice increases at the higher reverse bias voltage and as a result the internal gain will increase. Therefore the multiplication factor increases with increasing the reverse bias voltage. Moreover in figure (15) higher radiation fluence yields to lower multiplication factor. This result can be attributed to radiation induced defects created throughout the optically active volume tending to decrease the overall collection of optically generated minority carriers by reducing the minority carrier diffusion length. The crystal damage clusters serve as recombination sites causing optically generated hole-electron pairs to recombine before they can contribute to junction current [23]. However in figure (16) lower multiplication factor is observed at higher temperature. This result can be attributed to the fact that temperature plays a significant role in the number of radiation induced defects created throughout the optically active volume that take place during/after irradiation as a rise in 10^0C can double the reaction rates (Berejka and Cleland, 2011) [24] In addition these defects clusters serve as recombination sites causing optically generated hole-electron pairs to recombine before they can contribute to junction current [23].

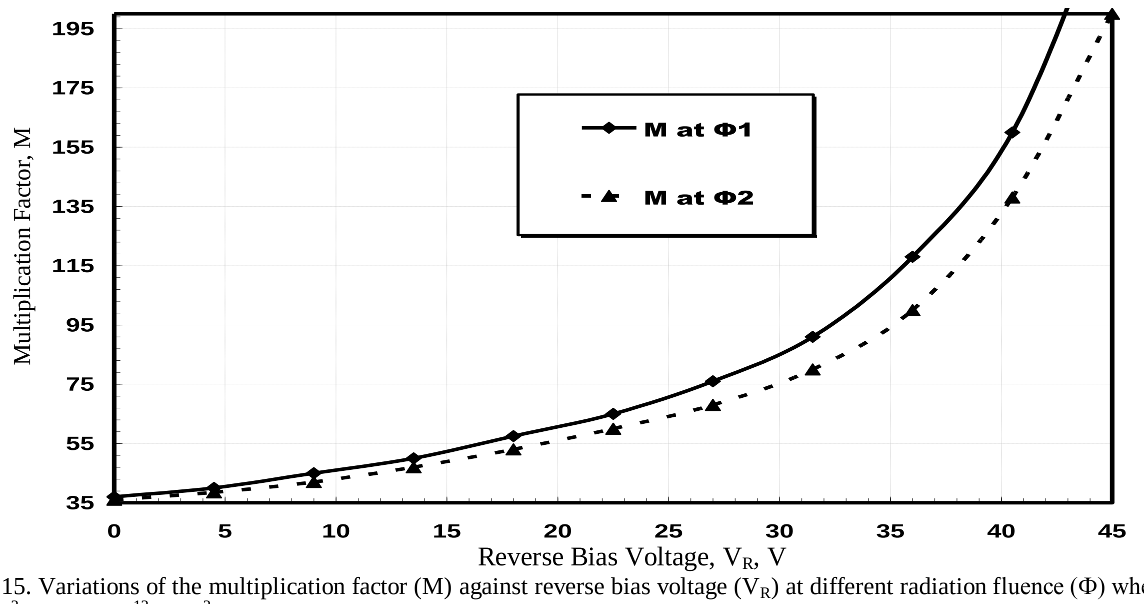

Fig.15. Variations of the multiplication factor (M) against reverse bias voltage (V_R) at different radiation fluence (Φ) where (Φ_1= 1x 10^{11} n/cm^2, Φ_2= 5x 10^{12} n/cm^2) with T=320K, P=10nW, and R_L=4 KΩ.

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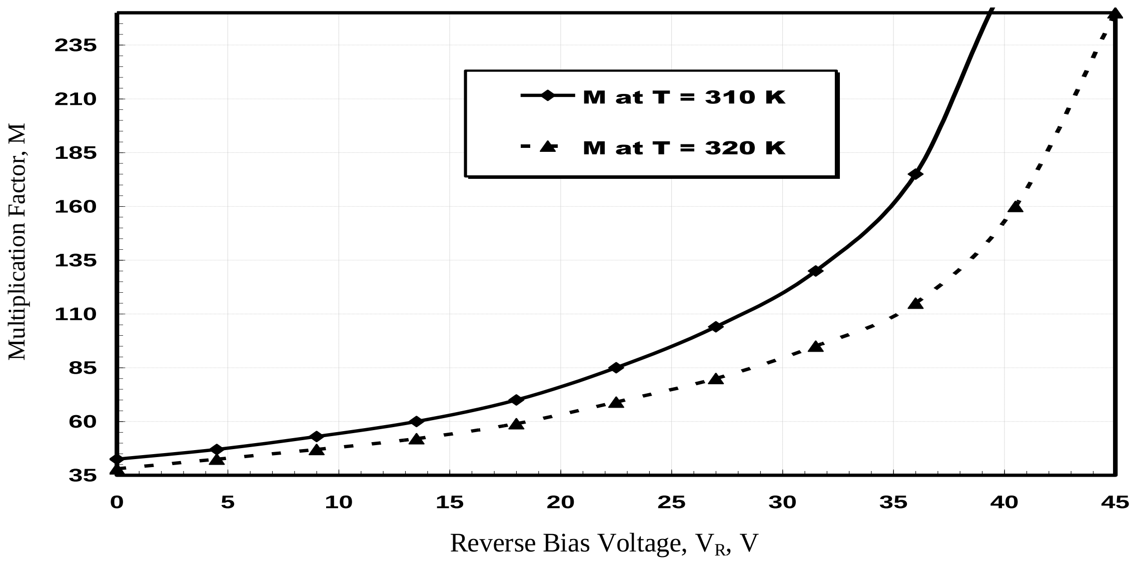

Fig.16. Variations of the multiplication factor (M) against reverse bias voltage (V_R) at different temperature (T) with $\Phi=1x10^{11}$ (n/cm^2), P=10nW, and R_L=4 KΩ.

IV. Conclusion

In this paper a block diagram model treating the radiation induced damage is proposed to provide a mean to control the optical properties of APDs in thermal radiation environments. The proposed treatment can be used to improve the efficiency, sensitivity, responsitivity and signal to noise ratio when APDs are selected to operate in these environments. A model is built using VisSim environment. The results showed that the key to reducing thermal radiation effect would expect in minimizing the active device volume. In the same time this provides higher detector sensitivity and responsitivity as well as detector efficiency. Moreover increase signal to noise ratio can be achieved by increase the load resistance. Furthermore increasing reverse bias voltage results in increase avalanche gain multiplication factor. These results are significant in designing optoelectronic systems, requiring immunity to the permanent and transient effects of thermal ionizing-radiation. The results are validated against the published experimental work and good agreement is observed.

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